Collaborative Innovation in the Context of Emerging Digital Technologies and the Fight against Climate Change

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This dissertation is dedicated to Erika & Junia Falcke.

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LIST OF ABBREVIATIONS

DV – Dependent Variable

EV – Electric Vehicle

IPCC – Intergovernmental Panel on Climate Change

IV – Independent Variable

IS – Information Systems

QCA – Qualitative Comparative Analysis

RSC – Relational Social Capital

SDG – Sustainable Development Goals

SC – Social Capital

SMN – Social Media Network

SSC – Structural Social Capital

UN – United Nations

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ZUSAMMENFASSUNG DER DISSERTATION

Kollaborative Innovationsstrategien erlauben Firmen innovativer und profitabler zu werden. Bislang wissen wir jedoch nicht, wie kollaborative Innovationsstrategien die großen Herausforderungen unserer Zeit bewältigen können. So ist die heutige Wirtschaft beispielsweise mit einer allgegenwärtigen Digitalisierung konfrontiert und muss vollständig dekarbonisiert werden, um die Schäden des globalen Klimawandels zu begrenzen. In dieser Dissertation werden daher Theorien entwickelt und getestet, die zu einem besseren Verständnis der kollaborativen Innovation im Kontext der Digitalisierung und des Klimawandels beitragen.

Die Dissertation präsentiert drei empirische Studien, die im Kontext einer kollaborativen Innovationsinitiative von 10 internationalen Energieversorgern angesiedelt sind, die im Rahmen eines jährlichen Programms gemeinsam 15 Clean-Tech Startups auswählen und mit ihnen zusammenarbeiten. Im Jahr 2016 schlossen sich diese Energieversorger - mit einem gemeinsamen Umsatz von über 173 Milliarden US-Dollar in mehr als 40 Ländern - mit dem Ziel zusammen, digitale Lösungen von Startups zu intergrien. Vor diesem Hintergrund habe ich eine 4 Jahre umfassende Datenbank aufgebaut die unter anderem 89 Interviews, 217 nicht-öffentliche Dokumente, digitale Längsschnittdaten und Umfragedaten (233 Antworten von 74 Personen), und Expertenbewertungen von Impact-Investoren enthält.

Die erste Studie der Dissertation zielt darauf ab, ein besseres Verständnis dafür zu entwickeln, wie mehrere Unternehmen ihre Innovationsstrategien koordinieren können, um ‘Grand Challenges’ wie den Klimawandel zu bewältigen. Sie stützt sich auf den theoretischen Ansatz der Innovationsökosysteme und kombiniert eine Qualitative Comparative Analysis (QCA) und eine Analyse von mehreren Fallstudien. Insbesondere wird untersucht, wie etablierte Unternehmen und Startups die Neuausrichtung von Ökosystemen koordinieren und wie und warum diese Ökosysteme zur Eindämmung des Klimawandels beitragen. Die Studie stellt ein theoretisches Modell für die Neuausrichtung von Ökosystemen zur Eindämmung des Klimawandels vor. Dieses trägt zu einem besseren Verständnis (1) der Rolle von kollaborativen Innovationsstrategien bei der Bewältigung von ‘Grand Challenges’ und (2) der Entstehung von Innovationsökosystemen in etablierten Industrien bei.

In der zweiten Studie wird anhand mehrerer Fallstudien ein theoretisches Modell für die späteren Phasen von kollaborativen Innovationsprozessen mit Schwerpunkt auf digitalen Lösungen entwickelt. Damit trägt die Studie zur Literatur über Wissensintegration und kollaborative Innovationsansätze bei. Das Modell deckt drei neuartige Mechanismen der Wissensintegration auf und bietet eine engere theoretische

Verbindung zwischen der Literatur über offene Innovation und dem ‘Knowledge Based View’ an. Ausserdem werden Argumente entwickelt, die erklären wie und warum diese Mechanismen der Wissensintegration durch verschiedene digitale Technologien und Schnittstellen beeinflusst werden.

Die dritte Studie kombiniert frühere Erkenntnisse aus der Sozialkapitaltheorie, und Forschung zum Netzwerken in Online- und Offline Kontexten mit Theorie zu Funktionen und Aktionspotentialen von digitalen Technologien. Damit wird ein theoretisches Modell für das Online-Netzwerken auf virtuellen Konferenzen entwickelt. Um dieses Modell zu testen, führe ich eine Längsschnittstudie durch, die Panel-Regressionsanalysen und Interviews umfasst. Mit einem empirisch qualifizierten Modell für ‘Online-Networking’ trägt diese Studie zur Literatur bei, indem sie die Theorie der zielgerichteten Nutzung von digitalen Technologien für den Aufbau von Sozialkapital im Kontext virtueller Konferenzen bestätigt. Die Theorie wird erweitert durch die Unterscheidung zwischen der strukturellen und relationalen Dimension, die Untersuchung zusätzlicher Funktionen und die Einführung von moderierenden Faktoren.

Insgesamt trägt diese Dissertation zu einem besseren Verständnis des Zusammenspiels von kollaborativen Innovationsstrategien, digitalen Technologien und dem Kampf gegen den Klimawandel bei. Die Erkenntnisse können Managern dabei helfen, kollaborative Innovationsstrategien in Zeiten von Digitalisierung und Dekarbonisierung zu nutzen.

DISSERTATION SUMMARY

Collaborative innovation increases firms' innovation and financial performance. However, so far, we lack an understanding of how collaborative innovation can tackle the grand challenges of our time. For instance, today's economy faces a ubiquitous digitalization and is required to completely decarbonize to limit the damages of global climate change. In response, this dissertation sets out to build, elaborate and test theory that contributes to a better understanding of collaborative innovation in the context of emerging digital technologies and climate change. It draws from several theoretical perspectives and presents three empirical studies at the inter-organizational, organizational, and individual levels of analysis.

All three studies are situated in the context of a collaborative innovation initiative amongst 10 international energy utilities that jointly select and collaborate with 15 energy technology startups in an annual program. In 2016, these utilities – with a joint revenue of over $173 Billion (USD) across more than 40 countries – joined forces intending to explore and adopt startups' digital solutions that could help the utilities navigate the transition towards a low carbon energy future. Over four years, I collected various data in this setting, including 89 interviews, 217 non-public documents, 290 hours of observations, longitudinal digital trace and survey data with 233 observations of 74 individuals, financial information on 133 contracts, and expert ratings from impact investors. This 4-year database is the basis for the three studies of this dissertation.

The first study aims to better understand how multiple firms can coordinate their innovative efforts to tackle grand challenges like climate change. It builds upon the theoretical lens of innovation ecosystems and combines a Qualitative Comparative Analysis (QCA) and a multiple case study approach. More specifically, it investigates how incumbents and startups coordinate via ecosystem realignments and how and why these ecosystem realignments contribute to climate change mitigation. It presents a theoretical framework of ecosystem realignment for climate change mitigation that contributes to a better understanding of (1) the role of firms' collaborative innovation in tackling grand challenges and (2) the emergence of innovation ecosystems from within existing industries.

The second study presents a multiple case study to develop a theoretical framework for understanding the open innovation back-end focusing on digital solutions. This framework contributes to the literature on knowledge integration and open innovation by uncovering three novel knowledge integration mechanisms and offering a tight theoretical connection between the open innovation literature and prior theorizing on the knowledge-based view of the firm. It further contributes by theorizing

how and why these knowledge integration mechanisms are shaped by different digital interfaces that sit between the digital layers provided by the external solution provider and the receiving firm.

The third study combines prior insights from social capital theory, online and offline networking, and digital features and affordances to develop a theoretical framework for online networking at virtual conferences. To test and substantiate it, I conduct a longitudinal mixed-methods study based on digital trace and survey data as well as complementary interviews. With an empirically qualified framework for online networking at virtual conferences, this study contributes to the literature by confirming the theory of purposeful feature utilization for social capital accumulation in the context of virtual conferences and extending it by (1) differentiating between structural and relational social capital, (2) expanding the set of investigated features, and (3) introducing contingency factors.

In sum, this dissertation contributes to a better understanding of collaborative innovation in the context of emerging digital technologies and climate change at the individual, organizational and inter-organizational levels. As such, it offers several insights for managers on how to conduct collaborative innovation in today's world facing the digitalization of everything and the need to rapidly decarbonize.

This is a cumulative dissertation that entails an introductory and concluding chapter and encapsulates the following three studies:

Study 1:

Falcke, L., Zobel, A.-K., and Comello, S. How Firms Realign to Tackle the Grand Challenge of Climate Change: An Innovation Ecosystems Perspective.

Abstract: Climate change is one of the most pressing grand challenges of our times. Firms play a fundamental role in the battle against climate change, as they must decarbonize and innovate products, services, and processes. Yet, grand challenges such as climate change are wicked problems that cannot be sufficiently addressed with stand-alone innovations. Instead, they often require complementary offerings that stem from multiple firms. Accordingly, we need a better understanding of how multiple firms can coordinate their innovative efforts to tackle grand challenges. Building upon the theoretical lens of innovation ecosystems, this study investigates how incumbents and startups coordinate via ecosystem realignments and how and why these ecosystem realignments contribute to climate change mitigation. Focusing on the electricity sector, we investigate 57 collaborative pilots between 10 large global electric utilities and 57 mature clean-tech startups using a Qualitative Comparative Analysis (QCA) and a multiple case analysis. We identify three ecosystem realignments that delineate how incumbents and new entrants unlock the climate change mitigation potential of their innovative products, services, and platforms by changing an existing carbon intensive industry structure through novel technological interfaces and strategic relations. We further derive mechanisms that detail how and why novel technological interfaces and strategic relations across firms address grand challenges through enhancing (1) resource efficiency, (2) the flexibility and resilience of infrastructure, and (3) the trading and leveraging of information and resources. We present a theoretical framework of ecosystem realignment for climate change mitigation that contributes to a better understanding of (1) the role of firms' collaborative innovation for tackling grand challenges and (2) the emergence of innovation ecosystems from within existing industries.

Keywords: Grand Challenges, Innovation Ecosystems, Climate Change, Qualitative Comparative Analysis (QCA), Multiple Case Study

Additional Information for Study 1:

- *This study is co-authored with Ann-Kristin Zobel (University of St. Gallen) and Stephen Comello (Stanford Graduate School of Business).*
- *The paper has been accepted and presented (or is scheduled for presentation) at the following peer-reviewed conferences:*
    - *World Open Innovation Conference 2021, Eindhoven, Netherlands (virtual)*
    - *Academy of Management Annual Meeting 2022, Seattle, US*
    - *GRONEN Conference 2022, Amsterdam, Netherlands*
    - *ARCS Conference 2022, Milan, Italy*
    - *European Group of Organization Studies (EGOS) Conference 2022, Vienna, Austria*
- *The paper has won or has been nominated for the following awards:*
    - *Winner of the Henry Chesbrough Best Student Paper Award at the World Open Innovation Conference 2021*
    - *Finalist for the Best Paper Award at the International QCA Paper Development Workshop (PDW) 2021*
    - *Finalist for the Best Student Paper Award at the GRONEN Conference 2022*
- *The paper has received a first-round revise and resubmit at the Journal of Product Innovation Management (VHB: A; AJG*: 4).

Study 2:

Falcke, L., Comello, S., and Zobel, A.-K. The Open Innovation Back-End: Knowledge Integration in the Context of Adopting External Digital Solutions.

Abstract: When engaging in open innovation, acquiring external knowledge is only half the battle. It is through the integration of external with internal knowledge – the open innovation back-end – that innovative solutions may be exploited. However, the mechanisms of how knowledge integration across firm boundaries takes place remain poorly understood. This is particularly salient in the case of digital solutions which increasingly are the loci of attention for firms seeking competitive advantage. Based on the qualitative analysis of 15 projects between startups offering digital solutions and electric utilities aiming at adopting them, we develop a theoretical framework for understanding the open innovation back-end with a focus on digital solutions. This framework contributes to the literature on knowledge integration and open innovation by (1) uncovering three novel knowledge integration mechanisms and offering a tight theoretical connection between the open innovation literature and prior theorizing on the knowledge-based view of the firm and (2) theorizing how and why these knowledge integration mechanisms are shaped by different digital interfaces that sit between the digital layers provided by the external solution provider and the receiving firm. For practitioners and policymakers, our findings provide implications for how to facilitate open innovation and the adoption of external digital solutions.

Keywords: Open Innovation, Knowledge Integration, Digital Technologies, Digital Interfaces

Additional Information for Study 2:

- *This study is co-authored with Stephen Comello (Stanford Graduate School of Business) and Ann-Kristin Zobel (University of St. Gallen).*
- *The paper has been accepted and presented (or is scheduled for presentation) at the following peer-reviewed conferences:*
    - *World Open Innovation Conference 2020, virtual*
    - *JPIM Research Forum, virtual*
    - *Academy of Management Annual Meeting 2021, virtual*
    - *Strategic Management Society Annual Conference, 2021, virtual*
    - *European Group of Organization Studies (EGOS) Conference 2021, virtual*
- *The paper has won or has been nominated for the following awards:*
    - *Winner of the Overall Best Conference Award at the Journal of Product Innovation Management (JPIM) Research Forum 2021*
- *The paper has received a second-round revise and resubmit at Research Policy (VHB: A; AJG*: 4**; FT50*).

Study 3:

Falcke, L. Online Networking at Virtual Conferences: Feature Usage and Relational vs. Structural Social Capital

Abstract: Nowadays, online networking takes place not only on Social Media Networks (SMNs) but also at virtual conferences - preliminary versions of a "metaverse", recently introduced as the future of making social connections by Mark Zuckerberg. But how can individuals effectively network at virtual conferences and build relationships that go beyond LinkedIn connections? Networking refers to individuals' strategic behavior to accumulate social capital (SC) – the number of relationships (structural) and the trust and reciprocity thereof (relational). Prior research has often neglected the relational dimension and virtual conferences as relevant settings for SC accumulation. In response, this study combines prior insights from social capital theory, online and offline networking, and digital features and affordances to develop a theoretical framework of online networking at virtual conferences. To test and substantiate it, I conduct a longitudinal mixed-methods study based on digital trace and survey data of 74 participants at four sequential virtual conference events in the energy sector, complemented with 19 interviews and 120 hours of observations. I find that visiting booths relates to increases in structural SC. Bi-lateral and multi-lateral web conferencing and direct messaging, instead, to increases in relational SC. The qualitative insights substantiate the theorized mechanisms, shed light on discrepancies between theory and empirics and provide relevant contingency factors. With an empirically qualified framework of online networking at virtual conferences, this study contributes to the literature by confirming the 'theory of purposeful feature utilization' for SC accumulation in the context of virtual conferences and extending it by (1) differentiating between structural and relational SC, (2) expanding the set of investigated features, and (3) introducing contingency factors. Thereby, this study sheds light on virtual conferences as a relevant online networking phenomenon and provides practical insights for participants and organizers of virtual conferences.

Keywords: Online Networking, Virtual Conferences, Feature Usage, Social Capital Theory

Additional Information for Study 3:

- *This study is single-authored.*
- *The paper has been accepted and presented (or is scheduled for presentation) at the following peer-reviewed conferences:*
    - *European Conference on Information Systems 2022, Timisoara, Romania*
    - *Academy of Management Annual Meeting 2022, Seattle, US*
- *The paper has won or has been nominated for the following awards:*
    - *Nominated for the William H. Newman Award for the Best Paper based on a Dissertation at the Academy of Management Annual Meeting 2022 by the CTO Division (i.e., Best Division Paper based on a Dissertation).*

Chapter 1

Introduction and Dissertation Framework

1.1 Motivation

Firms across all industries have increasingly adopted more collaborative approaches to innovation that leverage knowledge flows across firm boundaries (e.g., Afuah & Tucci, 2012; Chesbrough, 2003; 2019; Dahlander & Gann, 2010; Tucci et al., 2016; von Hippel, 1986). This openness to external knowledge has become an important source of a firm's competitive advantage, increasing its innovation and financial performance (Laursen & Salter, 2006; Lu & Chesbrough, 2021). Accordingly, a large body of literature has developed theoretical insights on this novel paradigm of open and collaborative innovation at different levels of analysis (see Bogers et al., 2017 for an overview). At the inter-organizational level, for instance, research revealed the importance of strategic alliances (e.g., Hagedoorn, 1993), inter-organizational networks (e.g., Shipilov and Gawer, 2020) and, more recently, coordination in innovation ecosystems to realize complex value proposition (e.g., Adner & Kapoor, 2010). Leveraging the power of innovation ecosystems has led to the rise of today's most profitable firms, platform businesses like Amazon, Facebook, Tesla, Apple, and Microsoft (Cennamo, 2020; Jacobides et al., 2018; Rietveld et al., 2019). The dominance of these platform businesses further emphasizes that understanding collaborative innovation deserves to be at the center stage in management and organization studies. Furthermore, understanding collaborative innovation becomes increasingly relevant not only for academics and managers but also for policymakers concerned with regulating such platform firms that leverage collaborative innovations across firm boundaries (e.g., Cusumano et al., 2021). Related work complemented this inter-organizational understanding by investigating the organizational capabilities and processes that firms employ to implement and benefit from collaborative innovation (e.g., Afuah & Tucci, 2012; Felin & Zenger, 2014; Zobel, 2017). Ultimately, however, the success of collaborative innovation depends on firms' employees that practice it. Thus, a growing body of research has moved to investigate collaborative innovation at the individual level (e.g., Bogers et al., 2018; Lifshitz-Assaf, 2018). In sum, collaborative and open innovation has become a vibrant research field with high practical relevance and emerging theories at the inter-organizational, organizational, and individual levels. Henry Chesbrough's (2003) seminal work on open and collaborative innovation has reached more than 25.000 citations on Google scholar in less than 20 years. This is another powerful illustration of the field’s importance.

Over the last 20 years, the world, however, has evolved rapidly, and the field of collaborative innovation, so far, has contributed little to a better understanding of how firms can tackle the grand challenges of our time. Grand Challenges are problems with

broad societal implications across the globe that are immune to easy fixes (George et al., 2016; Toetzke et al., 2022). Examples include global pandemics (Dahlander & Wallin, 2020), the pollution of our oceans (Porter et al., 2019) and the provision of affordable and high-quality healthcare (Vakili & McGahan, 2016). The Sustainable Development Goals (SDGs) promulgated by the United Nations (UN) provide a guiding framework for these grand challenges (UN, 2015). The complexity, uncertainty and evaluative nature of these challenges make them 'grand' challenges (Ferraro et al., 2015). Recently, the field of management and organization studies has acknowledged a shortcoming in researching such grand challenges (e.g., George et al., 2016). Accordingly, leading scholars in the collaborative innovation field also call for a shift of scholarly attention toward grand challenges (McGahan et al., 2021). Investigating collaborative innovation in the context of grand challenges is of high theoretical interest and practical relevance. Collaborative innovation is likely to be a crucial part of the solution to grand challenges. At the same time, these grand challenges are changing the nature of collaborative innovation and are thus challenging our current theoretical understanding of collaborative innovation across all levels of analysis. In response, this dissertation sets outs to investigate collaborative innovation in the context of grand challenges. More specifically, it focuses on two grand challenges: the fight against global climate change (related to, among others, SDG 13 – climate action) and the ubiquitous digitalization of our economy (related to, among others, SDG 9 – industry, innovation, and infrastructure).

Global climate change is caused by anthropogenic greenhouse gas emissions (GHG) and leads to, among other things, rising sea levels and more frequent and catastrophic floods and wildfires (Rogelj et al., 2021). Accordingly, the intergovernmental panel on climate change (IPCC) warns that we are approaching a climate catastrophe (IPCC, 2021). Limiting the damages caused by global climate change requires limiting the average global temperature rise to 1.5°C above pre-industrial levels (IPCC, 2021). In practical terms, this means the complete decarbonization of the global economy by 2050. This low carbon transformation is challenging and, among other things, relies on collaborative innovation approaches that combine the knowledge, resources, and capabilities of diverse actors from different firms, industries, jurisdictions, and disciplines (Ferraro, Etzion, and Gehman, 2015; Grodal & O'Mahony, 2017; Howard-Grenville et al., 2014; Porter, Tuertscher, and Huysman, 2019). At the same time, climate change transforms the nature of collaborative innovation. In the context of climate change, firms are increasingly concerned with realizing complex value propositions, must cope with higher

uncertainty, and are dependent on integrating diverse perspectives across a broader set of heterogeneous actors and individuals (George et al., 2016; McGahan et al., 2021).

Concerning the second grand challenge, exponential developments in and the pervasive use of digital technologies require and facilitate the adoption - and transform the nature - of collaborative innovation at an unforeseen speed and scale (e.g., Dahlander et al., 2021; Enkel et al., 2020; Nambisan et al., 2019). Broad examples of such pervasive digital technologies include cloud computing, machine learning, blockchain, and the internet of things. These digital technologies are increasingly permeating every enterprise, putting pressure on firms to engage in digital transformations (Appio et al., 2020). In response, firms are increasingly turning to external partners for collaborative innovation approaches to keep up with rapid developments in digital technologies (Nambisan et al., 2017; 2019). This collaborative approach to innovation is required because the architecture of digital technologies enables a generative and distributed innovation process where contributors and developers are geographically dispersed and often transcend firm boundaries (e.g., Afuah and Tucci, 2012; Yoo et al., 2012). At the same time, the pervasiveness of these digital technologies transforms the collaborative innovation process itself by reducing search costs, blurring spatial and temporal boundaries, and enabling digital platform business models (Gawer, 2014; Nambisan et al., 2019; Yoo et al., 2012).

Looking simultaneously at both the context of emerging digital technologies and climate change is important because digital technologies and platforms play a crucial role in the fight against climate change (Inderwildi et al., 2020; George et al., 2021). Machine learning applications, for instance, allow increasing the energy efficiency of firms and individual households. Similarly, digital platforms enable the rise of low carbon energy communities that leverage energy from residential solar panels. Finally, big data and advanced analytics can optimize the charging of electric vehicles at the system level – a necessity for a decarbonized mobility and energy future.

By focusing on collaborative innovation in the context of emerging digital technologies and climate change, this dissertation aims to make a first step towards understanding the role of collaborative innovation in the context of the grand challenges of our time. The following section provides a broad overview of the field of collaborative innovation by reviewing the literature at the inter-organizational, organizational, and individual levels. At each level, the section reveals research gaps that emerge at the intersection of collaborative innovation, climate change and digital technologies.

After reviewing the literature, this chapter introduces several theoretical perspectives and empirical approaches at different levels of analysis to make sense of this interplay and fill the research gaps. This introductory chapter concludes with an overarching framework of collaborative innovation in the context of emerging digital technologies and climate change. Subsequently, Chapters 2, 3, and 4 present the three studies that form the dissertation's core. Each chapter entails a more focused and detailed literature review and research question as well as more elaborate descriptions of methods, results and implications for theory and practice. The dissertation ends with a summary of findings and implications in chapter 5.

1.2 The collaborative innovation literature at different levels of analysis and research gaps in the context of digitalization and climate change

This section briefly reviews the literature on collaborative innovation at the inter-organizational, organizational, and individual levels of analysis. By introducing the context of emerging digital technologies and climate change, at each level, research gaps emerge at the intersection of collaborative innovation, digital technologies, and climate change.

1.2.1 Literature review and research gap at the inter-organizational level

Our understanding of collaborative innovation at the inter-organizational level builds upon initial insights from studies on strategic alliances (e.g., Chesbrough, 2003; Faems et al., 2008; Hagedoorn, 1993; Rosenkopf & Schilling, 2012) and inter-organizational networks (for an overview see Shipilov and Gawer, 2020). While these more traditional forms of collaborative innovation stand upon (primarily bilateral) contractual relations, engaging multiple increasingly heterogeneous actors in the innovation process also requires new, more relational forms of inter-organizational coordination (Zobel & Hagedoorn, 2020). Accordingly, the literature has shifted its focus towards coordination within new organizational forms such as meta-organizations – organizations comprised of organizational members not necessarily bound by contractual relationships but formed around a collective goal at the system level (Gulati et al., 2012; Kretschmer et al., 2020; Snow et al., 2011; Zobel & Comello, 2019). Another substream of the collaborative innovation literature adopted more of a technology focus and started to investigate innovation ecosystems (e.g. Adner & Kapoor, 2010; Hannah & Eisenhardt, 2018; Kapoor, 2018). In such innovation ecosystems, multiple heterogeneous actors coordinate to align their complementary technologies into a coherent value proposition (Jacobides et al., 2018).

Innovation ecosystems are particularly relevant in the context of emerging digital technologies. Digital technologies led to the rise of digital platforms (Nambisan et al.,

2017) that enable firms to create value by orchestrating ecosystems of complementary third-party developers (e.g. Cennamo, 2020; Gawer, 2014). Similarly, ecosystems seem to be particularly relevant in the context of the grand challenge of tackling climate change. Tackling climate change, for instance, requires firms to realize increasingly complex low carbon value propositions that combine the interdependent offerings of multiple heterogeneous firms (George et al., 2016; Howard-Grenville et al., 2014). These complex low carbon value propositions depend not only on modular physical technologies like solar panels or wind power plants but also on digital technologies and platforms (e.g., George et al., 2020; Inderwildi et al., 2020). The interplay of digital technologies and low carbon technology and infrastructure for tackling climate change further highlights the importance of investigating collaborative innovation in the context of both climate change and emerging digital technologies. More importantly, combating climate change requires the decarbonization of already existing industries with legacy structures (e.g. Frei et al., 2018). Thus, it is particularly important to understand better how firms can use ecosystems to realign these existing carbon-intensive industries.

While prior literature investigated how ecosystems emerge around digital platforms (Dattée et al., 2018) and disrupt incumbent industries (Ansari et al., 2016; Khanagha et al., 2022), we currently lack insights into how firms can realign ecosystems from within existing industries. More importantly, we lack an understanding of how firms can find the appropriate configuration of digital technology interfaces and ecosystem strategies to facilitate climate change mitigation. In response, the second chapter of this dissertation, situated at the inter-organizational level, aims to investigate *how and why different combinations of digital technology interfaces and ecosystem strategies enable contributions to climate change mitigation.*

1.2.2 Literature review and research gap at the organizational level

At the organizational level, prior work has established that firms generally benefit from openness to a variety of external innovation sources, albeit with diminishing returns (e.g. Katila and Ahuja, 2002; Garriga et al., 2013; Laursen and Salter, 2006, 2014). The benefits of openness further depend on, among other factors, firms' absorptive capacity (Cohen & Levinthal, 1990; Zobel, 2017). External innovation sources include, for example, universities, competitors, suppliers, consultancies, startups or individuals (e.g. Afuah & Tucci, 2012; Bogers et al., 2017; Chesbrough, 2003; West et al., 2014). Accordingly, most prior studies focused on investigating how firms can tap into such sources by scouting and searching for knowledge beyond their organizational boundaries (see West and Bogers, 2014 for an overview). More recently, studies have

also investigated the underlying processes in this front-end of collaborative innovation, uncovering, for instance, value-adding activities by scouting units (Monteiro and Birkinshaw, 2017), problem formulation processes (e.g. Wallin et al., 2018), innovation governance approaches (e.g. Felin & Zenger, 2014), or different external knowledge search paths (Lopez-Vega et al., 2016).

However, these activities in the front-end of collaborative innovation are only "half the battle," as benefiting from collaborative innovation requires not only the identification of promising solutions but also the integration of said solutions with internal knowledge and into existing technological systems at the focal firm (West and Bogers 2014, p. 821). Some scholars have started to examine this 'back-end' of collaborative innovation, focusing, for instance, on the rivalry between multiple business units (Seran & Bez, 2020). However, it remains rather poorly understood (Chesbrough, 2019).

In the context of emerging digital technologies, this lack of understanding of the collaborative innovation back-end becomes increasingly relevant. Digital technologies follow a layered-modular architecture, where interfaces connect functional elements across the device, network, data, and application layers (Henfridsson et al., 2018; Yoo et al., 2010). This architecture allows for independent developments at each level. Consequently, realizing a complete digital solution depends on post hoc integration across digital interfaces between the different layers (Yoo et al., 2012). The upper layers of the layered-modular architecture are intangible, allowing for instantaneous distribution across spatial boundaries. Furthermore, they are re-programmable, allowing continuous updates and innovations of products even during phases of use (Autio et al., 2021; Kallinikos, 2013; Yoo et al., 2010). This blurring of spatial and temporal boundaries enables more heterogeneous and geographically dispersed actors - often also dispersed across the boundaries of multiple organizations - to participate in the innovation process (e.g., Nambisan et al., 2019; Yoo et al., 2012). Accordingly, developments at each layer come from a wider variety of actors and thus need to be integrated not only across digital interfaces but also across firm boundaries – the collaborative innovation back-end (e.g. Yoo et al., 2012).

The context of climate change mitigation re-emphasizes the importance of understanding the collaborative innovation back-end. For instance, firms across industries are increasingly pledging to reach net-zero carbon emissions by 2030 or 2050 (Comello et al., 2021). As many of the solutions for this ambitious decarbonization build on digital technology and reside outside the firm's boundary, accessing external digital solutions becomes essential for realizing such pledges (e.g., Bumpus & Comello,

2017). However, to realize pledged carbon reduction targets, firms need to, not only, find and access external digital technologies but they especially need to integrate and deploy them at scale (e.g., Zobel et al., 2022). In response, the third chapter of this dissertation investigates *how firms can integrate different types of digital solutions relevant to climate change mitigation.*

1.2.3 Literature review and research gap at the individual level

Shifting the focus to the individual level, scholars acknowledge that the search for and integration of external knowledge ultimately depends on the behaviors and capabilities of individuals (e.g. Bogers et al., 2018; Salter et al., 2014; ter Wal et al., 2017; Dahlander et al., 2016). Individuals, for instance, act as the boundary spanners that connect the firm to its external environment and enable the flow and integration of knowledge across firm boundaries (e.g. Allen et al.,1979; Dahlander et al., 2016; Tushman, 1977; Zobel et al., 2021). Boundary spanners need to overcome the 'not-invented-here' syndrome (Antons & Piller, 2015). They immerse themselves in partner organizations (Salter et al., 2014; Zobel et al., 2020) and gate-keep or shepherd external knowledge into the home organization (ter Wal et al., 2017). Similarly, they need to accumulate social capital (Monteiro & Birkinshaw, 2017) and align their identity with those of the collaborative innovation partners (Bogers et al., 2017; Zobel & Hagedoorn, 2020). While some scholars have started to investigate the role of individuals, a detailed understanding of this 'human side' of collaborative innovation is lacking (Bogers et al., 2017; Bogers et al., 2018, Zobel et al., 2020).

The 'human side' of collaborative innovation becomes particularly important as the evaluative and uncertain nature of a grand challenge like climate change requires firms to engage a broader range of individuals in innovation and decision-making processes (Watson et al., 2017; Ansari et al., 2013). It is the integration and combination of knowledge and ideas from multiple different individuals that help make sense of a grand challenge (Ferraro et al., 2015). However, the success of such sensemaking largely depends on individuals' ability to accumulate social capital – the number and structure of interpersonal relationships and the trust and reciprocity embedded in these relationships (Monteiro & Birkinshaw, 2017; Tortoriello, Reagans, McEvily 2012; Kale, Singh, Perlmutter, 2000; Yli-Renko, Autio, Sapienza, 2001). However, building up social capital takes time and requires repeated social interactions (e.g. Cousins et al., 2006; Nahapiet & Ghoshal, 1998).

Better understanding how individuals accumulate social capital in collaborative innovation becomes particularly important in the context of emerging digital technologies. Exponential developments in digital technologies reduce search,

communication and transaction costs and thus facilitate the emergence of collaborative innovation activities in the virtual realm (e.g., Lanzolla, Pesce, Tucci, 2020: Lyytinen et al., 2016; Urbinati et al., 2020). For instance, firms and individuals engage on crowdsourcing platforms (e.g., Afuah & Tucci, 2012; Jeppesen & Lakhani, 2010; Piezunka & Dahlander, 2015) participate in open-source software development (e.g., Henkel, 2006; West & O'Mahony, 2008) and increasingly organize collaborative activities in a virtual setting (Urbinati et al., 2020). Related literature in the information systems field has already investigated how individuals can use digital technology features to accumulate social capital on Social Media Networks like LinkedIn (Weiler et al., 2021; Hinz et al., 2011; Lanz et al., 2019). However, we lack an understanding of how individuals can use digital technologies to accumulate social capital in virtual open innovation conferences. In such settings, multiple heterogeneous and formerly unconnected parties come together, and the provided digital communication technologies significantly differ from those on Social Media Networks. Developing a better understanding of virtual open innovation also plays a role in the fight against climate change. Effective and efficient collaboration across spatial boundaries with digital communication technology is likely an essential lever for facilitating climate innovation while limiting carbon emissions of the innovation process itself.

Accordingly, chapter 4 aims to investigate *how individuals can use digital technologies to accumulate social capital at virtual open innovation conferences concerned with accelerating climate innovation.*

1.2.4 Summary of research gaps at the intersection of collaborative innovation, digital technologies, and climate change

To summarize, this section derived three gaps at the different levels of analysis that emerge at the intersection of collaborative innovation, digital technologies, and climate change. At the inter-organizational level, we lack an understanding of how firms can realign carbon-intensive industries with digital technology interfaces and ecosystem strategies to contribute to climate change mitigation. At the organizational level, we lack an understanding of the collaborative innovation back-end that enables the adoption of external digital technologies relevant to tackling climate change. At the individual level, we lack an understanding of how individuals use digital communication technology to build social capital in emission-saving virtual collaboration settings concerned with climate innovation. Considering the pervasiveness of digital technologies, the pressing need for decarbonization and the accompanying acceleration of collaborative approaches to innovations, these gaps are relevant for scholars and practitioners alike. This dissertation applies different

theoretical lenses that are particularly suited to investigate collaborative innovation in the context of emerging digital technologies and climate change at the inter-organizational, organizational, and individual levels of analysis. The following section elaborates on these perspectives.

1.3 Theoretical perspectives

1.3.1 Innovation ecosystems

Following Adner (2017), innovation ecosystems describe the structure of technological interdependencies and the flow of inputs and outputs of firms (i.e. the structuralist approach). The center of these ecosystems builds the 'focal' firm that faces upstream and downstream interdependencies. Upstream, the focal firm is dependent on suppliers that provide components that the focal firm then integrates into its products or services. Downstream, the focal firm relies on intermediaries (between the focal firm and the customer) and on complementors, providing products and services that the customer combines or bundles with the focal firm's product or services to realize the desired value proposition. This structure gives rise to unique (where A doesn't function without B) and supermodular (where A makes B more valuable) complementarities that are not fully hierarchically controlled (Jacobides et al., 2018). Platform-based ecosystems, however, allow for more hierarchical control as the locus of integration of complementary offerings shifts from the customer to the platform owner (e.g. Cennamo, 2020; Gawer, 2014; Kapoor, 2018; Kretschmer et al., 2020). This rather new theoretical perspective has gained increasing traction in the field of collaborative innovation as it offers a framework to account for technological interdependencies between multiple firms that aim at combining their offerings into coherent value propositions (Adner & Kapoor, 2010; Kapoor, 2018). Given its focus on technological interdependencies and how multiple heterogeneous firms coordinate their innovative efforts, this lens is particularly suited to investigate collaborative innovation in the context of emerging digital technologies and climate change. Thus, chapter 2 uses this lens to investigate how firms can realign carbon-intensive industries with digital technology interfaces and ecosystem strategies to unlock climate impact.

1.3.2 Knowledge-based view

The knowledge-based view of the firm suggests that the creation, integration and transfer of knowledge across boundaries are of crucial strategic importance to the firm (Grant, 1996; Kogut & Zander, 1992). However, this knowledge transfer is difficult to achieve because knowledge is often 'sticky' (Szulanski, 1996). Sources of stickiness include, among others, the tacitness of knowledge (e.g. Nonaka, 1994), and the lack of a common language between actors involved in the process of knowledge integration

or transfer (e.g. Carlile, 2004; see also Zahra et al., 2020). Another source is the complexity – i.e. the number and nature of interdependencies of subcomponents of a technology (product) for which knowledge is exchanged (e.g. Zhao and Anand, 2013). To overcome such stickiness, actors need to engage in knowledge translation – making the knowledge available in the language that the recipient of the knowledge transfer can understand (e.g., Carlile, 2004; ter Wal et al., 2017). It further requires knowledge transformation – negotiating interests between knowledge exchange actors with opposing interests (e.g. Carlile, 2002; Bechky, 2003). Since collaborative innovation is predominantly concerned with transferring knowledge across organizational boundaries, the knowledge-based view is a suitable lens to investigate the back end of open innovation in the context of emerging digital technologies and climate change (chapter 2).

1.3.3 Social capital theory

Social capital theory proposes that relationships in a social network are valuable resources that form social capital (Bourdieu, 1986; Coleman, 1988). Prior work conceptualized social capital as a three-dimensional construct with a structural, a cognitive and a relational dimension (Nahapiet and Ghoshal 1998). The structural dimension (also structural social capital or structural embeddedness) captures the number of relationships an individual has in a network and also the structural configuration of the network – (e.g.) the existence of structural holes or network closure (Burt, 2005; Moran, 2005; Walker, Kogut and Shan, 1997). The relational dimension (also relational embeddedness or relational capital) captures the quality and strength of relationships – especially accounting for elements like trust and reciprocity embedded in relationships (Nahapiet & Ghoshal, 1998; Blutt, 2009). The cognitive dimension draws from social identity theory and social exchange theory and entails elements such as trust, obligation and identification (Nahapiet & Ghoshal, 1998). Prior work already showed that social capital is an essential and suitable lens that helps to understand better collaborative innovation processes at the individual level (e.g. Monteiro & Birkinshaw, 2017). Emerging digital technologies are likely to change the way individuals collaborate and accumulate the required social capital. Thus, applying a social capital lens to collaborative innovation conferences in a virtual setting seems to be a promising path to improve our understanding of collaborative innovation in the context of emerging digital technologies and climate change (chapter 3).

1.3.4 Architecture, features, and affordances of digital technologies

To complement the above-described theoretical perspectives, I introduce theoretical frameworks from the literature on managing information systems (see Nambisan et al.,

2017 for an overview). First, digital technologies follow a layered-modular architecture with four layers (Yoo et al., 2010; Henfridsson et al., 2018): the application, data, network, and device layers. The division into four separate layers allows for rapid independent innovations on each layer (Yoo et al., 2012). The malleability of layers allows for a post-hoc integration of innovations on each layer through digital interfaces to realize a coherent digital solution (Henfridsson et al., 2018). The resulting solution can be characterized by features and affordances. Features refer to the specific functionalities that a digital solution provides (Leonardi, 2013). For instance, a social media network like LinkedIn is a digital solution that provides features such as a chat window or a search button. Features describe a part of the technology (e.g., the search button on LinkedIn). Affordances, instead, refer to the action potential of certain features or technologies (Majchrzak & Markus, 2013). Put differently, affordances capture what different users can do with a particular technology or feature. As such, affordances result from a solution's technological feature and a user's intent and ability to use that feature in a certain way.

In sum, the information systems literature provides a theoretical toolkit that allows making sense of digital technologies along the dimensions of layers, interfaces, features, and affordances. This dissertation uses this theoretical toolkit and combines it with the above-described theoretical perspectives from the management field (innovation ecosystems, knowledge-based view, social capital theory). This combination of theoretical frameworks allows for filling the derived research gaps at the intersection of collaborative innovation, emerging digital technologies, and climate change.

The first study of this dissertation, presented in chapter 2, sheds light on different configurations of digital layers and interfaces and how their climate impact can be unlocked with the appropriate innovation ecosystem strategy. Chapter 3 uses the knowledge-based view to investigate the collaborative innovation back-end and, more specifically, how and why knowledge integration differs across the different digital interfaces of the layered-modular architecture. In building the mechanisms, it draws from the concept of affordances. Chapter 4 looks at the features and affordances of digital communication technologies to investigate how individuals accumulate social capital at virtual open innovation conferences concerned with climate innovation.

1.4 Research setting

All three studies of this dissertation are situated in the context of a collaborative innovation initiative amongst 10 international energy utilities that jointly select and collaborate with 15 energy technology startups in an annual program. In 2016, these

utilities – with a joint revenue of over $173 Billion (USD) across more than 40 countries – joined forces intending to explore and adopt startups' digital solutions that could help utilities survive, navigate, and accelerate the transition toward a low carbon energy future. The energy sector has recently seen rapid changes with the rise of renewables, the decentralization of energy systems, and the emergence of disruptive new technologies (Bumpus & Comello, 2017). Digital solutions are core to this transition. They can substantially enhance energy systems' safety, productivity, and sustainability by making existing infrastructure (e.g., electricity grids) 'smart' and by offering new intelligent energy services to end-consumers (e.g., home automation). The annual collaborative innovation program at hand enables the co-development of such digital solutions by combining startups' innovative digital solutions with utilities' experience and resources to refine and deploy such solutions at scale.

Each year the 10 utilities select 15 startups into a 6-month program that includes 4 one-week-long modules during which all members co-locate to intensify their collaborative activities. At the beginning of the program, each startup pairs with at least one of the utilities to kick off a collaborative project (pilot). In these pilots, the utilities explore the startups' digital solutions, test their integration into the utilities' existing systems and experiment with use-cases. By the program's conclusion, each project group (startup-utility pairing) shares the collaboration results and decides whether and to what extent 'pilots' are being transformed into a commercial roll-out. From 2017 to 2019, three editions of the program took place in a physical format. For each of the four modules of the program, all participants flew to a dedicated location that could be the headquarters of the participating utilities or renowned startup hubs (e.g., Silicon Valley). In 2020, the fourth edition of the program took place in a virtual format. The modules were organized as four virtual conferences where participants interacted through digital communication technologies.

The above-described setting of a collaborative innovation program situated in the electricity sector is very well suited to investigate collaborative innovation in the context of emerging digital technologies and climate change. This is because the electricity sector is at the core of climate change mitigation efforts, as it accounts for over 35% of global CO2 emissions itself (IEA, 2020) and is seen as the key to enable the reduction of CO2 emissions in other industries (Schmidt, 2021). Critical to achieving such decarbonization are not only innovations and technological developments in renewables (e.g., solar, wind) but also in complementary digital technologies such as smart grids, virtual power plants, and intelligent charging algorithms (George, Merrill, Schillebeeckx, 2021; Inderwildi et al., 2020). However,

those electricity incumbents that control critical infrastructure and retain large market shares are often not able to develop these on their own and are thus increasingly engaging in collaborative innovation with digital innovators (Bumpus and Comello 2017).

For the first study that uses data across four years, the setting provides a rich variety of different combinations of technologies and ecosystem strategies. This allows me to investigate how heterogeneity in these combinations relates to potential climate mitigation impact. For the second study, situated in the third edition of the program, the wide variety of digital solutions enabled me to theorize about the implications of digital interfaces for knowledge integration. Finally, in the virtual format of the fourth edition, the conference organizer provided a central virtual conference platform on which individuals had access to a wide variety of virtual communication features. Accordingly, I could track and investigate how heterogeneity in the usage of these features relates to the accumulation of social capital.

Another key advantage of this setting is that it holds many parameters constant. For instance, all firms are situated in the electricity industry, the utilities are of similar size, the startups are at a similar stage, and most importantly, the program provides the same structure for all participating firms and individuals. As such, the setting controls for potential influences from these parameters and allows to focus specifically on the described variables or processes of interest.

1.5 Data and methodology

The above-described research setting allowed me to build up a novel and unique four-year database with data at the inter-organizational, organizational, and individual levels of analysis. It consists of (1) 217 non-public documents with 10-30 pages each entailing detailed descriptions of technologies and the collaborative innovation process, (2) 290 hours of in-person observations, (3) 89 interviews with participating startups, utilities and program managers, (4) four waves of surveys with 233 responses from 74 individuals (collected in the 2020 edition of the program), (5) longitudinal digital trace data on collaboration and communication patterns (collected in the 2020 edition of the program), (6) expert ratings on climate-related contributions for 57 pilot project by 12 of the world's largest impact investor firms, (7) a database with financial information on all 133 pilot and commercial roll-out contracts over four years.

The unique depth, variety, and longitudinal nature of data on such a relevant phenomenon allow me to develop and test theories about collaborative innovation in the context of emerging digital technologies and climate change. Such theorizing and the empirical testing thereof require applying various methods. Table 1.1 summarizes

the collected data in that research setting and the applied methodology for the four studies.

Table 1.1 Data and methods

	Data Collection	Level of Analysis	Data	Methodology
Study1 – How Firms Realign to Tackle the Grand Challenge of Climate Change	2017-2021	Ecosystem: 57 Ecosystem Configurations	• 117 non-public presentation docs (10-20 p. each) • Financial database on 133 contracts • 30 interviews • Expert ratings from 12 impact investors • Expert ratings from 7 utilities • 67 Websites & press releases	Qualitative Comparative Analysis & complementary Interview Study (see also Fiss 2007 & Eisenhardt, 1989)
Study 2 – The Open Innovation Back-end	2019-2020	Firm/Project: 15 projects	• 40 Interviews • 170 hours of in-person observations • 55 non-public presentation docs (20 p. each) • 45 non-public updates in digital project management tool	Multiple case study (Eisenhardt, 1989)
Study 3 – Online Networking at Virtual Conferences	2020-2021	Individual: 74 individuals	• Longitudinal survey data: 233 responses from 4 survey waves from 74 individuals • 233 data points of digital trace data (from virtual collaborative online environment) data on 74 individuals at 4 time periods • 19 Complementary Interviews • 120 Hours of (virtual) observations	Fixed effects panel model (Woolridge, 2002) & complementary qualitative analysis of interviews (Gioia et al., 2012)

While the respective chapters provide extensive descriptions, this section briefly summarizes the methods used in the different studies. First, leveraging both the in-depth qualitative insights and quantitative data on 57 pilot projects collected over four years, chapter 2 combines a qualitative comparative analysis (QCA) with a multiple case study approach (e.g., Ragin, 2008; Eisenhardt, 1989). This allows me to investigate the interplay of digital technology interfaces and ecosystem strategies and their implications for climate change. The configurational perspective of QCA allows for incorporating multiple interdependent dimensions, thus enabling more complex forms of causation (Fiss, 2007; 2011). The multiple case study approach builds on the QCA results and allows to focus on developing mechanisms that explain the QCA results.

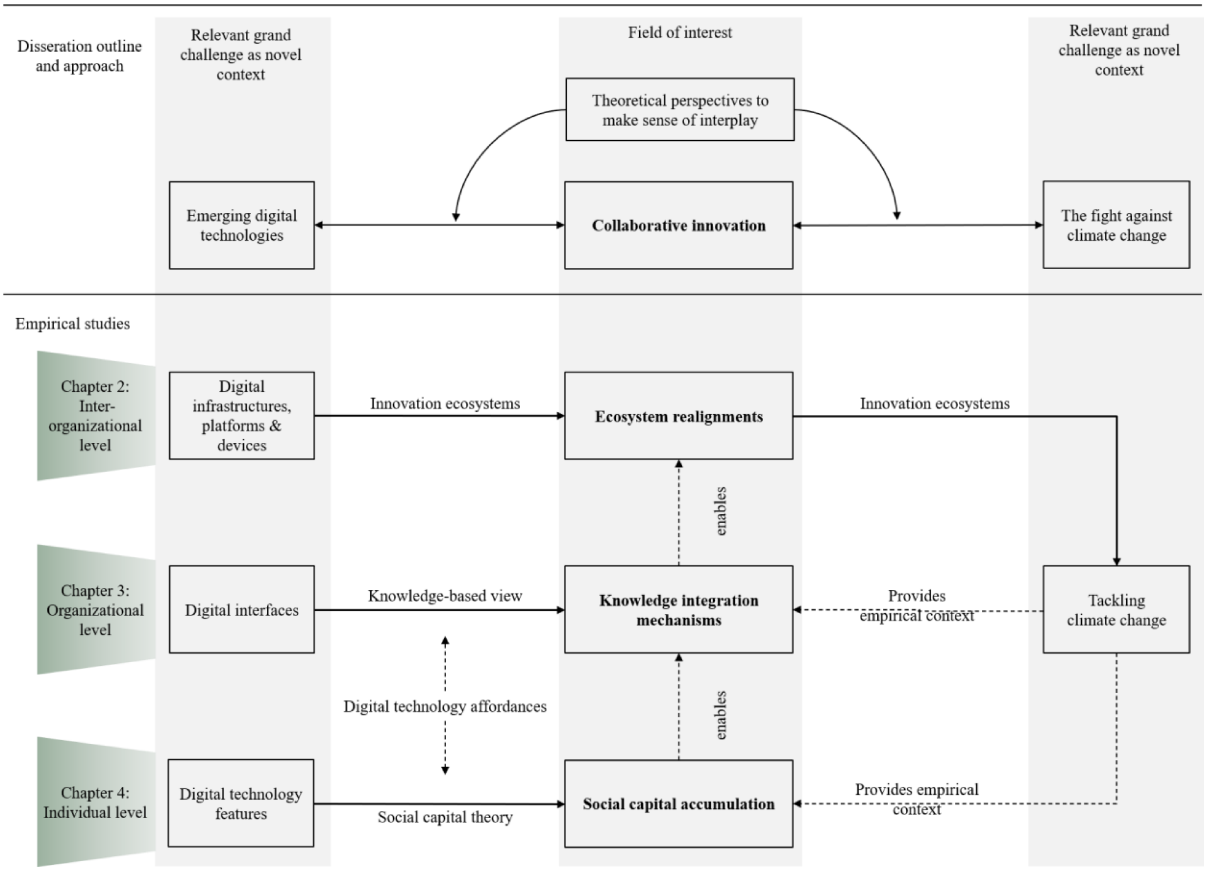
Second, chapter 3 focuses on one edition of the collaborative innovation program and applies a more in-depth multiple case study (e.g., Eisenhardt, 1989). This methodological approach leverages the data's rich qualitative nature to develop theory about the interplay of digital and collaborative innovation in the context of climate change mitigation.

Finally, in the third study (chapter 4) of this dissertation, I employ a fixed-effects panel model (Woolridge, 2002) to test a theoretical framework of social capital accumulation at virtual conferences with longitudinal surveys and digital trace data. Furthermore, I use a complementary qualitative analysis (e.g., Gioia et al., 2021) to qualify and extend the framework based on interviews and observations.

1.6 Conceptual framework

After motivating the dissertation, deriving research gaps at different levels of analysis, and introducing the different theoretical perspectives and research designs, figure 1.1 brings together all these pieces in an overarching dissertation framework.

Figure 1.1 Conceptual framework and study overview



The top of figure 1.1 visualizes the dissertation outline and approach. Collaborative innovation and its theoretical perspectives are the primary interest of this dissertation. Emerging digital technologies and the fight against climate change are grand challenges that provide a novel and relevant context for investigating and theorizing in the field of collaborative innovation. This dissertation looks at different levels of analysis and uses several theoretical perspectives to make sense of the interplay of collaborative innovation, emerging digital technologies and climate change.

The study presented in chapter 2 is situated at the inter-organizational level and looks at climate change mitigation as the outcome of interest. Regarding digital technologies, it focuses on digital platforms, digital infrastructures and innovations at the device and application layer. It introduces the theoretical lens of innovation ecosystems to make sense of the interplay of collaborative innovation, digital technologies, and climate change.

Moving to the organizational level, chapter 3 presents a study that focuses on digital interfaces and knowledge integration – the collaborative innovation back-end – in the context of climate innovation. By building mechanisms that explain the interplay of digital interfaces and knowledge integration processes, it combines the knowledge-based view and the theoretical lens of affordances. The grand challenge of climate change provides the empirical context for this study. Further, while not empirically investigated, prior work on collaborative innovation (e.g., Dattée et al., 2018) suggests that knowledge integration processes enable the implementation of ecosystem realignments, as presented in chapter 2. As such, the framework suggests that knowledge integration mechanisms might indirectly facilitate climate change mitigation by enabling impactful ecosystem realignments.

The bottom of the framework visualizes the approach for the third study of the dissertation, presented in chapter 4. This study is situated at the individual level of analysis and investigates the accumulation of social capital in virtual collaborative innovation programs concerned with climate innovation. The digital technology focus is on features of digital communication technologies. It combines the theoretical perspectives of digital technology affordances and social capital theory to make sense of the link between feature usage and social capital accumulation. Firms' collaborative innovation efforts for tackling climate are the empirical context of the study. Prior work on collaborative innovation (e.g., Monteiro & Birkinshaw, 2018) suggests that an individual's social capital accumulation enables knowledge integration in collaborative innovation programs. While not empirically investigated in this dissertation, social capital accumulation can thus be understood as one of the lower-level processes that facilitates knowledge integration (chapter 3) and thus ultimately enables the realization of ecosystem realignments with climate change mitigation impact (chapter 4).

1.7 Summary of results and contributions

This dissertation makes a first step towards theorizing about collaborative innovation in the context of grand challenges. More specifically, it provides several contributions to the literature on collaborative innovation, digital technologies, and grand challenges.

Chapter 2 investigates how and why configurations of technological interfaces and ecosystem strategies – also referred to as ecosystem realignments – unlock the climate impact of digital innovations. It presents a framework of ecosystem realignment and climate change mitigation. The framework entails 3 ecosystem realignments and details the mechanisms that explain why these ecosystem realignments unlock climate impact. Finally, it reveals boundary conditions to the scaling of ecosystem realignments and their climate impact. The study sheds new light on collaborative innovation in the context of emerging technologies and climate change by introducing the innovation ecosystems perspective (e.g., Kapoor, 2018) to the grand challenge's literature (e.g., George et al., 2016) and incorporating a digital technology dimension (e.g. George et al., 2021). It further contributes to the literature on collaborative innovation at the inter-organizational level by illuminating the interplay of multiple technological and strategic dimensions, different forms of ecosystem realignments, and barriers to the scaling of innovation ecosystems (e.g., Adner, 2017; Hannah & Eisenhardt, 2018; Jacobides et al., 2018; Kapoor, 2018).

Chapter 3 presents 3 knowledge integration mechanisms that detail how firms integrate knowledge across firm boundaries in the context of digital solutions with climate impact. Accordingly, these novel mechanisms extend the literature on open and collaborative innovation (e.g., Chesbrough, 2003; Monteiro and Birkinshaw, 2017, West and Bogers, 2014) by going beyond the open innovation front-end. They illuminate how firms integrate external with existing internal knowledge in later phases of the collaborative innovation process – the open innovation back-end. Interestingly, the study also reveals that these knowledge integration mechanisms are shaped by digital interfaces about which knowledge is integrated. Further detailing this relationship, it presents theoretical arguments that explain why digital interfaces shape the three knowledge integration mechanisms. By taking digital technologies and their characteristics seriously, the framework opens the 'black-box' of digital technologies often employed by treating all digital technologies the same in the collaborative innovation literature (see also Nambisan et al., 2019). Thus, it is a first step toward illuminating the interplay of digital and collaborative innovation (e.g., Nambisan et al., 2017). As the study is situated in the electricity sector, it nicely illustrates the role of digital interfaces and according knowledge integration in the context of realizing climate change mitigating ecosystem realignments as presented in chapter 2.

Chapter 4 investigates how the usage of digital technology features relates to the accumulation of social capital at virtual open innovation conferences concerned with the acceleration of climate innovation. It develops, tests, and qualifies a theoretical

framework of social capital accumulation. The framework contributes to the literature on collaborative innovation by revealing antecedents to social capital accumulation in virtual open innovation focused on climate innovation. This is important as social capital has been identified as an essential enabler of successful knowledge integration (Monteiro & Birkinshaw, 2017). This link established by prior literature illustrates the connection to chapter 3, which presents knowledge integration mechanisms at the organizational level. Ultimately, the successful implementation of these mechanisms depends on individuals and, among other factors, their accumulated social capital. Furthermore, taking the context of emerging digital technologies seriously, the study contributes to the literature on information systems by shedding light on virtual (open innovation) conferences as a novel and relevant phenomenon of online networking. Lower carbon emissions are among the key arguments for sticking to virtual conference formats (Arsenault et al., 2019; Fraser et al., 2017), so better understanding them also relates to the fight against climate change.

In sum, this dissertation contributes to a better understanding of collaborative innovation in the context of emerging digital technologies and the fight against climate change at the individual, organizational and inter-organizational levels**.**

Chapter 2

How Firms Realign to Tackle the Grand Challenge of Climate Change: An Innovation Ecosystems Perspective

2.1 Introduction

Climate change is one of the most pressing grand challenges of our times and thus prominently featured within the UN's Sustainable Development Goals (SDGs) (UN, 2015). Firms play a fundamental role in the battle against climate change and its related grand challenges, as they must decarbonize and innovate products, services, and processes (Comello, Reichelstein, and Reichelstein, 2021; Demirel and Kesidou, 2019; Olson, 2013; Varadarajan, 2017), as well as coordinate their efforts with stakeholders like governments or non-profits (Watson, Wilson, Smart, and Macdonald, 2017; Venugopal and Viswanathan, 2019). However, grand challenges are wicked problems that need to be addressed with more complex value propositions (e.g., George, Howard-Grenville, Joshi, and Tihanyi, 2016). These complex value propositions require complementary innovations that often stem from multiple firms, which thus face multilateral interdependencies (e.g., Grodal and O'Mahony, 2017; Vakili and McGahan, 2016). For example, electric mobility solutions that minimize greenhouse gas emissions across their lifecycles not only require a new type of vehicle with innovative components, but are also dependent on a range of complementary innovations including, inter alia, charging infrastructure and emissions-free electricity. Accordingly, recent literature acknowledges that multiple firms need to increasingly coordinate their innovative efforts to tackle grand challenges (McGahan, Bogers, Chesbrough, and Holgersson, 2021; Slotegraaf, 2012). Yet, *how* exactly firms can coordinate their innovative efforts and navigate multilateral interdependencies is less well understood.

The theoretical perspective of *innovation ecosystems* lends itself well to investigating this issue as it offers insights into the alignment of firms that must combine complementary offerings into a coherent value proposition (e.g., Adner and Kapoor, 2010; Jacobides, Cennamo, and Gawer, 2018; Kapoor, 2018; Shipilov and Gawer, 2020). Prior literature has investigated ecosystems in which alignment is envisioned by a lead firm – often a new entrant – that elucidates the value proposition upfront and coordinates different actors in the ecosystem accordingly to realize that value proposition (e.g., Iansiti and Levien, 2004; Ozcan and Eisenhardt, 2009). However, there are multiple rapid technological developments related to climate change, for instance, solar, wind, and digital control technologies (Bumpus and Comello, 2017). Similarly, uncertainties arise around which low carbon technologies will succeed in the market (Howard-Greenville, Buckle, Hoskins, and George, 2014). Thus, finding alignment to tackle climate change is less likely to work with a blueprint approach, but rather requires more experimentation. Accordingly, recent work – not concerned with

climate change or grand challenges – investigates how new entrants maneuver the emergence of nascent ecosystems around novel technological innovations when uncertainty is high (e.g., Dattée, Alexy, and Autio, 2018; Trabucchi, Moretto, Buganza, and MacCormac, 2020).

However, new entrants often depend on incumbents' existing offerings (Ansari, Garud, and Kumaraswamy, 2016; Khanagha, Ansari, Paroutis, and Oviedo, 2022). This particularly applies to the grand challenge of climate change, which requires the decarbonization of the electricity sector. This sector accounts for over 35% of all anthropogenic CO2 emissions (IEA, 2020) and is key to decarbonizing other carbon-intensive sectors (Schmidt, 2021). In this context, new entrants (e.g., startups) often develop clean technology innovations (Bumpus and Comello 2017). However, they can only unlock their climate impact when they interface with the existing industry structure (e.g., the electricity grid), which is controlled by incumbent electric utilities (Frei, Sinsel, Hanafy, and Hoppmann, 2018). This results in multilateral interdependencies between new entrants and the incumbents. Thus, realizing innovative value propositions with a substantial climate impact shifts the focus from disruptive new entrants to the joint efforts of incumbents and new entrants and how they collaboratively change the existing industry structure to achieve climate impact. This requires *ecosystem realignment*, which we define as the way that incumbents and new entrants change the existing industry structure through novel strategic relations and interfaces between existing and new complementary technologies.

While prior literature acknowledges that ecosystem realignment is required to realize complex innovative value propositions (e.g., Hannah and Eisenhardt, 2018), we need a better understanding of *how* incumbents and new entrants achieve realignment and *how and why* this can tackle the inherent interdependencies and complexities of grand challenges like climate change. Thus, we address the following research question: *How and why can ecosystem realignments between incumbents and startups in the electricity sector contribute to climate change mitigation?* We examine this question in the empirical context of 57 collaborative pilots between 10 international electric utilities and clean technology startups. Over the course of four years, we collected qualitative data (30 interviews, 117 documents), which we complemented with quantitative data provided by 12 impact investors who rated the pilots' contributions to climate-related SDGs. Pilots are designed to explore, implement, and test a value proposition, by scrutinizing a solution's underlying technological architecture, and the strategic relations between incumbents, startups, and other required actors. As such, pilots can be understood as ecosystem realignments. We analyzed this data with a qualitative

comparative analysis (QCA) to delineate a set of dimensions that characterize different ecosystem realignments and to identify the realignments that contribute most to climate-related SDGs. We further conducted a qualitative multiple case analysis to uncover the mechanisms that explain *why* these realignments are particularly valuable for achieving climate-related SDGs.

With our results, we contribute to prior work on innovation for grand challenges and to the literature on innovation ecosystems. First, by applying the theoretical lens of innovation ecosystems (e.g., Adner, 2017; Jacobides, Cennamo, and Gawer, 2018; Kapoor, 2018), we add to existing research on the role of product or service innovations for tackling grand challenges (e.g., Demirel and Kesidou, 2019; Olson, 2013; Varadarajan 2017). We identify three ecosystem realignments that detail *how* multiple firms can coordinate to unlock the full potential of innovations for tackling grand challenges (Bertello, Bogers, and De Bernardi, 2021; McGahan et al., 2021). Furthermore, we provide three mechanisms that explain *how and why* specific ecosystem realignments between firms tackle the inherent interdependencies and complexities of grand challenges (George et al., 2016; Grodal and O'Mahony, 2017; Vakili and McGahan, 2016). By focusing on how incumbents and new entrants jointly experiment with different realignments from within the existing industry, we complement prior insights on entrant-driven approaches in the ecosystem literature (Ansari et al., 2016; Dattée et al., 2018).

2.2 Theoretical background

2.2.1 Grand challenges and innovation

Grand challenges constitute critical unsolved problems with broad societal implications (George et al., 2016), including, among others, diseases and the provision of fundamental health care (Vakili and McGahan, 2016), climate change and the provision of decarbonized products and services (e.g., Howard-Greenville et al., 2014), or the development of smart and resilient cities (e.g., Ferraris, Erhardt, and Bresciani, 2017; Snow, Håkonsson, and Obel, 2016). Grand challenges are characterized by complexity, uncertainty, and multilateral interdependencies, which make them immune to easy fixes (Grodal and O'Mahony, 2017; Porter, Tuertscher, and Husyman, 2019). Thus, tackling them requires the alignment of various actors and technologies, often across different sectors (Ferraro, Etzion, and Gehman, 2015).

This is particularly true for the grand challenge of climate change. Due to its scale and scope, and the time horizon over which decarbonization efforts must take place, climate change is a wicked problem (George et al., 2016). Tackling it requires not only novel institutions (Ansari, Wijen, and Gray, 2013), policies (Rogelj, Geden,

Cowie, and Reisinger, 2021) and changes in consumer behavior (Carmeli, Brammer, Gomes, Tarba, 2017; Gregory-Smith, Manika, and Demirel, 2017; Shoham, Almor, Lee, and Ahammad, 2017), but also new approaches by firms that facilitate climate innovations. Accordingly, scholars are increasingly calling for more (qualitative) research on the role of firms and their strategies and innovative efforts to tackle climate change (e.g., Howard-Greenville et al., 2014; Eisenhardt, Graebner, Sonenshein, 2016).

A related stream of literature has begun to investigate the importance of innovation to address environmental problems – also referred to as sustainable, green, or environmental innovations (e.g., Slotegraaf, 2012; Varadarajan, 2017; Watson et al., 2017) – and societal problems – also referred to as social innovations (e.g., Venugopal and Viswanathan, 2019). This literature has shed light on the role of innovations developed by non-profits and hybrid organizations (e.g., Venugopal and Viswanathan, 2019), as well as by for-profit firms (e.g., Demirel and Kesidou, 2019; Olson, 2013; Varadarajan, 2017). Regarding the latter, scholars suggest that the need for decarbonization is a key driver for innovation (Klein et al., 2019). Yet, trade-offs between "demands of the grand challenge and business imperatives" remain (Wright and Nyberg, 2017, p. 1633), and firms must carefully assess both the environmental and financial impact of their innovations (Olson, 2013). Focusing on climate-benign innovations may allow firms to not only contribute to mitigating climate change but also to better fulfill customer expectations (Paparoidamis et al., 2019), create new jobs (Kunapatarawong and Martinez-Ros, 2016), and build competitive advantage (Ambec and Lanoie, 2008).

Empirical studies on social and green innovation have so far primarily focused on single firms and the impact of their innovative products (Paparoidamis et al., 2019), their linear supply or value chains (Olson, 2013), or how these firms interact with stakeholders like NGOs or regulators (Varadarajan, 2017; Venugopal and Viswanathan, 2019; Watson et al., 2018). Recent work suggests that tackling the complexities inherent in grand challenges requires multiple firms to coordinate their innovative efforts (George et al., 2016; McGahan et al., 2021). Yet, we still lack deeper insights into how multiple firms can align to realize value propositions that are composed of complementary innovations and how they can thus only unlock their potential to mitigate climate change as part of a collaborative effort (Ansari et al., 2013; Wright and Nyberg, 2017). The theoretical perspective of innovation ecosystems lends itself well to analyzing this issue.

2.2.2 Innovation ecosystems as a theoretical lens

Innovation ecosystems can be defined as "the alignment structure of the multilateral set of partners that need to interact in order for a focal value proposition to materialize" (Adner, 2017, p. 42). Innovation ecosystems emerge when a value proposition is based on modular technological components and when the relationships between these components are characterized by non-generic complementarities (Baldwin and Clark, 2000; Jacobides et al., 2018). Non-generic complementarities include *unique* complementarities – when module A cannot function without module B – and *supermodular* complementarities – when more of module A makes module B more valuable (Baldwin 2020; Jacobides et al., 2018). Complementary offerings are sometimes bundled on digital platforms where a larger number of supermodular complements (e.g., Apps) increases the value of a unique complement – the digital platform (e.g., IOS operating systems) (Gawer and Cusumano, 2014). The modularity and complementarity of firms' offerings create multilateral interdependencies between actors in an innovation ecosystem (Kapoor, 2018).

To cope with multilateral interdependencies, actors need to find an alignment structure, that is, they need to agree on how different technological components interface, and which role each actor assumes (Adner, 2017). The set of actors is not restricted to firms, but could also include governmental agencies (Shipilov and Gawer, 2020), universities (Ferraris, Belyaeva, and Bresciani, 2020), or customers. Creating this alignment of technologies and determining the roles of various actors constitutes a novel theoretical perspective on firm strategy and innovation (Adner and Kapoor, 2010; Jacobides et al., 2018; Kapoor, 2018). One of the key questions for firms in an ecosystem is to agree on who takes on the role of the "orchestrator" (Trabucchi et al., 2020), "keystone" (Iansiti & Levien, 2004), or "hub" firm (Jacobides et al., 2018), and which entities take on complementary roles. While the orchestrator sets the rules for engagement in an ecosystem and leads coordination efforts, complementors assume a more peripheral position (see also Kapoor, 2018; Gawer and Cusumano, 2014). Prior work has highlighted two different approaches to how orchestrators and complementors can achieve alignment. One line of thought highlights that the orchestrator develops an ecosystem blueprint that explicates the value proposition and alignment upfront (e.g., Iansiti and Levien, 2004). Another line of thought highlights a more emergent approach (Dattée et al., 2018) that requires actors to experiment with different forms of alignment (Jacobides et al., 2018). Realignment is particularly difficult from within existing industries that are already dominated by incumbent firms with their existing

technologies and roles that have manifested themselves over decades (Ansari et al., 2016; Khanagha et al., 2022).

While prior research has started to investigate the issue of realignment, it has focused on the perspective of new entrants that achieve realignment around a novel disruptive technology (i.e., digital platforms) (Ansari et al., 2016; Dattée et al., 2018; Hannah and Eisenhardt, 2018; Khanagha et al., 2022). To complement this work, we focus on the joint roles of incumbents and new entrants in order to study ecosystem emergence from within the existing industry and to investigate the interplay of multiple technological and strategic dimensions of realignment. As detailed below, the electricity sector is key to tackling climate change and it also offers a very suitable context to elucidate ecosystem realignment given its increasing complementarities and resulting multilateral interdependencies.

2.2.3 The electricity sector: complementarities and multilateral interdependencies

To avoid the worst effects of climate change, average global temperature rise must be limited to 1.5°C above pre-industrial levels by midcentury (IPCC, 2021). This requires complete decarbonization across all sectors of the economy by 2050, an end-state scenario that relies largely on the transition from a carbon-intensive electricity system to a renewable, decarbonized one (Rogelj et al., 2021). The traditional and carbon-intensive way of generating and distributing electricity is an example of integral architecture, where a single vertically integrated firm operates large-scale fossil-fueled power plants (e.g., coal, natural gas, etc.), meeting end-consumer demand with a continual supply of electricity. Through the rise of renewable electricity generation and the electrification of transportation, the underlying architecture of electricity systems is becoming much more modular. It consists of a mix of centralized and decentralized wind and solar production sites and energy storage facilities (Comello and Reichelstein, 2019), as well as electric vehicles and their charging infrastructure (Needell, McNerney, Chang, and Trancik, 2016). The interdependencies between the modules of a renewable electricity system are characterized by complementarities. For instance, the value of wind or solar production increases with more energy storage resources that can bridge the volatility of supply (because the wind does not always blow and the sun does not always shine, yet electricity demand remains continuous). These complementarities are further broadened by the rise of digital control technologies – software and hardware – that enable the optimization of a renewable electricity system (Morstyn, Farrell, Darby, and McCulloch, 2018).

The electricity sector is characterized by capital intensive long-lived assets that interconnect and form a critical infrastructure (i.e., the electricity grid), which is highly

regulated given its centrality within the modern economy. This industry has manifested itself across geographies over many decades and is largely dominated by incumbent electric utilities that house expertise charged with ensuring the cost efficient and reliable generation, transmission, and distribution of electricity. Consequently, incumbent utilities companies still retain large market shares or act as regulated monopolies (Frei et al., 2018) and thus will continue to play an important role in a decarbonized electricity system. Yet, given their legacy business and the general inertia of incumbents (Frei et al., 2018), complementary clean-energy innovations are increasingly being developed by startups (Bumpus and Comello, 2017). In this study, we thus explore how incumbents can realign with startups and other ecosystem actors around different kinds of technologies and investigate how and why ecosystem realignments contribute to climate change mitigation.

2.3 Data and methods

2.3.1 Research setting

Given that there is little prior theory on the role of ecosystem realignment for climate change mitigation, we adopt a qualitative research design. Following the approach of theoretical sampling (Eisenhardt and Graebner, 2007), we sought a research setting in which actors in the electricity sector experiment with ecosystem realignment. Accordingly, we situated our study within a global open innovation program, in which electric utilities and startups collaboratively experiment with novel strategic relations and interfaces between new clean-tech solutions and the existing infrastructure. The program is co-owned by 10 utility companies that constitute a global footprint (over 80 million customers in 40 countries; managing ~ 2 million km of grid lines) and have experience in innovation. On an annual basis, the utilities select 12-15 startups out of ~500 applications to participate in the 6-month open innovation program, which is facilitated by external program managers. The startups in the program come from multiple countries, are well resourced, revenue-positive, and offer products and services that already have commercial traction.

Throughout the program, utilities and startups jointly develop pilots. In these pilots, they discuss, implement, and test strategic relationships and technology solutions that interface between themselves and other ecosystem actors (e.g., customers or third party complementors). Pilots are thus our focal unit of analysis as they can be understood as ecosystem realignments. For instance, in one pilot, a utility and a startup discussed how a novel smart battery can connect to other third-party smart home devices that are already contributing to a utility's demand response program (financial incentives for customers to reduce electricity usage during peak demand hours). This

pilot is concerned with the realignment of technological interfaces (device-device, device-grid) as well as with strategic relations (startup-utility, startup-customer, customer-utility, utility-third party complementors). In addition to having an extensive selection procedure, the global open innovation program requires upfront commitment from utilities that they will implement a pilot. Thus, all pilots in our sample moved beyond the conceptualization phase and were implemented and tested on a small to medium scale (e.g., 1000 test customers) before an eventual roll-out on a larger scale. The setting is well suited to understanding the role of ecosystem realignment for climate change mitigation as it offers a broad variety of pilots (i.e., ecosystem realignments) that are concerned with different value propositions and entail different approaches and combinations of technological interfaces and strategic relations.

2.3.2 Data

Our data collection spans four editions of the program from 2017 – 2020 inclusive, totaling 57 *different* pilots with 57 startups. Our database comprises primary and secondary data on each pilot and is both qualitative and quantitative in nature (see Table 2.1). Data was collected by various means. First, in 2017, for each of the selected startups, we joined the program managers to conduct and transcribe 12 "onboarding" interviews. In these interviews, the startups provided an overview of their technological offerings and shared their thoughts on different strategic relations with the utilities and other players in the ecosystem that would unlock new value propositions. Additionally, we collected documents about the 12 joint pilots, allowing us to assess the kinds of ecosystem realignments that were being explored. In 2018, which entailed a new cohort of startups, we focused on collecting detailed (non-public) documents provided by the program about the "new" 15 pilots to gain in-depth insights into the technological interfaces and strategic relations between actors. We complemented our documents with 3 semi-structured interviews with utility representatives to better understand the utilities' roles in the pilots. Across 2019 and 2020 (one new startup cohort per year) we conducted 6 more utility key informant interviews and collected documents about the 30 pilots. We also compiled public documents (from websites and press releases) about the startups, utilities, and pilots. In total, our initial pilot database consists of 21 interviews, 117 non-public presentation documents, and 67 public documents. Further, as this study is embedded in a larger research portfolio conducted in the same setting, at least one of the authors participated in collaborative meetings in each of the four iterations of the program, resulting in approximately 16 weeks (240 hours) of observations. Detailed notes from these observations were used as a complementary

data source, allowing us to triangulate and validate insights derived from the interviews and document data.

Table 2.1 Data collection

	STEP 1				**STEP 2**		**STEP 3**	
Type of Data	Program ed. 1 *(2017)*	Program ed. 2 *(2018)*	Program ed. 3 *(2019)*	Program ed. 4 *(2020)*	Post-program *(2020/21)*	Post-program *(2020/21)*	Post-program (2020/21)	**TOTAL**
Interviews	12 startup onboarding interviews	3 key utility informant interviews	3 key utility informant interviews	3 key utility informant interviews			2 utility key informant interviews; 4 startup key informant interviews; 3 impact investor interviews	**30 interviews**
Non-public documents	12 pilot presentations	15 startup pitches; 10 utility presentations; 40 joint presentations	15 joint pilot presentations	15 joint pilot presentations; 10 utility presentations	Financial information on all pilots from 2017–2020); 133 contracts			**117 documents & quantitative database on 133 contracts**
Public documents	Websites & press releases of utilities and of 12 startups	Websites and press releases of 15 startups	Websites and press releases of 15 startups	Websites and press releases of 15 startups				**67 websites & collection of press releases**
Surveys					12 expert surveys with impact investors	7 surveys with utilities on resource allocation		**Two different surveys with 19 experts**

Second, to assess each pilot's contribution to climate-related SDGs, we collected independent expert ratings. In the design of our expert rating, we followed prior work that has conceptualized and measured sustainability and contributions to the SDGs (e.g., George et al., 2016; Juntunen, Halme, Korsunova, and Risto, 2019). We collected 12 responses to a survey (out of 22 distributed surveys) of mid- to senior-level investors at twelve large, globally focused impact- and climate-tech venture capital firms (average fund size ~ $1 bn), whose vocation is evaluating the economic and SDG potential of new value propositions in the electricity sector. These investment firms had geographic diversity, with headquarters located on 4 different continents. None of these individuals or their firms were involved in the focal open innovation program, therefore they provided an independent assessment. In the survey, we provided a short description of the 57 pilots and asked for a rating of the pilot's contribution to a pre-selected set of climate-related SDGs (ranging from not at all (0) to a great extent (3)) (see Table 2.2).

In-depth interviews with a subset of the surveyed experts confirmed that respondents had crucial abilities to rate the presented pilots, as illustrated by the following quotes: *"It's my daily job to assess sustainability of new solutions. In the energy sector, oftentimes, this will be avoidance [of emissions], right? To do this, we have a climate impact assessment scale and a framework for not as much quantifying them but rather like qualitatively getting a sense of, you know, does it have a low, medium, or high, impact […] and that's really not easy but I can do it because I have all the IPCC and IEA scenarios about climate change mitigation in my head and have looked at this in the energy sector for years."* (Impact Assessment Expert)
"Actually, your survey looked a bit similar to some of the stuff we do internally. The SDGs, are also an element that we are looking at in our impact assessment." (Senior Investment Analyst)

Third, after the conclusion of the fourth program in 2020, we conducted an additional round of 9 interviews (with 2 utilities, 4 startups, 3 impact investors) to better understand the underlying mechanisms of the relationships between ecosystem realignments and climate-related SDGs.

Table 2.2 Focal sustainable development goals in the electricity sector

SDG	Short Description
Goal 7 – Affordable and Clean Energy	Ensure access to affordable, reliable, sustainable, and modern energy for all
Goal 9 – Industry, Innovation and Infrastructure	Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation
Goal 11 – Sustainable Cities and Communities	Make cities and human settlements inclusive, safe, resilient and sustainable
Goal 12 - Sustainable Consumption and Production	Ensure sustainable consumption and production patterns
Goal 13 – Climate action	Take urgent action to combat climate change and its impacts

Note. Source: United Nations (2015)

2.3.4 Data analysis

To address our research question, we combined a qualitative comparative analysis (QCA) (Fiss, 2011; Ragin, 2008) with a multiple case analysis (Eisenhardt, 1989). This combined approach allows us to (1) delineate a set of dimensions that characterize

different ecosystem realignments and identify those realignments that contribute most to climate-related SDGs, and (2) more deeply analyze the mechanisms that explain *why* these realignments are particularly valuable to achieving climate-related SDGs.

Qualitative Comparative Analysis. QCA is a case-oriented method that applies set-theory and Boolean algebra to systematically compare cases (Fiss, 2007; Ragin, 2008). This method is particularly suited to investigating our research question as it allows us to investigate a larger set of cases and to explore *causal conditions* (i.e., dimensions of ecosystem realignment) that are – in combination – consistently associated with an *outcome* (i.e., high contribution to climate-related SDGs). We follow the crisp-set QCA approach where both the causal conditions and the outcome of interest can only take the values of 1 – indicating full membership in a set (i.e., an ecosystem realignment dimension is present) – or 0 – indicating full non-membership in a given set (i.e., an ecosystem realignment dimension is not present) (Ragin, 2008). Details on the QCA can be found in the technical appendix in the supporting online information.

To construct our *outcome* variable, we followed best practices in QCA to calibrate the aggregated ratings of each pilot's contribution to climate-related SDGs by defining a threshold value (e.g., Aversa, Furnari, and Haefliger, 2015). We set the threshold value such that we assigned a 1 to each pilot with an aggregated rating indicating a "moderate" or "high" contribution to climate-related SDGs. Each pilot with an aggregated rating indicating "no" or a "low" contribution to climate-related SDGs was coded with a 0 and thus assigned to the low climate-related SDG contribution set. We triangulated and validated the threshold value with interview data, observation notes, and the expertise of one of the authors in the electricity sector.

To construct the set of *causal conditions* that describe each case (i.e., pilot), we relied on qualitative analysis. Following best practice in qualitative research (Eisenhardt, 1989), our data collection and analyses were guided by two *a priori* constructs derived from the ecosystem literature: technological interfaces and strategic relations. During data analysis, we were looking for instances and examples in which new technological interfaces or strategic relations were described. For instance, guided by our *a priori* construct "technological interfaces", we identified instances and data

chunks where informants or documents described these interfaces, e.g., “transaction platforms”, “smart grids”, or “intelligent charging stations”. In the second step of our analysis, we iteratively aggregated these first-order codes to higher-level dimensions (Miles, Huberman, and Saldaña, 2020). For instance, “smart grids” and “intelligent charging stations” could be aggregated with other codes to the higher-level dimension of “digitalized infrastructure”. Throughout this process, we triangulated between our interviews, documents, and observation notes, and iterated with prior literature on innovation ecosystems to inform the labeling and aggregation of codes, resulting in 6 higher-level dimensions.

Three of these dimensions describe technological interfaces and delineate whether (or not) a pilot: (1) entails a new physical device, (2) is mediated by a digital platform, or (3) entails digital control of the physical infrastructure (i.e., the grid). The next three dimensions are related to new strategic relations between ecosystem players and capture whether (or not) a pilot: (4) includes a new role for the end-customer, (5) entails the integration of new complementors, or (6) implies the emergence of a new orchestrator. Table 2.3 provides an overview of the codes and higher-level dimensions with definitions and examples.

We used the six dimensions to calibrate the 57 cases for the QCA. Following best practices for QCA (Aversa et al., 2015), two authors independently analyzed all documents belonging to each pilot and coded a condition (i.e., dimension) as 1 if it applies to the pilot or as 0 if the condition is not present in the pilot. As the coding was based on precise definitions (see Table 2.3), there were very few disagreements, and those were quickly resolved in one meeting with all of the authors. As a result of this calibration process, each case (i.e., pilot) has a 1 or 0 assigned for each of the six dimensions of ecosystem realignment. Table 2.4 shows the results of the QCA analysis. Following Fiss (2011), we use black bold circles to indicate the presence of a condition and crossed circles to indicate the absence of a condition. Empty fields in the table indicate that the condition can either be absent or present (i.e., “don’t care”).

Table 2.3 Dimensions of ecosystem realignment

A-priori constructs	Aggregated second-order themes	Description	Descriptions of first-order codes
Changes in Technological Interfaces Captures the technological interdepen-dencies in the ecosystem (E.g., Jacobides et al., 2018, Gawer 2014)	New Device Layer	The ecosystem realignment entails new physical devices	A smart micro-battery, drones, controls
	Digital platform mediated	The ecosystem realignment uses a digital platform to realize its value proposition. Digital platforms can be innovation platforms that enable internal or third-party developers to offer additional applications on top of a platform core and/or transaction platforms that match user (groups) and leverage network effects	A transaction platform that directly connects energy prosumers and enables peer-to-peer energy trading An energy service sales platform that enables the development and integration of other internal or third-party applications
	Digital control of physical infrastructure	The ecosystem realignment makes use of sensing and controlling physical infrastructure	A smart grid solution that monitors and controls the existing physical infrastructure – the grid.
Changes in Strategic Relations Captures the "alignment of partners and [how the focal firm] secures its role in a competitive ecosystem."(Adner 2017, p. 42)	Customer participation in value proposition	The ecosystem realignment enables the customer to actively participate in the creation of the value proposition	Electricity consumers installing their own residential electricity generation assets
	Adding new complementors to the ecosystem	The ecosystem realignment introduces complementary smart products – physical products enriched with digital capabilities – or digital services that are offered by new third-party providers	A smart residential appliances control system that increases customer comfort Energy saving recommendations included in electricity billing
	New orchestrator	The ecosystem realignment entails the rise of a new orchestrator implying that the focal incumbent becomes a complementor (or seller)	Smart charging solutions that connect utilities to charging infrastructure and EV drivers Aggregator that enables benefits from reaching multiple complementors

Table 2.4 QCA Results

	Main analysis			Post-hoc analysis	
	High potential to contribute to climate-related SDGs			Low incumbent resource allocation	
	Configuration 1	Configuration 2	Configuration 3	Configuration 5	Configuration 6
Technological Interfaces					
New Device Layer		●		●	●
Digital Platform	●		●	⊗	●
Digitalized infrastructure	●	●		●	●
Strategic Relations					
Customer Co-Creation		●	●	●	●
New Complementor	●	●		●	⊗
New Orchestrator			●		●
Consistency	0.90	0.83	0.91	0.80	0.75
Raw Coverage	0.26	0.14	0.32	0.13	0.09
Unique Coverage	0.15	0.11	0.20	0.13	0.09
Overall solution consistency	0.87			0.78	
Overall solution coverage	0.59			0.22	

*Note for Table 2.4. Black bold (crossed out) circles indicate the presence (absence) of a condition. Empty fields indicate "don't care". The big (small) size indicates a stronger (weaker) causal link (*see Fiss, 2011 for detailed descriptions of causal inference with QCA).

The QCA results imply that three configurations of ecosystem realignment dimensions are consistently associated with a high contribution to climate-related SDGs. The first configuration (ecosystem realignment 1) that is consistently associated with a high contribution to climate-related SDG is characterized by the joint presence of (1) a new digital platform that mediates the ecosystem, (2) a digitalized infrastructure, and (3) the addition of a new complementor. The second configuration (ecosystem

realignment 2) is characterized by the joint presence of (1) active participation by the end-customer in the value proposition, (2) the addition of a new complementor, (3) a new device layer, and (4) a digitalized infrastructure. The third configuration (ecosystem realignment 3) is characterized by the joint presence of (1) a new digital platform that mediates the ecosystem, (2) active participation by the end-customer in the value proposition, and (3) the emergence of a new orchestrator. All other cases in which none of these combinations of dimensions is present, the pilot is not consistently associated with high contributions to climate-related SDGs. The identified configurations represent different combinations of technological interfaces and strategic relations and thus constitute *ecosystem realignments* that contribute most to climate-related SDGs.

Qualitative Multiple Case Analysis. We continued with an embedded research design (Eisenhardt, 2021) and focused on those pilots that were aggregated into these three ecosystem realignments to understand more deeply *how and why* these ecosystem realignments contribute most to climate-related SDGs. To identify theoretical mechanisms, we adopted a *within-case* logic (each of the three realignments with their nested pilots) and a *cross-case* logic (across the three ecosystem realignments) (Eisenhardt, 1989). In a first step, we sorted all data belonging to cases that are entailed in ecosystem realignments 1, 2, and 3, respectively. We then conducted a first round of coding to identify instances where informants spoke about contributions to climate-related SDGs. Examples include "balancing the grid", "reducing idle time of EVs", "increasing capacity of wind-farms", or "reducing electricity usage". In an iterative process of within and cross-case analysis, we aggregated these first-order codes to higher level constructs (Miles et al., 2020), resulting in one mechanism per ecosystem realignment. For instance, for cases that are part of ecosystem realignment 1, we could aggregate "balancing the grid", "reducing idle time of EVs" and other codes to the higher-level construct of *"enhancing infrastructure flexibility and resilience*". Based on axial coding (Miles et al., 2020), we iteratively identified the relationships between ecosystem realignment dimensions and climate contributions to develop arguments that explicate the mechanisms.

In this last step of the data analysis, we divided roles between the authors. One of the authors was the "data expert", another author – who has expertise in the electricity sector – was the "climate change contribution expert", and a third author was the "ecosystem literature expert" (see also Gioia et al., 2012). With this division of roles, we ensured that emerging constructs and arguments were constantly challenged with regards to their alignment with the data and received knowledge of climate change and

innovation ecosystems. To further increase the internal validity of our findings, we followed best practices in qualitative research (Gibbert and Ruigrok, 2010; Goffin et al., 2019) and discussed emerging findings with key informants.

2.4 Results

2.4.1 Three ecosystem realignments and their contributions to climate-related SDGs

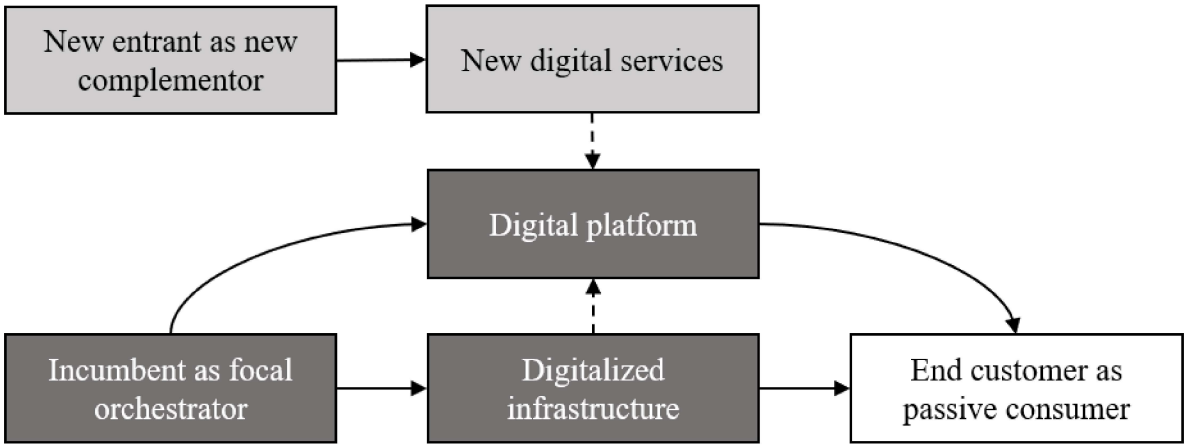
Via the QCA, we identified three ecosystem realignments that have particularly high contributions to climate-related SDGs. These ecosystem realignments are characterized by the joint presence of specific technological interfaces and strategic relations as indicated in Table 2.4. Figures 2.1b-d visualize how these technological interfaces and strategic relations realign the existing industry structure (see Figure 2.1a). Complementing the QCA with our multiple case analysis, we distilled a set of climate change mitigating mechanisms that can be traced back to the joint presence of technological interfaces and strategic relations as specified in each ecosystem realignment. Table 2.5 provides an overview of these mechanisms explaining how and why the ecosystem realignments contribute to climate-related SDGs. In the following, we draw from both the QCA and the case analysis to describe each ecosystem realignment and the corresponding mechanisms of how and why they contribute to climate-related SDGs.

Figure 2.1 The existing industry structure and ecosystem realignments with high contributions to climate-related SDGs

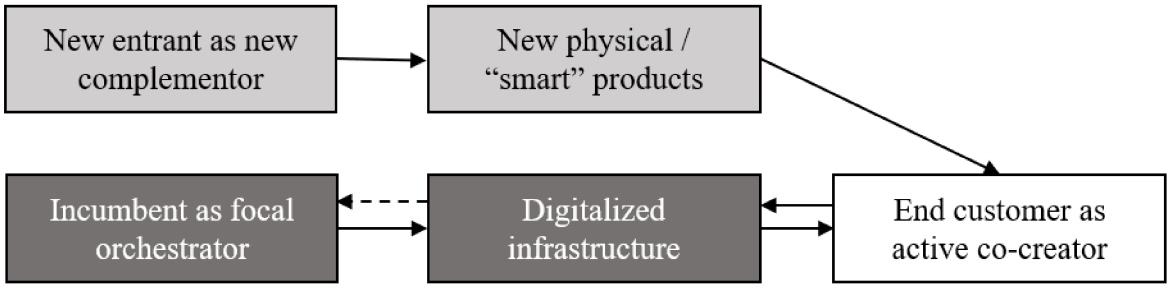
a) Existing industry structure



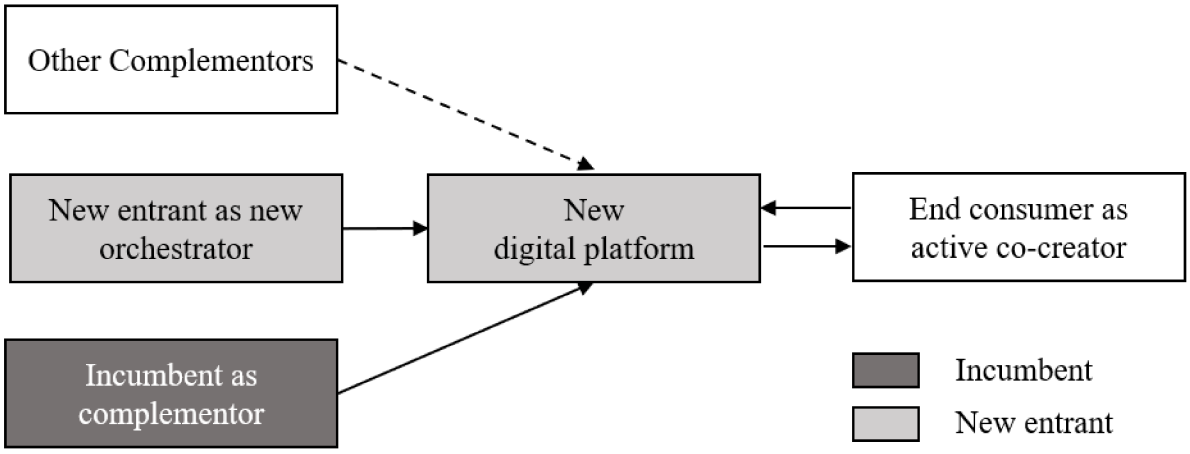
b) Ecosystem realignment 1



c) Ecosystem realignment 2



d) Ecosystem realignment 3



Ecosystem Realignment 1: How incumbents leverage the digitalized infrastructure through a digital platform and new software complementors to increase resource efficiency.

The first ecosystem realignment that is particularly beneficial for climate change mitigation represents instances in which incumbents are changing the existing industry structure by digitalizing their infrastructure, adding a digital platform, and opening it up to third party software complementors (see Figure 2.1b). Notably, the results from the QCA (see also Table 2.4) indicate that the climate benefits of this ecosystem realignment are *not* contingent upon the presence of a new device layer, the emergence of a new orchestrator, or the active participation of the end-customer in the value proposition. This is also reflected in Figure 2.1b, indicating that the digitalized infrastructure and the digital platform are managed by the incumbent, which thereby retains its position as orchestrator of the ecosystem. The new entrant acts as a complementor and offers software solutions that reach the customer through the incumbent's platform and infrastructure. The customer remains passive.

Examples of this ecosystem realignment in our sample include pilots in which incumbents have developed smart grid solutions that collect data on electricity

consumption, production, and instantaneous demand. In these pilots, utilities bundle various data streams on a digital platform and make them available to third-party providers via application programming interfaces. The third-party providers leverage the data with machine learning or other advanced analytic approaches to offer customer-facing automated energy management solutions through the utility's digital platform. These solutions allow consumers to reduce electricity consumption (and thereby reduce emissions) while still receiving the desired service.

Having outlined the nature of this ecosystem realignment, we now turn to describing how and why it is particularly beneficial for climate change mitigation. We find that the interplay of a digitalized infrastructure, a digital platform, and new third-party complementors *increases efficiency of resources* (see also Table 2.5), which in turn contributes to climate-related SDGs. In the electricity sector, increased resource efficiency relates to lower electricity use, reducing emissions from fossil-fuel fired electricity generation, as illustrated below:

"With our software application, we are helping electric power utilities to provide digital services to the customer that helps them and the end-customer to save energy and to use renewable resources more efficiently." (Startup CEO)

Our findings suggest that this enhanced resource efficiency can be achieved because the ecosystem realignment combines a digitalized infrastructure with the addition of third party complementors via a digital platform. First, digitalizing the existing infrastructure is a necessary condition because it allows for the expanded monitoring of the infrastructure and the collection of data. This is illustrated by the following quote:

"To really optimize the distribution and usage of electricity, there's automation that has to kick in. I'm talking about various levels of machine learning and deep learning […] and this all depends on sufficient data from the grid, that lies in the hand of utilities" (Startup CTO)

Second, adding complementors is a necessary condition as the incumbents are primarily concerned with the business of producing and distributing electricity and not necessarily with the development of novel algorithms, data analytics, or customer centric software applications. This, instead, is the strength of technology startups. As such, solutions developed by third party technology startups are likely to perform relatively better at increasing resource efficiency and are more likely to be adopted by customers, as explained by a utility manager:

"We know that there is lots of potential to use artificial intelligence to identify targets for energy retrofits and for optimizing the grid. And that's something that [some of the startups] can do right away. We cannot do that because we don't have the software capabilities."

Third, adding a digital platform allows the utility to make data available to third party complementors. This platform enables utilities to offer customers multiple applications from specialized third-party providers, allowing for optimization of the grid. This is illustrated by the following quote from a utility manager:
"We allowed them to plug into our algorithms and our back end. […] This back end is like a platform that aggregates all the different data streams [about the electricity grid], you know […], so we only need one repository, but we can offer different energy management services."

To conclude, digitalizing existing infrastructure and bundling the resulting data into a digital platform that is accessible to third party software complementors, allows incumbents to realign the ecosystem from within the industry and increase the efficiency of resources. Interestingly, our QCA results suggest that this cannot be achieved if any of the 3 identified elements (causal conditions, indicated by bold circles in Table 2.4) is missing. For instance, if utilities digitalize their infrastructures and build their own solutions for energy management and energy saving services (instead of adding new third-party complementors), the climate benefits are generally lower. Our qualitative analysis suggests that this is because of lower optimization performance and reduced customer centricity of software solutions developed by incumbents compared to specialized new entrants. Yet, new entrants with software solutions cannot achieve benefits on their own without interfacing with an incumbent digital platform. This is because incumbents control the physical infrastructure, much of the input data that new entrants' solutions require, and access to the customer that is required to optimize a system at scale.

Ecosystem Realignment 2: How incumbents and new device complementors enable the customer to contribute to a more resilient and flexible infrastructure.
The second ecosystem realignment represents cases in which incumbents are digitalizing their infrastructure and coordinating with third-party complementors that provide devices (hardware as opposed to software) that allow customers to interact with each other and the existing infrastructure (see Figure 2.1c). The QCA results (see also Table 2.4) indicate that the benefits of this ecosystem realignment are not contingent upon the presence of a digital platform or a new orchestrator. This is also reflected in

Figure 2.1c, indicating that the digitalized infrastructure is managed by the incumbent, which retains its position as orchestrator of the ecosystem and continues to sell electricity to its customers. However, the new entrant, in contrast to ecosystem realignment 1, can often offer its complementary devices directly to the customer (instead of selling them through an incumbent's digital platform).

Examples of this ecosystem realignment in our sample include instances where third-party providers offer smart appliances, batteries, or EV chargers to customers. If the focal electric utility provides a digitalized grid infrastructure, customers can use third-party devices to actively adapt their usage of electricity. In the case of a smart battery installed at a home for instance, it allows customers to actively take advantage of changing electricity prices and carbon intensity throughout the day. Thus, by allowing consumers to optimally charge batteries, it enables flexibility. Furthermore, in the event of an electricity blackout from the grid (e.g., due to a storm), customers can continue to "keep the lights on", enabling resiliency.

As also shown in Table 2.5, we find that this specific ecosystem realignment *enhances the resilience and flexibility of existing infrastructure*. In the electricity sector, increased flexibility and resilience of infrastructure allows incumbents to replace more controllable carbon intensive electricity sources (e.g., coal) with more renewable but variable electricity sources (e.g., wind or solar). This is because adapted electricity use by customers allows them to be more responsive to the intermittency of renewable electricity generation, as illustrated by these quotes:

"With smart energy storage [via an in-home battery] you can realize demand response [i.e. shape the demand for electricity so that it follows the available supply of electricity]. We're targeting shifting the load to balance the grid […] this is essential to reach the SDGs." (Startup CTO)

"Because of the intermittent nature of renewable energy, matching that intermittency with the same fidelity and frequency [on the energy demand side] is critical to getting more renewable energy in. Otherwise, renewable energy has to be backed up by fossil fuels." (Utility Manager)

This enhanced resilience and flexibility of infrastructure can be achieved because of the specific ecosystem realignment that entails a new device, which in turn enables the active participation of the end-customer, a digitalized infrastructure, and new complementors. First, in contrast to ecosystem realignment 1, the existence of new physical devices is critical, as they enable end-customers to actively contribute to the value proposition by adapting their electricity usage. The device further enables this

active customer contribution through automated control of the customers' appliances, as further detailed below in a quote from a startup executive:
"Consumer engagement, having these devices in the consumer's home, and having people understand that they too can make a difference. […] Our hardware device allows for automatic behavior where the device can just trigger on to energy storage [which at scale adds flexibility and allows the integration of more renewables in the energy system]."

Second, the presence of a digitalized infrastructure and the fact that the utility company acts as the focal orchestrator allows the utility to coordinate both flexible electricity supply (from wind and solar) and flexible electricity demand (through adaptive customer behavior) to balance the electricity grid:
"*You need the customer because they're the ones that are making the change. But you definitely need the utility as well, because they're the ones that own and control everything up to the grid edge, the meter […]"* (Startup CEO)

"I think that if you're a utility you have access to the grid information and [thus] the ability to control the big picture. Then, it allows you to directly access those assets and pool them [to realize the demand response]." (Utility Manager)

Third, the benefits of this ecosystem realignment depend on third-party providers that offer novel devices. Electricity incumbents sometimes have restrictions imposed that prevent them from easily direct-selling devices to customers if they operate as regulated monopolies. Moreover, utilities typically do not have the capability to develop customer friendly and high performing smart products. In contrast, third-party providers are often better able to adapt to customers' needs, as they are less restricted by legacy businesses and regulatory frames. Accordingly, a utility manager explains:
"I think, utilities themselves aren't, despite what they might think, they're not customer centric. They're okay at selling bigger things but smaller appliance type things with high volumes, that's not their natural place […] The customers participate in our [the utility's] demand response programs but we are not going to own like the smart [devices][…]"

To conclude, ecosystem realignment 2 entails third-party device complementors that interface with a digitalized infrastructure and enable customers to interact with this infrastructure, thereby increasing its resilience and flexibility. In contrast to ecosystem realignment 1, this implies that the complementor might directly sell their devices to

customers, not necessarily requiring integration into the digital platform of an incumbent. Our QCA results suggest that climate benefits are not achieved if any of the elements are missing (causal conditions, indicated by bold circles in Table 2.4). For instance, if utilities digitalize their infrastructure and try to build their own smart devices (instead of coordinating new third-party complementors), the climate benefits are lower. Our complementary qualitative analysis suggests that this is because of relatively high regulatory barriers and lower incumbent device building capabilities compared to specialized startups. In addition, while the new complementors disrupt utilities to a certain extent as they gain direct access to the utility's end customers, incumbent utilities still need to manage this realignment from within the existing industry.

Ecosystem Realignment 3: How new entrants connect customers with a digital platform to enable the sharing and leveraging of resources and information. The third ecosystem realignment that is particularly beneficial for climate change mitigation represents instances where new entrants are disrupting the existing industry structure by introducing a new digital platform and connecting customers through it. Climate benefits of this realignment do not depend on the introduction of new complements, nor on an integration with digitalized infrastructure controlled by the incumbent. This is also reflected in Figure 2.1d, which indicates that a new entrant becomes the orchestrator (instead of being a complementor as in realignments 1 and 2) and positions itself between the incumbent and the customer. Crucially, the incumbent gives up its role as orchestrator and becomes a complementor.

Examples of the third ecosystem realignment in our sample include aggregator platforms, peer-to-peer energy trading platforms, and EV fleet management platforms. Peer-to-peer energy trading platforms, for instance, allow customers to leverage their residential electricity sources (e.g., solar and batteries) and sell and exchange the energy with other households. In another example, a new entrant offers a digital platform where customers can co-fund and co-own wind farms, which then guarantees them access to renewable electricity for a contracted period of time. In both cases, a new entrant offers a digital platform and manages the pricing and exchange of electricity with the customer. The incumbent is only responsible for physically transporting the electricity through the grid (in some cases) and does not necessarily interact with the end customer. Instead, the new entrant manages the relationships and orchestrates incumbents, customers, and other actors in the ecosystem.

The interplay of a new orchestrator, a novel digital platform, and customer co-creation enables *the sharing and leveraging of resources and information* (see Table

2.5). In the electricity sector, this directly relates to using fewer resources and/or the scaling of renewable electricity sources and thus to the avoidance of GHG emissions, as is illustrated in the following quote:
"So, with [our platform] we gather together 1000s of people to enable them to collectively access the economies of scale that you get with energy infrastructure." (Startup CEO)

In contrast to ecosystem realignments 1 and 2, having a new orchestrator in ecosystem realignment 3 might be particularly important to realize the benefits of sharing and leveraging information. This is because new entrants are better positioned to implement innovative business models without the encumbrance of legacy approaches, thereby enabling adoption at speed. With respect to climate change, time is a critical factor, as decarbonization must occur at a rapid pace to limit total emissions that drive cumulative effects. This is illustrated in the following quote:
"[...] Now, having this new orchestrator, might be good for decarbonization, because I just think they move much quicker [than utilities] because they don't have the baggage of the existing assets. And so, this allows them to [e.g.] add more electrification of transport to the system." (Senior impact investment analyst)

The introduction of a new platform allows the emergence of multi-sided markets that displace incumbents and facilitate seamless transactions between customers, as further explained here:
"Why those companies have been successful in the first place, is that the cost of communication software [i.e. digital platforms] and orchestration has gone down. There used to be traditional barriers to entry. […] now with these digital platforms they can directly access and connect our customers." (Utility manager)

Finally, the benefits of this ecosystem realignment also depend on the active participation of customers. They need to change from being passive consumers of electricity to becoming active co-owners and co-contributors (i.e., provision of electricity to other entities) to an electricity community that is orchestrated by a new entrant. This is illustrated in the following quote:
"Individually, they can't own a wind farm, because your consumption is such a tiny part of it. But if you come together with 20,000 people, it works … otherwise your only option is rooftop solar which is really expensive." (Startup CEO)
However, as also illustrated in Figure 2.1d, new orchestrators often still require the incumbent electric utility to provide complementary services as further explained in the following quote:

"We have the direct relationship to the customer … but we're not doing the utility bit in terms of, you know, physically getting the electricity from the wind farm to the owner's home, that is what the utility still does." (Startup CEO)

To conclude, in the third ecosystem realignment, a digital platform introduced by a new orchestrator enables a new entrant to connect customers and to subsequently allow them to share and leverage resources and information. Our QCA results suggest that this cannot be achieved if any of the elements are missing (causal conditions, indicated by bold circles in Table 2.4). For instance, if a utility aims to implement such innovations by remaining the focal orchestrator (instead of letting a new entrant become the new orchestrator), they have to compete internally with their legacy business and might thus not achieve the necessary speed and scale to realize climate benefits (and to establish a profitable business). At the same time, new entrants cannot successfully adopt an orchestrating role without leveraging a digital platform and actively engaging the customer.

Table 2.5: Cross-case comparison of identified ecosystem realignments and climate change mitigation mechanisms with selected evidence

	Climate Change Mitigation Mechanism	**Ecosystem realignment dimensions and their roles for realizing climate change mitigation**					
		New Device Layer	**Digital Platform Mediated**	**Digitalized infrastructure**	**Customer Co-Creation**	**New Complementor**	**New Orchestrator**
Eco-system realign-ment 1	***Enhancing resource efficiency*** *"they [complementary services] decrease the need to use fossil fuels, because every time we switch off a device that can be switched on it saves you having to produce a megawatt hour*	*N.A.*	Digital platform allows third party developers to access data and control systems via APIs *"When you transition to become a solutions provider with energy efficiency and savings solutions,*	Bundling of data and control systems enables the development of an open digital platform and the scaling of analytics approaches *"So, the utilities are the ones who have the data,*	*N.A.*	New software complementor has capability to use cutting edge analytics approaches to enhance resource efficiency *"Dedicated software startups are able to create*	*N.A.*

	at a power station that might be fostered by coal or gas."		*rather than just being an energy provider, you need a digital platform where you can plug in the third-party applications."*	*let's say about consumption, or generation. And you need this data for any kind of algorithms that helps customers to be more efficient in their consumption or increase the amount of green energy that they're using."*		*much better energy efficiency applications [than a utility]. Many utilities were trying to build this themselves but like after six years they realize they're not able - they wasted a lot of money on this just because they wanted to own it."*	
Eco-system realign-ment 2	***Increasing infrastructure resilience and flexibility***	Device enables automized system-level optimization, by reducing energy usage at peak times	N.A.	Grid load information enables the coordination between electricity supplier and third party complementors	Customer can actively contribute to balancing the grid by using the device	Complementor has the capability to offer customer-centric device and is allowed to sell it directly to the customer	N.A.
	"So anytime you start to integrate solar with storage, you're able to take advantage of more solar. So, you're increasing the amount of avoidance. And there's that	*"Because with the new devices at the customer's home you can make demand respons*		*"There needs to be a lot of coordination. So, this is the role of the utility, because they're the only ones that can do this broader*	*"Selling devices from the startup directly to customers is often the better approach because this might just be a faster way*	*"I think they're [utilities] often not the best conduit and they often don't actually manage the customer*	

	there's a systems impact, too, if you have more of these smart batteries and devices in place the entire system can take in more renewables."	*e possibl e. And we need a lot of this because it is a necessit y to make the grid more stable."*		*grid managemen t. So, if you have that and the new devices at every customer's home this is how you can smooth the overall system."*	*of going to market and customers are often willing to optimize [for climate impact] in different ways than utilities are."*	*relationshi p all that well. So, I think you need new players that should be the conduit for new devices in the home that are smart."*	
Eco-system realign-ment 3	***Trading, sharing and leveraging information & resources*** *"Orchestrator models heavily impact the SDGs, because you're using existing assets, all you're doing is using them more effectively. So if you go through the carbon cost abatement curve, I think one of the cheapest mechanisms is just, is through orchestration of existing assets. It's already there, you still get the energy service that you want, right, but you do it in a more intelligent way."*	*N.A.*	Digital platforms allow to attract multiple sides and enable seamless transactions *"A digital platform is crucial because it connects to the multiple sides. And this enables us to achieve our mission of connecting people with clean energy. It's the whole point of what we do: creating that relationship and enabling transactions between consumers and wind parks."*	*N.A.*	Customer becomes supplier and consumer of electricity *"I think [our model] is far more about putting the consumer in charge of that whole value chain. And I think you need a new orchestrat or in that. Because it's not really in utilities' interest to change that model, change that set up."*	*N.A.*	New orchestrato r is free from legacy business and fast in scaling new solutions *"Utilities are heavily regulated so that doesn't always make them a proper home for these things. Sometimes that [new digital platform] is best housed in a smaller leaner entity that is serving the needs of different stakeholde rs and directly optimized for climate impact."*

2.4.2 Boundary conditions to the scaling of ecosystem realignments

We now have a better understanding of three ecosystem realignments and the mechanisms via which they contribute to climate-related SDGs. While our empirical setting enables us to investigate ecosystem realignment at the scale of pilots (e.g., 1000 test customers), a more substantial contribution to climate change mitigation – through scaling to dozens of millions of customers – is contingent on, among other things, the strategic support and funding from incumbents. This is because the identified ecosystem realignments happen partly from within the existing industry. The willingness and ability of incumbents to realign might thus constitute boundary conditions of unlocking mechanisms for climate change mitigation at scale.

Given this important role of incumbents, we conducted a post-hoc analysis to investigate to what extent the incumbent electric utilities in our sample allocated resources to those ecosystem realignments that have the highest contributions to climate-related SDGs. Following a similar procedure as in our main analysis, we conducted an additional QCA, utilizing the same causal conditions (i.e., ecosystem realignment dimensions) but adopting "low incumbent resources allocation" as the outcome variable. The variable captures the amount of resources that utilities have dedicated to different ecosystem realignments. The results are shown in the last two columns of Table 2.4. More details on the outcome variable and the QCA implementation can be found in the technical appendix in the supporting online information.

Our analysis confirms that incumbents' strategic support indeed poses a boundary condition to the scaling of ecosystem realignments 2 and 3. For instance, our findings imply that incumbents are more reluctant to financially support ecosystem realignments when a third party complementor makes its offerings directly to the customer (ecosystem realignment 2) as opposed to channeling them via a utility orchestrated platform (ecosystem realignment 1) (see also Table 2.4). A utility manager elaborates on this resistance, highlighting the uncertainty of working with devices provided by third parties and sold directly to customers:

"The fundamental change in our industry is the interface to the customer… I think the more you enable other people [e.g., third party complementors] to suddenly have an interaction with your customer providing the same service that you could be providing, why would you do that? So, everything that directly gets in between us, and our customer makes us uncomfortable."

Similarly, our findings imply that when a new orchestrator manages the customer relationship and pushes the incumbent into a complementary position (as in ecosystem realignment 3), utilities might be conflicted and resist supporting the scaling of such a realignment (see Table 2.4). A utility manager elaborates on the reluctance of utilities to support the rise of a new orchestrator and the implied role for these utilities as complementors:

"And if you ask these people [utilities], do you want to step into the second [complementary] role and become a solutions provider? Or do you want to run the platform? Their initial response will always be of course, we run the platform, we have millions of customers […]"

Finally, the results in Table 2.4 show that we do not identify ecosystem realignment 1 as a configuration with low incumbent resource allocation. This implies that incumbents are less reluctant to support this ecosystem realignment 1. However, we conducted another qualitative analysis to better understand the potential boundary conditions for the scaling of this and the other ecosystem realignments. Our qualitative analysis reveals that utilities may struggle to attract the necessary amount and quality of third-party software complementors, which limits the ability to scale ecosystem realignments 1 and 2. This is illustrated in the following quote:

"If you [as a utility] now decide to be a platform provider, I mean, is that really going to make anybody excited about it? Is that really going to attract the necessary momentum that it needs to actually be successful? And I'm very doubtful of that. … So rather than us [as utility] being the platform, yeah, maybe it's necessary for us to be the third-party provider. That's something that I think you'll need to seriously think about." (Utility Manager)

To conclude, incumbents' strategic support poses a boundary condition to the scaling of ecosystem realignments 2 and 3, and the ability to attract third-party complementors poses a boundary condition to the scaling of ecosystem realignments 1 and 2.

2.4.3 A theoretical framework of ecosystem realignment and climate change mitigation

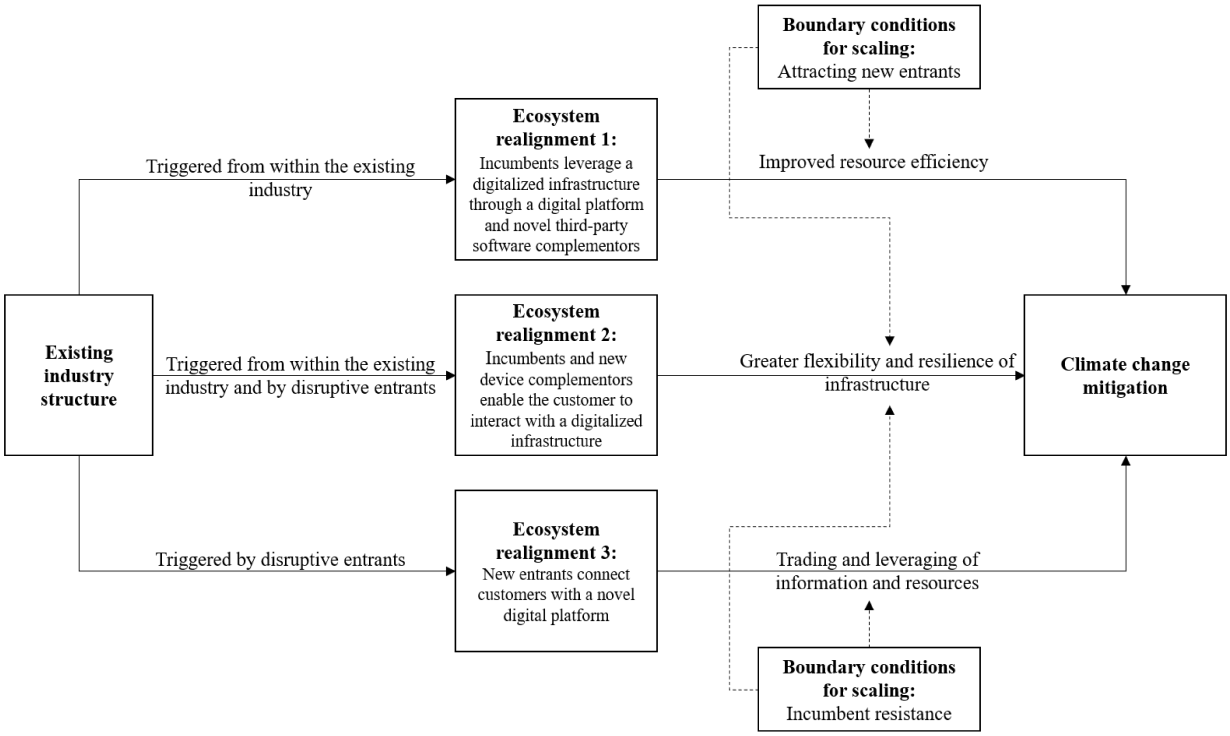
We can now combine our insights from the empirical analysis into a theoretical framework that explains the role of ecosystem realignment for climate change mitigation. Figure 2.2 depicts the three identified ecosystem realignments that transform the existing industry structure and how and why they mitigate climate change via three distinct mechanisms.

In ecosystem realignment 1, a new digital platform offered by the incumbent and made available to third party software complementors leverages a digitalized infrastructure. The new technological interfaces and strategic roles increase resource efficiency and thereby mitigate climate change. Given the prominent role of the incumbent as the orchestrator and owner of infrastructure and customer access, this realignment emerges from within the industry, but also requires complementary innovations from new entrants. The primary boundary condition to the scaling of this ecosystem realignment relates to the incumbent's ability to attract the necessary third-party innovators to its digital platform.

In ecosystem realignment 2, new third-party device complementors that interface with a digitalized infrastructure enable customers to interact with the existing infrastructure. These interfaces and the new roles of complementors and customers increase the resilience and flexibility of the infrastructure, thereby mitigating climate change. While the incumbent remains the focal orchestrator of the ecosystem, it shares access to customers with new entrants. As such, this ecosystem realignment is triggered both from within the industry as well as by disruptive new entrants. Therefore, boundary conditions to scaling are the strategic support from incumbents and the attractiveness for third-party complementors to join the ecosystem.

In ecosystem realignment 3, a digital platform offered by a new orchestrator enables it to connect customers to each other in novel ways. Through these connections, resources and information can be shared and leveraged, which generates a positive effect in terms of climate change mitigation. In contrast to ecosystem realignments 1 and 2, this realignment represents the entrance of a disruptive player that gains control of customer access. Yet, the new entrant often still depends on complementary support from the incumbent. As such, a lack of strategic support from incumbents is likely to slow down the scaling of such an ecosystem realignment and thus constitutes an important boundary condition.

Figure 2.2 A theoretical framework of ecosystem realignment and climate change mitigation



2.5 Discussion

Our research examines how and why ecosystem realignments can mitigate climate change. Acknowledging the specificity of our research setting (i.e., the electricity sector), we now turn to discussing how the identified ecosystem realignments and mechanisms within our theoretical framework are useful for answering our research question more broadly and how they shed new light on the role of innovation for tackling grand challenges.

The first ecosystem realignment reveals that innovative software solutions can only fully unlock their contributions to climate change mitigation under two conditions. First, relatively greater impact is achieved when novel software solutions are developed by new entrants (as opposed to incumbents). This aligns with prior studies that have highlighted the role of new entrants and entrepreneurship in delivering innovative products and services for sustainable development (Bertello, Battisti, De Bernardi, and Bresciani, 2022; George, Merrill, and Schillebeeckx, 2021). Second, these software solutions are best utilized when new entrants become complementors on digital platforms that are controlled by incumbents who can channel solutions to their existing customers. This finding lends some support to arguments around the potential of digital platforms to generate environmental or social value (Bonina, Koskinen, Eaton, and Gawer, 2021) by facilitating a generative digital innovation process (Gawer and

Cusumano, 2014). However, since the ecosystem realignment around the digital platform is led by an incumbent from within the industry, our findings contrast with prior studies that have highlighted the role of new entrants as disruptive platform leaders (e.g., Dattée et al., 2018; Khanagha et al., 2022). In the context of mitigating climate change, the incumbent may retain its position as the orchestrator given its control of the existing infrastructure. The climate change mitigation mechanism of increased resource efficiency stems from the interplay of an incumbent-controlled infrastructure, a digital platform, and third-party software complementors. Prior work has already pointed to the importance of resource and innovation efficiency for achieving climate impact (e.g., Bresciani, Puertas, Ferraris, and Santoro, 2021). Our findings add to this work. Specifically, they complement previous studies on the optimization and digitalization of operations and supply chains (e.g., Del Giudice, Scuotto, Papa, Tarba, Bresciani, 2021; Olson, 2013; Sjödin, Parida, and Visnjic, 2021) by revealing how benefits for resource efficiency can be achieved through realigning actors around a digital platform.

The second ecosystem realignment around the introduction of a novel (physical) product has climate mitigating properties under the following conditions. First, it is implemented as a complementary offering to customers within a digitalized infrastructure that is controlled by an incumbent. This is in line with prior studies, which highlight that new entrants are often dependent on complementary offerings by incumbents (e.g., Ansari et al., 2016). However, as the incumbent still leads the ecosystem realignment from within the existing industry, our finding contrasts with the typical disruptor story (Christensen, 1997; Dattée et al., 2018; Khanagha et al., 2022). This finding is similar to that described for the first ecosystem realignment. Second, in addition to adopting a new green product (TM, Kaur, Bresciani, and Dhir, 2021; Papadoridamis et al., 2019), we find that customers need to actively participate in the value proposition. This finding substantiates the importance of changing individuals' behavior regarding climate action (Carmeli et al., 2017; Gregory-Smith et al., 2017; Shoham et al., 2017) and of customer co-creation as a form of open innovation (e.g., Bertello et al., 2021; McGahan et al., 2021; Porter et al., 2019; Randhawa, Wilden, and Hohberger, 2016). Accordingly, it is via the combination of digitalization, customer co-creation, and smart products that the flexibility and resilience of climate-relevant infrastructure is enhanced.

While the third ecosystem realignment also relies on a digital platform, it radically transforms the role of the incumbent. In contrast to the others, this ecosystem realignment more closely follows the story of disruption (Christensen, 1997), since it is the new entrant that becomes the platform orchestrator, while the incumbent is moved

to the periphery of the ecosystem. Identifying incumbents' strategic support as a boundary condition for the scaling of this ecosystem realignment further substantiates the disruptor's dilemma (Ansari et al., 2016). It adds to prior work by revealing how and why the disruptor's dilemma might slow down climate change mitigation. Furthermore, we identify a novel digital platform coupled with customer co-creation as further conditions for enabling climate impact through sharing and leveraging resources and information. As such, this finding further supports and details the role of digital platforms (e.g., Bonina et al., 2021) and customer co-creation (e.g., Bertello et al., 2021) for tackling grand challenges

While our empirical analysis has focused on software solutions (e.g., machine-learning enabled energy management), physical products (e.g., smart batteries, residential solar panels), and digital platforms (e.g., aggregator of wind-farm ownership) in the electricity sector, the identified ecosystem realignments are likely to be relevant in related sectors, such as mobility (e.g., Olson, 2013), smart cities (e.g., Ferraris et al., 2020), or manufacturing (Del Giudice et al., 2021; Sjödin, et al., 2021). For instance, ecosystem realignment 1 could be applied to a manufacturing setting. Incumbents like ABB, Siemens, or General Electric could trigger a realignment from within the existing industry by aggregating data from factories and products on a digital platform. Third-party developers could then apply analytical methods like machine learning to this data to improve the efficiency of their factories and products. In ecosystem realignment 2, operators of public transportation systems could realign an ecosystem by coordinating with providers of complementary smart products such as smartphones and new digitally connected vehicles. This would enable customers to adapt their bookings of different mobility options according to the current utilization rates, congestion, and customer preferences. Jointly, such an ecosystem realignment would increase the flexibility of the public transportation infrastructure, enabling more customers to replace resource-intensive mobility with individual or multi-modal mobility solutions. Ecosystem realignment 3 could also be applied to disruptive entrants in the mobility sector, like Uber, Lyft, or Careem, companies that use digital platforms to allow end-customers to share existing resources (i.e., cars) and offer incentives to both drivers and passengers for climate-benign actions (e.g., higher revenue share is given to drivers of electric vehicles relative to internal combustion alternatives).

Finally, the underlying logic of our proposed ecosystem realignments and mechanisms might help to better understand the role of coordinating the innovative efforts of firms to tackle other grand challenges beyond climate change. One hypothesis is that in the context of the grand healthcare challenge (e.g., Vakili and McGahan,

2016), similar degrees of digitalization have led to a rise in complementary digital and physical products and services, as well as an "empowerment" of the patient. This requires incumbents with infrastructure (e.g., hospitals, insurance companies) and new entrants (digital health startups) to engage in similar ecosystem realignments to increase the resource efficiency and infrastructure resilience of the healthcare sector, as well as to enable patients to share and leverage information.

2.5.1 Theoretical implications

Prior research shows that tackling grand challenges requires firms not only to innovate products and services (e.g., Paparoidamis et al., 2019; Varadarajan, 2017; Watson et al., 2017) but also to coordinate their innovative efforts with other firms (McGahan et al., 2021; Porter et al., 2019; Slotegraaf, 2012). With our theoretical framework, we contribute to this literature by providing a more detailed understanding of how and why the coordination of innovative efforts across firms contributes to addressing the complexities, uncertainties, and interdependencies inherent to grand challenges (Ferraro et al., 2015; George et al., 2016; Grodal and O'Mahony, 2017; Wright and Nyberg, 2017).

First, building upon the theoretical lens of innovation ecosystems (e.g., Adner, 2017), we identify three ecosystem realignments that delineate *how* incumbents and new entrants – in their quest to address grand challenges – innovate not only in products or services but also in their technological interfaces and strategic relations. Our study reveals how and why tackling grand challenges requires new technological interfaces between (1) existing infrastructure (e.g., the grid, factories, transportation infrastructure), (2) physical products from new entrants that connect to this infrastructure, and (3) novel digital platforms and services that can optimally utilize the infrastructure. Regarding strategic relations, our results indicate that the multilateral interdependencies inherent in grand challenges not only limit the value of (stand-alone) incumbent transformations (Hartmann, Inkpen, and Ramaswamy, 2021) but can also not be fully addressed via typical disruption (Christensen, 1997; Khanagha et al., 2022). Instead, it requires the joint effort of incumbents, new entrants, and customers who explore new strategic relations. Mirroring the complexities of grand challenges, our configurational approach (QCA) reveals that there is not one configuration to address grand challenges, such as climate change, but multiple equifinal ecosystem realignments that co-exist. This ecosystem perspective adds to prior work that has highlighted the importance of innovative products and services to tackle grand challenges (Paparoidamis et al., 2019; Varadarajan, 2017; Watson et al., 2017) by explaining which technological and strategic realignments can be used by firms'

innovative products, services, and platforms to unlock their full potential to address grand challenges.

Second, we contribute to prior work by explicating underlying mechanisms: how and why the identified ecosystem realignments tackle the complexities, uncertainties, and interdependencies inherent in grand challenges. While prior work has highlighted the importance of more open and collaborative approaches to innovation (Bertello et al., 2021; McGahan et al., 2021; Porter et al., 2019), our mechanisms detail how technological interfaces and strategic relations across firms address grand challenges by enhancing (1) resource efficiency, (2) the flexibility and resilience of infrastructure, and (3) the trading and leveraging of information and resources. Moreover, we contribute to the literature by revealing the boundary conditions to scaling such ecosystem realignments, thus also providing a better understanding of the predicates to the value of open approaches of innovation for tackling grand challenges (e.g., Slotegraaf et al., 2012).

In addition, our theoretical framework contributes to the innovation ecosystem literature (e.g., Adner, 2017; Jacobides et al., 2018; Kapoor, 2018) by shedding new light on ecosystem emergence and scaling. While there is a consensus in the literature that novel and complex value propositions require innovation ecosystems (e.g., Hannah and Eisenhardt, 2018), prior work has often focused on how novel ecosystems are triggered by disruptive new entrants (e.g., Ansari et al., 2016; Dattée et al., 2018; Trabucchi et al., 2020). We shift the focus to the joint role of incumbents and new entrants for the emergence of ecosystems that have the potential to tackle grand challenges. Extending our understanding of the disruptor's dilemma (Ansari et al., 2016), our findings reveal that ecosystem realignment can be triggered from within an industry, through external disruption, or by both. With our focus on pilots between incumbents and new entrants, and by deriving dimensions of technological interfaces and strategic relations that constitute ecosystem realignments, we provide a better understanding of how ecosystem realignment can be achieved (Dattée et al., 2018). Incumbents and new entrants need to find the "right" combination of technological interfaces between digitalized infrastructures and new products or services coupled with strategic relations between themselves and other actors in the ecosystem. Our three ecosystem realignments provide suggestions about which combinations might be particularly promising if the ecosystem aims to tackle a grand challenge. Finally, we also provide some insights into the scaling of ecosystem realignments (e.g., Hannah and Eisenhardt, 2018; Khanagha et al., 2022). Depending on the type of ecosystem

realignment, scaling is contingent on strategic support from incumbents and/or an incumbent's ability to attract third-party complementors.

2.5.2 Managerial implications

Our findings have several implications for managers who need to coordinate and navigate entire ecosystems in order to tackle grand challenges, such as climate change. Incumbent firms from all industries are increasingly making pledges to achieve "net-zero" corporate emissions, that is, the public disclosure of voluntary emission reduction targets. While these pledges are of variable quality, expectations are being set by stakeholders ranging from suppliers and financiers, to interested advocacy groups, governments, and the general public. To close the gap between expectation and reality, managers will have to consider the role their firms assume within the ecosystems in which they reside. In the case of incumbent firms, there will be instances where new technologies and entrants are able to aid said incumbents to sustainably – and in line with net-zero pledges – make the important contributions demanded by society. The framework described in this paper outlines three ecosystem realignments with new entrants from which incumbent managers can form portfolios based on an understanding of the value and SDG-addressing propositions offered by the combined capabilities of various actors. By sharing customer access, incumbents may coordinate with new entrants to increase the end customer value within a device complementor ecosystem (realignment 2). Or by creating an open (digital) platform, new entrants can offer technologies that enhance resource efficiency across the incumbent orchestrated system (realignment 1). And by both sharing customer access and allowing a new open platform offered by a dominant new entrant to emerge, the incumbent can thrive as a complementor within a new orchestrator ecosystem (realignment 3).

New entrants, such as clean-tech startups with a strong climate-related mission, can use our ecosystem realignment framework to strategically consider how to maximize the climate-related impact of their novel solutions. In some cases, close coordination and collaboration with incumbents is necessary to integrate the solutions with the physical infrastructure and to access large existing customer bases, allowing for the scaling of renewables and increasing resource efficiency. In other cases, fulfilling climate-related SDGs requires new entrants to develop innovative, customer-centric approaches in order to surpass the incumbent and connect customers to share, trade, and leverage information and resources.

For policymakers, policies that help lower the cost of producing and sharing knowledge between incumbents and startups would increase the speed with which actors can learn from each other, assess joint value propositions and the resultant

ecosystem structures, and devise strategies to enable ecosystem realignments. Given that climate change is a grand challenge with a "ticking clock", policies that recognize time is of the essence would be advantageous. Specific examples of such policies include technology/innovation grants requiring joint incumbent/new entrant participation as well as the sharing of detailed lessons learned and case studies developed in startup incubator and accelerator facilities, detailing the different ecosystem realignments that resulted through new solution commercialization. Finally, the existing business models of incumbents are often advantaged because of preferential tax, incentive, or regulatory mechanisms which "crowd out" the innovations that may emanate from outside the existing ecosystem. Policymakers would be wise to examine those policies that are perhaps no longer fit for purpose to address climate change.

2.5.3 Limitations and future research

Our QCA allows us to capture the complex interdependencies between multiple technology and strategy dimensions in the electricity industry and the resulting causal complexity by identifying three equifinal ecosystem realignments that contribute greatly to climate-related SDGs. However, we cannot compare the extent of these SDG contributions. While our qualitative insights suggest that all three realignments in co-existence are necessary to fulfilling climate-related SDGs, future research could investigate to what extent the different configurations compete with each other. Can the development of one "push out" the others? In addition, while robustness tests show that our results hold for different combinations of climate-related SDGs and other decarbonization measures, we cannot investigate trade-offs between the individual SDGs (e.g., climate action vs. reduced inequality) that organizations must work towards achieving (McGahan et al., 2021).

Furthermore, our selected cases are subject to limitations. While our focus on pilots allows us to systematically investigate and compare different ecosystem realignments, the assessment of climate change mitigation was based on pilot-sized implementation (e.g., 1000 customers). The in-depth knowledge of our experts in assessing the actual climate change mitigation if the pilots were implemented at scale allows us to identify those pilots (ecosystem realignments) with the highest potential contributions to climate-related SDGs. However, as we also point to the boundary conditions of scaling such ecosystem realignments, future research should track and measure the climate change mitigation of ecosystem realignments over time and when implemented on a global scale.

Third, we specifically focus on new entrants and incumbents and how they realign ecosystems while considering other ecosystem actors (especially customers).

Yet, the literature on ecosystems and grand challenges points towards a larger number of relevant actors (Ferraro et al., 2015; George et al., 2016; McGahan et al., 2021). Accordingly, another promising path for future research would be to investigate and elaborate on the interplay and tensions in ecosystem realignment between incumbents, new entrants, and other actors, such as universities (Ferraris et al., 2020) or regulators.

2.6 Technical appendix

2.6.1 Technical appendix on the implementation of QCA in the main analysis

n our main analysis we apply a Qualitative Comparative Analysis (QCA). Starting with a truth table that indicates all possible configurations of conditions (i.e., ecosystem dimensions), QCA subsequently applies a counterfactual analysis and minimization algorithm to identify the configuration of conditions that are most consistently associated with membership in the outcome set (i.e., high contributions to climate-related SDGs) (Fiss, 2011). In our analysis we introduce 6 conditions – that can be either true or false. This implies that there are 64 logically possible configurations as listed in the truth table of the QCA algorithm. Prior work suggests that one can include up to 8 conditions for a sample size of 57, indicating that per design the maximum coverage of possible configurations would be only about one fifth (Greckhamer et al., 2013; Marx, 2010). However, QCA is suited to overcome this limited diversity in empirical instances through counterfactual analysis (Fiss, 2011). Our sample includes about a third of the logically possible configurations, indicating a decent yet incomplete coverage as common for QCA.

We follow prior work in applying a consistency threshold of 0.8, indicating that the algorithm only includes configurations in which at least 80% of cases are also part of the "high contribution" set for calculating the complex solution (Ragin, 2008; Greckhamer et al., 2018). From there, the minimization algorithm calculates a parsimonious solution and an intermediate solution, which allow us to extract core and peripheral causal conditions, i.e., the ecosystem dimensions that explain high contributions to climate-related SDGs (Fiss, 2011). Following best practices in QCA for our sample size, we set a frequency threshold of 2 cases – indicating that only configurations are included in the analysis that apply to at least 2 cases (Greckhamer, Misangyi, and Fiss, 2013).

As a result of our analysis, we identified three distinct ecosystem configurations that are consistently associated with a high contribution to climate-related SDGs (Greckhamer et al., 2018). The measure of "Overall Solution Coverage" indicates that the three configurations jointly account for 59% of the cases that were rated with a high contribution to climate-related SDGs. The measure of "Overall Solution Consistency"

indicates that 87% of the cases that are part of the three configurations in Table 2.4 (see main paper) (those that fulfill the identified conditions) are also part of the high climate-related SDG contribution set (Those assigned with a 1 in the outcome variable).

For configuration 1,2, and 3, the consistency scores of 0.9, 0.83, and 0.91 implies that 90%, 83% and 91% of those ecosystem configurations that fulfill these characteristics were rated with a high contribution to climate-related SDGs. The raw coverage scores for configuration 1 indicate that out of the 34 cases that are part of the high climate-related SDGs contribution set, 26% (i.e., 9 cases) are described by this configuration. The unique coverage score indicates that 15% of these 34 cases (i.e., 5 cases) are not included in any other configuration. This implies that 4 cases in configuration 1 can also be described by other configurations. For configuration 2, the coverage scores of 0.14 (0.11) indicate that this specific configuration (uniquely) accounts for 14% (11%) of the ecosystem configurations that are part of the high climate-related SDGs contribution set. For configuration 3, the coverage score(s) of 0.32 (0.20) indicate that this ecosystem configuration (uniquely) accounts for 32% (20%) of the ecosystem configurations that are part of the high climate-related SDGs contribution set.

2.6.2 Technical appendix for post-hoc QCA on barriers for scaling of ecosystem realignments

To further explore the nature of these trade-offs, we conducted an additional QCA. This analysis included an alternative outcome variable that captures to what extent the 10 utilities in our sample allocated resources (money, time, and access to facilities and customers) to the different pilots. We calibrated our 57 pilot cases into a set of ecosystem configurations with “high incumbent resource allocation” and into a set of ecosystem configuration with “low incumbent resource allocation”. To code our set accordingly, we used information on the number and financial value of collaborative contracts signed between utilities and startups. We set the threshold such that pilots for which contracts with at least 3 utilities were signed, or with a total cumulated contract size of at least $150k, were coded with 1 and thus assigned to the “high incumbent resource allocation” set. On the former, we assume that the ecosystem configuration remains the same across pilots between a given startup and additional utilities that may sign subsequent pilot contracts. This assumption is fair, given the similarities of business models exhibited across all utilities in the program. Pilots below that threshold were coded as 0 and thus assigned to the “low incumbent resource allocation” set. We validated the secondary data and our threshold value with answers to a survey from 7 of the 10 utilities in our sample.

Table 2.4 (see main document) shows the QCA results. We find two configurations (5 and 6) that are consistently (0.8, 0.75) associated with low incumbent resource allocation. Ecosystem configuration 5 is characterized by the joint presence of (1) a new device layer, (2) digital control of physical infrastructure, (3) an active co-creation with the customer, (4) new complementors, and (5) the absence of a digital platform. Interestingly, this configuration is a specification of ecosystem configuration 2, that we previously identified as contributing highly to the SDGs. Ecosystem configuration 6 is characterized by (1) the joint presence of a new device layer, (2) digital control of physical infrastructure, (3) mediation through a digital platform, (4) an active co-creation with the customer, (5) a new orchestrator, and (6) the absence of new complementors. Notably, this configuration is a specification of ecosystem configuration 3, that we previously identified as one contributing highly to the SDGs.

Chapter 3

The Open Innovation Back-End: Knowledge Integration in the Context of Adopting External Digital Solutions

3.1 Introduction

Firms are increasingly reaching beyond their organizational boundaries to acquire external knowledge (e.g., Afuah and Tucci, 2012; Cassiman and Veugelers, 2006; Chesbrough, 2003; Dahlander and Gann, 2010; Du et al. 2014; Wallin et al., 2018; West et al., 2014; West and Bogers, 2014). Prior empirical work reveals the benefits of such openness for firms' innovative performance (e.g., Ebersberger et al., 2021; Garriga et al., 2013). However, recent work also examines the potentially negative implications of openness (Laursen and Salter, 2006; Lhuillery and Pfister, 2009, Un et al., 2010; Lu and Chesbrough, 2021), and the relatively high number of open innovation failure cases (Chesbrough, 2019). One explanation for these mixed results is that the effectiveness of openness not only depends on access to external knowledge - the open innovation front-end - but crucially on whether and how external knowledge is integrated by the focal firm - the open innovation back-end (Chesbrough, 2019). Put differently, acquiring external knowledge is only "half the battle" (West and Bogers 2014, p. 821). It is through the integration of external and internal knowledge that innovative solutions (i.e., new products and services) can be exploited (Wallin and von Krogh, 2010). While extant work points to the importance of this open innovation back-end (Seran and Bez, 2020; Ter Wal et al., 2017), we know little about how knowledge integration across firm boundaries occurs.

Building upon the knowledge-based view of the firm (e.g., Grant, 1996; Iansiti and Clark, 1994; Kogut and Zander, 1992; Nonaka, 1994), a dispersed body of literature has emerged around knowledge integration (see Zahra et al., 2020 for an overview). Yet, this literature stream also acknowledges that "…there is considerable attention to issues of knowledge acquisition or sharing, but there is little or no empirical work on activities related to […] the integration processes itself" (Zahra et al., 2020, p. 184), especially when knowledge integration takes place across firm boundaries. Hence, our study focuses on the mechanisms that explain how this knowledge integration occurs within the open innovation back-end.

To explicate *how* knowledge integration takes place, it is critical to first understand *what* is being integrated. Following the knowledge-based view, firms integrate knowledge about the products and services (i.e., solutions) that they aim to provide (Grant 1996; Iansiti and Clark, 1994) which is also referred to as the raw material of knowledge integration (Zahra et al., 2020). This raw material entails two kinds of knowledge; specialized knowledge about components and architectural knowledge about how to combine such components (Grant, 1996; Henderson and Clark, 1990; Iansiti and Clark, 1994). In this study, we focus on digital solutions and hence on their

underlying architecture as the raw material of knowledge integration. This is particularly relevant as digital solutions are fundamentally transforming entire industries (Porter and Heppelmann, 2014). Firms are thus increasingly adopting external digital solutions, requiring them to integrate knowledge across the digital architecture (Dahlander, Gann, Wallin, 2021; Enkel et al., 2020; Nambisan, et al., 2017; 2019).

Prior work on digital architecture suggests that specialized component knowledge is divided across four stacked layers: the application, data, network, and device layers (Yoo et al., 2010; Porter and Heppelmann, 2014). Architectural knowledge about how to combine specialized knowledge across layers is mainly concerned with three digital interfaces, namely the application-data, data-network, and network-device interfaces (Henfridsson et al., 2018; Yoo et al., 2012). These interfaces represent loci of knowledge integration that have heretofore been neglected in the literature. Yet they provide a promising pathway to better understand how knowledge integration within the open innovation back-end occurs. Therefore, we investigate: *In the context of adopting external digital solutions, what are the knowledge integration mechanisms that constitute the open innovation back-end? How and why do digital interfaces shape these knowledge integration mechanisms?*

To generate insights into these research questions, we conducted a nested, multiple-case study on 15 projects between 15 startups offering digital solutions and 10 incumbent energy utilities seeking to adopt them. We collected longitudinal data (105 non-public documents, 40 interviews, 170 hours of observations) in the context of an open innovation program in which these projects took place. The program's purpose is to connect utilities to startup digital solutions that can enhance the incumbents' prospects of navigating the energy transition. This setting is well suited for uncovering knowledge integration mechanisms and theorizing about the role of digital interfaces, as it (1) marks the open innovation back-end where knowledge gets integrated across firm boundaries (2) entails a variety of digital solutions that can be clustered at different digital interfaces and (3) controls for many confounding factors (e.g., project size, funding, timeline) as all projects are part of the same program.

Our findings offer two contributions at the intersection of open innovation, knowledge integration and digital technology, thereby addressing a prominent gap regarding the lack of theoretical and empirical insights into how knowledge integration occurs. First, we extend prior literature by uncovering three knowledge integration mechanisms, detailing how external and internal knowledge is integrated in the context of adopting external digital solutions. As such we illuminate the open innovation back-

end (e.g., Chesbrough, 2019). We describe and discuss these mechanisms through the dimensions of knowledge heterogeneity, tacitness, and interdependence. Thereby we offer a tighter theoretical connection between the open innovation literature (e.g., Chesbrough, 2003; Laursen and Salter 2006) and prior theorizing on the knowledge-based view of the firm (e.g., Grant 1996; Kogut and Zander 1992; Nonaka 1994).

Second, we use the digital technology characteristics of re-programmability, intangibility, and specificity of affordances to explicate how and why digital interfaces shape knowledge integration mechanisms. Thus, we combine an in-depth understanding of digital architecture (Henfridsson et al., 2018; Yoo et al., 2012) with insights from open innovation and knowledge integration research (e.g., West and Bogers, 2014; Zahra et al., 2020; Wallin and von Krogh, 2010) to establish digital interfaces as antecedents to knowledge integration mechanisms. Taken together, we offer a digital interface – knowledge integration framework that clarifies (1) how knowledge gets integrated across firm boundaries and (2) how and why digital interfaces shape knowledge integration mechanisms.

For managers, our framework may help to avoid unrealistic expectations and misallocation of resources during the process of adopting external digital solutions. For policymakers concerned about supporting industries as they pursue digital solutions, our results may inform the design of collaborative environments, charged with effective knowledge integration between digital solution providers and potential adopters.

3.2 Theoretical Background

3.2.1 Knowledge integration across firm boundaries

Knowledge integration is an essential function of organizations (Iansiti and Clark, 1994; Kogut and Zander, 1992; Grant, 1996) and can be defined as "creating novel combinations of different strands of knowledge […] sourced from within and beyond the organization" (Zahra et al., 2020, p. 163). In the context of open innovation, knowledge is (1) acquired from external sources, (2) transferred across firm boundaries, and (3) synthesized with internal knowledge to exploit novel solutions (e.g., West and Bogers, 2014; Zahra et al., 2020). Related literature on absorptive capacity has delineated a set of corresponding capabilities that firms require to benefit from the integration of external knowledge, including (1) recognition-, (2) assimilation-, and (3) exploitation capacity (e.g., Cohen and Levinthal, 1990; Zahra and George, 2002; Zobel, 2017).

First, to *recognize and acquire* external knowledge, firms search broadly and deeply across different sources (Cassiman and Veugelers, 2006; Laursen and Salter, 2006; 2014; Garriga et al., 2013; Hagedoorn et al., 2018), including, for instance,

suppliers (Homfeldt et al., 2019), startups (Weiblen and Chesbrough 2015), or universities (Laursen and Salter, 2003; Veugelers and Cassiman, 2005). To be able to recognize relevant knowledge embedded within these external sources, firms need to build up potential absorptive capacity by investing in internal R&D (Fabrizio, 2009; Jansen et al., 2005; Noteboom et al., 2007; Zahra and George, 2002).

Second, the *transfer and assimilation* of externally acquired knowledge is facilitated through a set of underlying processes. If actors on both sides of the transfer process already share a common language, knowledge can be simply channeled across source and recipient (Carlile, 2004; Monteiro and Birkinshaw, 2017). If that common understanding is lacking, however, knowledge needs to be translated to develop a common lexicon (Szulanski 1996) and to convert tacit knowledge – knowledge that is embedded in human skills and/or collaborative social arrangements – into explicit knowledge (Polanyi 1966; Nonaka, 1994; Nonaka and von Krogh, 2009). Furthermore, assimilation of external knowledge often requires political efforts, especially when exchanging parties have conflicting interests and their extant knowledge is 'at stake' (Carlile 2004) or when the 'Not-Invented-Here' syndrome needs to be overcome (Katz and Allen, 1982).

Third, to *synthesize and exploit* knowledge, actors creatively combine various types of knowledge (Andreu and Sieber, 2001). This includes the re-combination (e.g., Galunic and Rodan, 1998) as well as the categorization, re-classification and merging of existing internal knowledge, often across multiple units or teams (Majchrzak et al., 2012). In the context of open innovation, it is through the late-stage synthesis of external and internal knowledge that new solutions can be exploited (Mitchell, 2006; Zahra and George, 2002; Zobel, 2017). However, we still lack a detailed understanding of how this integration and synthesis of external and internal knowledge takes place, making this third phase and the mechanisms of knowledge integration the focus of our study (Zahra et al., 2020).

Gaining a better understanding of such knowledge integration mechanisms requires a deep engagement with the underlying raw material of knowledge integration (Zahra et al., 2020). This raw material includes knowledge about different components (i.e., specialized component knowledge) and knowledge about interfaces between these components (i.e., architectural knowledge) (Grant, 1996; Iansiti and Clark, 1990; Henderson and Clark, 1990). It is therefore both the components of a solution as well as the interfaces between them that are likely to shape how knowledge gets integrated across firm boundaries. Considering that firms across all industries are increasingly aiming at adopting external digital solutions (e.g., Enkel et al., 2020; Nambisan et al.,

2017), we focus on these digital solutions and their underlying architecture as the predominant raw material of knowledge integration.

3.2.2 The raw material of knowledge integration: layers and interfaces of the digital architecture

To understand the raw material of knowledge integration in the context of adopting external digital solutions, we draw from the literature on information systems. This literature has introduced a framework of the digital architecture that explicates how knowledge around digital solutions is structured. This layered-modular architecture comprises four layers – application, data, network, and device (Henfridsson et al., 2018; Porter and Heppelmann, 2014; Yoo et al., 2010), each representing specialized component knowledge. This specialized knowledge is integrated at digital interfaces – connections between two adjacent layers – representing the loci of knowledge integration (Yoo et al., 2012). Because the four layers represent different design hierarchies and are stacked such that one layer only directly interacts with adjacent layers (see also Henfridsson et al., 2018), three interfaces emerge: the (1) application-data, (2) data-network, and (3) network-device interface. We can describe how this architecture structures knowledge through the concepts of these layers and interfaces, as well as by means of their characteristics and affordances - what an actor can do with a technology (Majrchzak,& Markus, 2013). We complement our description with examples in figure 3.1.

First, the *application layer* requires specialized knowledge about digital solution contents and services (Henfridsson et al., 2018). Contents describe any data that is accessible to the end-user. Services describe functionalities of the solution and the resulting affordances.

Second, the *data layer* requires knowledge about processes and infrastructures related to data and the systems within which data is contained (Cappa et al., 2020; Hartmann and Henkel, 2019). The *application-data interface* links these two layers and enables knowledge specialization on applications with specific functionalities (i.e., enabling rather specific affordances). As these functionalities can be edited and re-tasked, the interface affords re-programmability (Kallinikos et al., 2013). Re-programmability allows separation of the application's services from its physical instances (i.e., the device layer) thus also implying intangibility (Autio et al., 2021).

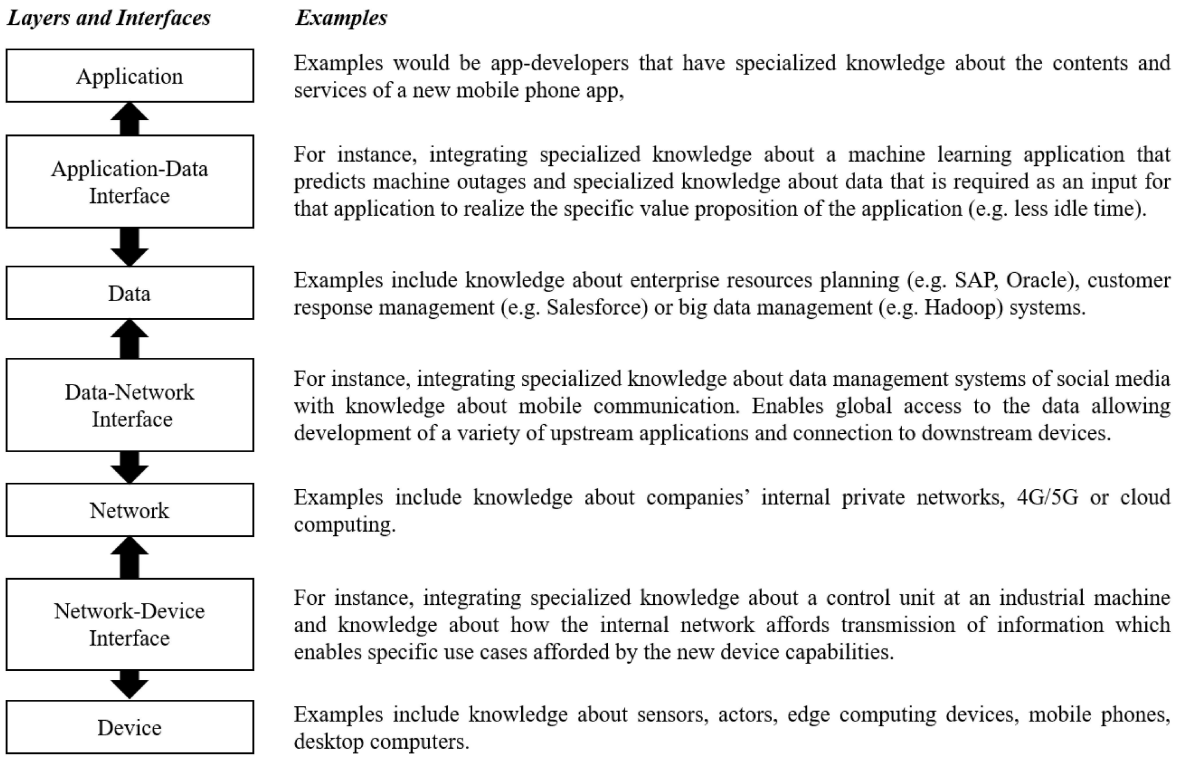
Third, the *network layer* requires knowledge about connectivity and protocols for transmitting data (Yoo et al. 2010; Tilson et al., 2010). The *data-network interface* connects data and network layer, sitting at the core of the architecture with more general affordances as it possesses downward and upward flexibility (Tilson et al., 2010).

Downward flexibility implies that it connects to multiple physical devices through the network layer. Upward flexibility implies that, through the data layer, it allows a solution to make use of any capabilities provided by the network and device layers.

Fourth, the *device layer* requires knowledge about the digital solution's physical components (Yoo et al., 2010; Porter and Heppelmann, 2014). These physical components (e.g., edge computers) afford specific sensing and/or acting capabilities of which some are fixed and cannot be easily re-programmed. The *network-device interface* builds the bridge between the physical (tangible) and the digital (intangible) (Yoo et al., 2010). Thus, it enables the transformation of continuous analog information to discrete digital information (i.e., data homogenization).

To conclude, the architecture of digital solutions explicates (1) four layers that constitute specialized component knowledge (2) three digital interfaces at which architectural knowledge is required to integrate this knowledge to create novel combinations, and (3) varying characteristics and affordances of these layers and interfaces. It allows us to consider the raw material of knowledge integration and thus to theorize about the role of digital interfaces for knowledge integration in the context of adopting external digital solutions.

Figure 3.1 Digital architecture (adapted from Henfridsson et al., 2018; Porter and Heppelmann, 2014; Yoo et al, 2010)..



3.3 Methods

3.3.1 Research context and design

We conducted a multiple case study (Eisenhardt, 1989) to build theory on knowledge integration in the context of adopting external digital solutions. This method is well suited as our understanding of later stages of knowledge integration across firm boundaries (i.e., the open innovation back-end) is limited and as we know even less about how such knowledge integration is shaped by digital interfaces. Following the procedure of theoretical sampling (Eisenhardt and Graebner, 2007), we sought a setting in which we could closely track and systematically compare how knowledge gets integrated across firms at different digital interfaces.

Our setting is a multi-firm open innovation program comprised of 10 international energy utilities and 15 startups. In this program, the utilities aim at adopting different kinds of external digital solutions from the startups. The energy sector has recently seen rapid changes with the rise of renewable energy generation (e.g., solar and wind), the decentralization of energy systems, and the emergence of new digital solutions (Bumpus and Comello, 2017). These digital solutions are widely understood as core to utilities' prospects of successfully navigating this industry transformation. Specifically, digital solutions hold the promise of enhanced safety, productivity, and sustainability of energy systems by making existing infrastructure (e.g., electricity grids) intelligently responsive to complex energy supply/demand dynamics and by offering novel energy customer services (e.g., home automation). To adopt such digital solutions, the 10 utilities jointly formed an annual open innovation program in which they select 15 startups into a 6-months program that includes 4 one-week-long modules (equally distributed over time) during which all members co-locate to intensify their collaborative activities. Our study is set in 2019, the third edition of the annual program.

A key advantage of this research setting is that the beginning of the program already marks the initiation of the open innovation back-end, allowing us to build theory about the later phases of knowledge integration. At the program outset, the utilities have already largely concluded both the knowledge acquisition and transfer phases which included (1) launching the open innovation program, (2) issuing and marketing a call for applications with digital solution target areas based on input from the utilities' business units, (3) the analysis of 500+ applicants and their digital solutions (4), transferring the externally acquired knowledge to internal business units to pre-select 30 out of 500 startups that align most with internal needs and interests, and (5) the final

selection of 15 out of these 30 startups for which business units commit to fund and participate in projects with the aim of adopting the external digital solution.

At the beginning of the program, each startup pairs with a utility to initiate a project in which the utility aims to adopt the startup's digital solution (i.e., 15 different projects in total). Drawing from the digital architecture (Henfridsson et al., 2018; Yoo et al., 2010), we clustered projects according to how digital layers provided by the startup and the utility connect (i.e., digital interfaces). We thus have a nested case study design (Thomas, 2011), whereby we cluster 15 projects into three cases according to the digital interfaces present. We based the clustering on the analysis of a rich database of non-public documents of each project which entailed detailed descriptions of the layers that were provided by the startup and by the utility (e.g., machine learning application from startup and energy consumption data from utility). We validated the clustering with insights from observations and interviews. Table 3.1 provides an overview of the cases and nested projects.

Table 3.1 Overview of nested cases and descriptions of digital interfaces.

Cases	Projects	Interfaces	Interface Descriptions
Case 1	1. Machine Learning (ML) driven price pre-diction	**Application -data Interface** Startup provides application that draws from utility-owned data	1. Startup provides ML price prediction application that acts upon historic energy generation data from the utility
	2. Energy services sales automation		2. Startup provides SME energy sale automation application that requires access to the utility's data on previous SME sales
	3. ML driven infra-structure planning		3. Startup provides ML infrastructure planning application that acts upon historic and real time energy consumption data from the utility
	4. Renewable certificate marketplace		4. Startup provides renewable certificate marketplace that requires access to consumption data from the utility
	5. Structural modeling of energy assets for digital twins		5. Startup develops structural model of asset (e.g., hydro plant) based on the utility's CAD (computer-aided design) data of the asset and the real time inflow/outflow data
Case 2	6. Energy savings data management platform	**Data-Network Interface** Startup provides data management system that needs to run on internal utility networks to interface with other operational systems	6. Startup provides energy consumption data management platform that runs utility networks and connects to other internal systems such as a customer relation management (CRM) system
	7. Grid data management platform (a)		7. & 8. Startup provides grid data management platform that needs to run on the utility's platform and connects to other internal systems such as the ERP (Enterprise Resource Planning – e.g., SAP) or GIS (Geo Information System)
	8. Grid data management platform (b)		
	9. IoT data management platform		9. Startup provides IoT data management platform that needs to run on the utility's cloud and connects to other internal systems such as the SCADA (Supervisory Control and Data Acquisition) system

Table 3.1 Continued

Case 3	10. Smart air condition solution	**Network-Device Interface** Startup provides device that needs to connect to the utility's network to enable its sensing and acting capabilities	10. Startup provides smart air condition device that needs to be installed at the customer site and connected to the utility's network to send and receive data
	11. Smart electric vehicle charger		11. Startup provides smart EV charger that needs to be installed at the customer site and interfaces with the utility's charging operating system
	12. Smart transformer maintenance solution		12. Startup provides transformer maintenance device that needs to be installed at the utility's transformers and connects to the networking infrastructure to send data
	13. Smart micro-battery		13. Startup provides smart micro-battery that needs to be installed at the customer site and connects to the utility's smart home network
	14. Distributed energy resource control (a)		14. & 15. Startup provides control device that communicates (for sensing and acting) with distributed energy resources via the utility's network infrastructure (e.g., ethernet, 3G/4G/5G)
	15. Distributed energy resource control (b)		

In case 1 (projects 1-5), utility and startup layers connect at the application-data interface. The startups provide new applications that draw from the utility's data. For example, a startup application predicts energy prices with machine learning models using utility-provided energy generation and consumption data. In case 2 (projects 6-9), startups provide new data management infrastructures (data layer) that connect to existing utility systems (network layer), resulting in a data-network interface. For instance, the startup provides a new electricity grid data management solution (offering data aggregation and operational planning capabilities) that needs to run within the utility internal network. In case 3 (projects 10-15), startups provide a new device (device layer) that needs to connect to internal networks (network layer) to enable its functionalities (i.e., device-network interface). One example is a smart air conditioner requiring installation at the utility's customer site and connecting to the utility's cloud service to enable its control functionalities.

Finally, our nested research design controls for many confounding factors and alternative explanations. The startups are pre-selected out of 500 applications, the projects are part of the same program and dimensions such as startup size, industry, partner-type, governance structure, timing, etc. were relatively homogeneous. This increases the likelihood that we could trace back differences in knowledge integration mechanisms to the different digital interfaces, increasing the internal validity of our emerging theoretical framework.

3.3.2 Data collection

We collected a variety of longitudinal data on the 15 projects (see table 3.2 for an overview). First, we had access to various program-specific, non-public, documents such as joint presentations of utilities and startups. Most of these documents were produced and/or collected during the 4 one-week long modules during which program participants met in person. These documents contain detailed descriptions of the digital layers and interfaces, project timelines and milestones, collaborative activities, challenges, and achievements of the projects (60 documents with ~20 slides each). Additionally, we had access to a project management tool which contained further detailed documents on project progression in-between the 4 modules (45 documents). This rich document database allowed us to cluster projects into cases according to their digital interfaces and to develop an in-depth understanding of the activities related to knowledge integration in each project.

Second, we conducted a total of 40 semi-structured interviews with representatives of the startups (e.g., CEO, CTO, etc.) and utilities (e.g., Innovation Manager, Business Unit Manager, etc.) throughout the progression of the projects. For each project we conducted 1-3 interviews over time with one representative from both the startups (15 informants in total) and the utilities (10 informants in total). This dual perspective helped us to reduce single firm bias. During the interviews, we covered the following topics: (1) digital layers and interfaces (e.g., *"What are the technology components that you provide and that your partner provides to make the entire solution work?"*), (2) project progression and timelines (e.g., *"What are the main activities, and milestones in your project?*"), (3) knowledge integration processes ("*What were the main integration challenges? How do you share knowledge with your collaboration partner? What is the relevant knowledge that you need from your partner?"*), (4) communication between actors (*"How do you communicate with your collaboration partner?"*), and (5) resources used (*"What are the relevant people and units that need to be involved in the project?"*). Fourteen of these interviews were formal interviews, lasting between 30-70 minutes while twenty-six of the interviews were more spontaneous informal interviews conducted in 'real-time' during the program modules, lasting between 20-30 minutes. We audio recorded and transcribed all forty interviews. The interviews provided a nuanced understanding of the nature of knowledge integration and the role of digital interfaces beyond what was understood from the gathered documents.

Third, during the four one-week-long program modules, two researchers observed – in person – approximately 170 hours of project presentations and (non-

public) meetings between startups and utilities of all 15 projects. We created, compared, and discussed detailed notes of these observations. Additionally, we recorded 980 minutes of these project discussions. The observations allowed us to triangulate with insights from the documents and interviews.

Four out of the 40 interviews were retrospective interviews in which we discussed preliminary results and frameworks with senior managers from four of the utilities that were involved in 9 of the 15 projects. We used these throughout our analytical process to check and validate emerging findings. Having this mix of real-time observations, interviews, and documents as well as retrospective interviews, further adds to the validity of our findings (see also Leonard-Barton, 1990).

Table 3.2 Data collection and description of use of data sources in the analysis

		T1	T2	T3	T4	T5	**Tot.**	
Non-public documents (presentations and updates from digital project management tool)	***Startups*** – presentations about digital solutions and potential projects	15					**15**	*We used the documents (1) to cluster projects into cases at the different digital interfaces (2) as a starting point for creating temporal activity maps for each project (3) to assess the extent to which the knowledge integration mechanisms entailed the management of knowledge interdependencies and (4) to validate the assessments of heterogeneity and tacitness of knowledge*
	Utilities – presentations about project agreements and progress			15			**10**	
	Joint – presentations about project scope, progress and outcome		15		15		**30**	
	Updates on contractual agreements between startups and utilities		15				**15**	
	Updates on project progress and barriers			15			**15**	
	Updates on project progress and outcomes				15		**15**	
	Total # of non-public documents	**15**	**30**	**30**	**30**		**105**	
Interviews	Startups		11	12	5		**28**	*We used interviews to (1) validate temporal activity maps for each case (2) derive dimensions of knowledge integration mechanisms (3) assess heterogeneity , tacitness and interdependence of knowledge*
	Utilities		4		4	4	**12**	
	Total # of interviews		**15**	**12**	**9**	**4**	**40**	
Obser-vations	Module 1 – initial discussions about digital solutions and potential projects	40					**40**	*We used insights from our observations to develop an in-depth understanding of digital interfaces and activities related to knowledge integration in each project, to detect emerging patterns and to validate all subsequent data analysis steps*
	Module 2 – project onset discussions		62				**62**	
	Module 3 – discussions about project progress			36			**36**	
	Module 4 – discussion about project progress and outcomes				32		**32**	
	Total hours of observations	**40**	**62**	**36**	**32**		**170**	

3.3.3 Data analysis

First, following best practice in theory building from multiple cases (Eisenhardt & Graebner, 2007), we started our analysis by creating rich descriptions of the 15 projects (7-10 pages each; 120 pages in total). What emerged was that knowledge integration across the projects was substantially shaped by the nature of digital interfaces. Thus, we inspected the project descriptions for instances of activities that were associated with integrating knowledge related to each interface. In this exercise, we could largely draw from the collected project documents that describe the kind and timing of activities throughout each project. Subsequently, for each project, we categorized activities related to knowledge integration into activities led by startups vs. those led by utilities and placed them on a timeline. These analytical steps produced 15 temporal activity maps (one per project). These temporal activity maps make explicit the timing, duration, and kind of activities related to knowledge integration. This gave us an important tool for condensing, inspecting, and comparing projects through the lens of our research questions.

Second, we compared the temporal activity maps of projects clustered by case (within-case logic) to look for emerging patterns. We used this comparison to create one aggregated temporal activity map per case (i.e., 3 maps). These aggregated maps capture the timing, duration and intensity of activities that were consistent (appearing in the same or similar format and timing in at least 75% of the projects within the same case) across projects within each case (see also figures 3.2, 3.3, 3.4). We then used insights from interviews and observation notes to validate the emerging temporal activity maps and add descriptive richness.

Third, we adopted a cross-case logic to develop and sharpen our understanding of the differences in knowledge integration across our three cases (i.e., across different types of digital interfaces). For this purpose, as also elaborated in the next section, we primarily used insights from our interviews, complemented by the temporal activity maps. We compared how knowledge integration in one case is different from the other two cases and distilled emerging patterns. We then formed preliminary constructs (i.e., three different knowledge integration mechanisms) and built theoretical arguments (i.e., how, and why digital interfaces shape these knowledge integration mechanisms) based on the emerging patterns and used replication logic to refine them. In this process, we iterated within cases and across cases. Furthermore, we iterated with literature related to knowledge integration, open innovation, and information systems to refine definitions of constructs and to increase the precision of our theoretical arguments.

3.3.4 Capturing differences in knowledge integration mechanisms

As the analysis progressed, we uncovered that the emerging knowledge integration mechanisms differ (across the three cases) across three underlying dimensions that capture differences in the type and nature of the knowledge that is being integrated: the extent to which (a) multiple heterogeneous knowledge domains are required during the integration process (b) tacit knowledge is present and (c) knowledge interdependencies are germane and need to be considered. To sharpen our cross-case analysis, following best practice in multi-case study research (Eisenhardt, 2020), we developed criteria to assign values of "low", "moderate", or "high" for each case along these dimensions. Two of the authors developed these criteria based on their in-depth knowledge of the cases and data. The third author took on a "theory-hat" and provided an independent view, from which we refined the criteria. Then two authors independently assigned values, following principles of intercoder agreement (Campbell et al., 2013).

First, we assigned "low" for the number of heterogenous knowledge sources, if both utility and startup knowledge sources come from the same (i.e., one) knowledge domain, "moderate" if there are 2-3 knowledge domains and "high" if there are 4 or more knowledge domains involved. Different knowledge domains could be, for example, sales and marketing vs. research and development (see also Carlile, 2002) or the physical knowledge domain (e.g., field engineers) vs. the digital knowledge domain (e.g., cybersecurity experts) (see also Pershina et al., 2019). We systematically extracted this information for each project from non-public documents including, for instance, lists of people and their functions that participated in meetings; interviews during which we explicitly asked about the number and kinds of knowledge domains that are involved in each project; and our own observations where we observed at least one meeting per project and took note of participants' primary knowledge domains.

Second, to the extent tacit knowledge is involved, we assigned "low" if informants in interviews primarily mentioned the transfer of explicit knowledge (e.g., sharing data via e-mail), "moderate" if explicit and tacit knowledge were mentioned about equally often (e.g., presenting codified specifications and giving additional training), and "high" if mainly tacit knowledge was mentioned (e.g., intense in-person workshops to access knowledge embedded in individuals). We extracted this information from our interview data where we explicitly asked about knowledge integration and communication methods from which we could then infer to the tacitness of knowledge. Furthermore, we validated our assessment by inferring the tacitness of

knowledge from the kinds of meetings/workshops that we observed and that were described in documents.

Third, to the extent that knowledge interdependencies need to be accounted for, we assigned "low" if startup and utilities could work in parallel (e.g., startup does not have to wait for additional input from the utilities to reach the next milestone), "moderate" if startups and utilities sometimes have to wait for input from the other party, and "high" if startup and utilizes mostly or always have to wait for input from the other party before they can work towards the next project milestone. We derived this assessment from our project descriptions and temporal activity maps, informed by detailed timelines that describe the timing of startup-led and utility-led activities (see figures 3.2, 3.3, 3.4). We further validated our assessments with insights from interviews and observations.

Figure 3.2. Activity map of case 1 (application-data interface) as aggregation of projects 1-5.

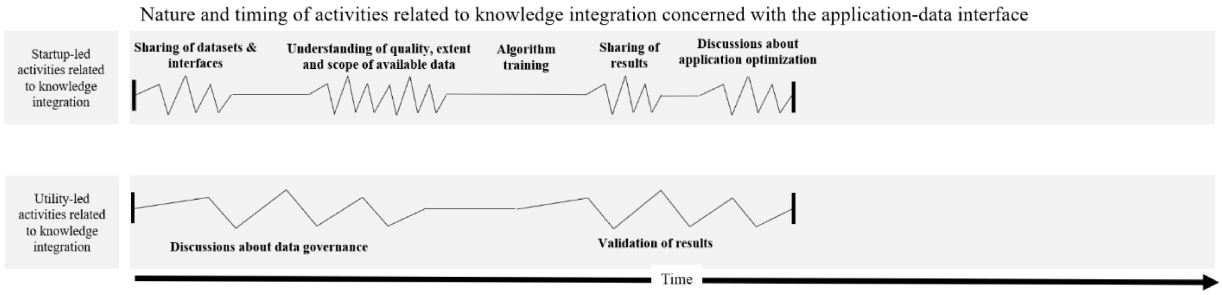


Figure 3.3. Activity map of case 2 (data-network interface) as aggregation of projects 6-9.

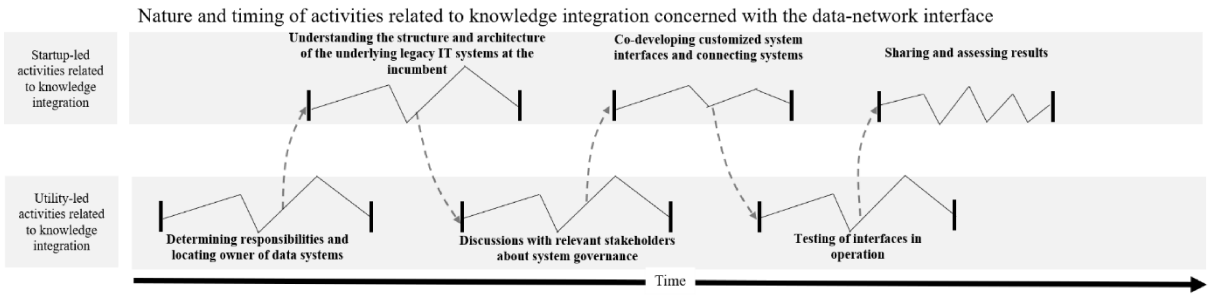
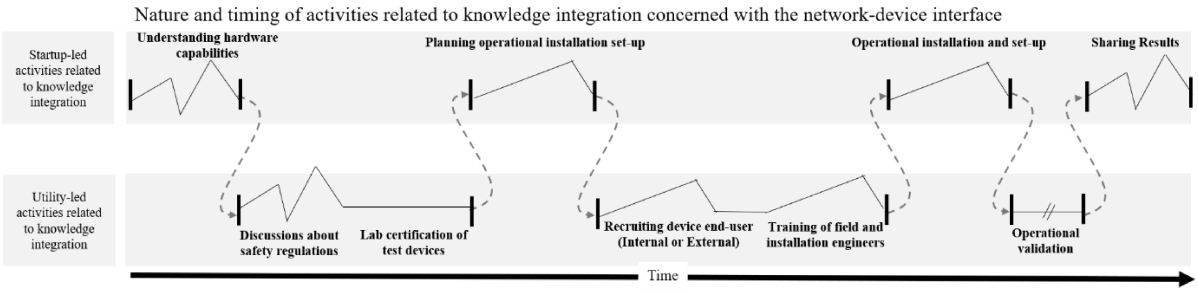


Figure 3.4. Activity map of case 3 (network-device interface) as aggregation of projects 10-15.



Interpretation of figure 3.2 – 3.4 is as follows: the black lines/graphs represent the duration (x-axis), the frequency (frequency of zigzag pattern), and the intensity (amplitude of zigzag pattern) of activities related to knowledge integration. A bold horizontal line indicates a discontinuity where the proceeding of one actor (e.g., startup or utility) is contingent on the progression of the activities of the other actor. Accordingly, the position on the x-axis captures the temporal ordering of the different activities related to knowledge integration.

3.4 Results

First, our data analysis uncovers three distinct knowledge integration mechanisms in the context of adopting external digital solutions (see table 3.3). Second, based on our data analysis and iterations with literature on open innovation, knowledge integration and information systems we develop theoretical argument that trace differences between these knowledge integration mechanisms back to characteristics of the digital interfaces at which knowledge integration takes place. As such, we offer an emerging digital interface-knowledge integration framework. In the following we explicate knowledge integration mechanisms and our theoretical arguments by case. We start with case 1 which contains all projects clustered at the application-data interface, proceed with case 2 (data-network interface) and end with case 3 (network-device interface).

Table 3.3 Cross-case comparison with selected evidence.

Case	Digital Interfaces	Knowledge Integration Mechanisms			
			Heterogeneity of knowledge sources	**Converting tacit knowledge**	**Managing knowledge interdependencies**
Case 1	**Application-data Interface** *"Data ingestion and configurations; Upload; Client metadata and consumption data" (project 2)* *"Yeah, and then there are technical challenges around where the data is and how to get access to the data" (project 3)* *"STAGE 1: [we have to] move from 1970's drawings to digital asset" (project 5)* *"Problem: Connectivity data not complete (project 4)"*	***Connecting Back & Forth*** **Definition:** integrating knowledge by iteratively connecting existing external and internal knowledge **Illustrative Example:** In project 3, startup and utility iteratively connected their knowledge about data on SME (Small and Medium Enterprises) sales with knowledge about advanced analytics to automize the SME sales proposal process (i.e. for selling customized solar energy solutions)	**Low** (one specific domain) *"With [our collaboration partner] we mainly had the direct contact to the people doing statistical analyses. So, [this was our main] operational contact, effectively. Which I think is also one of the reasons why the process went quite well" (project 3)* *"We need this time series data but it's not an issue, because typically the people who work with this are just very few inside the organization — and they know what it is." (project 4)* *"With [our collaboration partner] it's also been a good process. But that's filtered through [the utility manager], so, we're having this one key contact which works fine for us." (project 2)*	**Low** (mostly explicit) *"[There are] emails, lots of exchanges coming back-and-forth, because we are basically saying, do you have this [data], can you find out? And the response from [the incumbent] has been really fast too. I mean, they're not every two hours, but that's within a 24-hour cycle." (project 5)* *"And then they were like, what we need is the data and then we got like six sets of data [from the utility] and then the guy from our side said for this task, we want thousand sets. This is going to be minimum otherwise it ain't working." (project 4)* *"We want to predict renewable energy output. That means they got to give us data, to learn from. This will inevitably be time series data. That's the basis of what we do. So, then we are really talking about time resolution, and if it is clearly labeled for our use case?" (Project 3)*	**Low** (parallel) *"We do need a lot of stuff now from other internal stakeholders. But we can already do a lot on our own [together with the startup] there in terms of building stuff out." (project 4)* *"As soon as you have the use case and the right partner to talk to who provides you the data we have less exchange … we can feed that data into [our application], to train models specifically for these guys [the utility]." (Project 1)* *"We received the final data update from them three days before … and then we ran the [structural physics] models for the digital twin and we showed them initial output. Which they seemed reasonably happy with, in terms of progress." (project 5)*

Table 3.3 Continued.

Case 2	**Data-Network Interface** *"Create integration configuration to ingest real time SCADA, AMI, GIS data" (project 8)* *"[Develop] a concept for integration ... Onboard the [utility's] legacy systems into the [startups' smart grid platform]" (project 7)* *Integration and system setup: GIS, connect" (project 9)* *"They have to connect with our IT systems and with the solution that we have to store data from the smart meters and organize the data starting from there." (project 8)*	***Fusing from heterogenous sources*** **Definition:** integrating knowledge by fusing knowledge from heterogenous sources **Illustrative Example:** *In project 6, startup and utility fused their heterogenous knowledge about energy data management (startup knowledge) and existing internal utility systems to set up an energy data management infrastructure that enables the development of customer energy saving solution.*	**High** (4 or more domains) *"[We are trying to] find a way to integrate with their existing systems [... therefore] we want people from the marketing team, people from the product team. Obviously, the integration team all, or maybe even a sales team, depending on how deep they want to go [with integrating the new energy management software]. So, it might be between 10 and 20 different experts that are responsible to pull up things." (project 6)* *"We are working with an innovation unit that give us an entry. But usually, the users are the DSOs. They have a unit that is especially part of the system integration part of our project. And then of course the business units, the grid planning unit, and the grid operating unit. So in total 4-5 people units in the project." (project 8)*	**High** (mostly tacit) *"[It requires] intense workshops with internal data experts to discuss relevant data systems and data structure ... this discussion, if possible, we prefer to do it on site. Because, you know, it's important to be close to them, it's necessary for these kind of discussions" (project 9)* *"It's especially about integrating and combining different systems. Because we source the data from several different systems. So we don't just get data from one system but we have data from different systems and somehow we have to combine them and then it's always the question do we get the critical information that enables us to combine and aggregate it. Usually these information exist somewhere, but it is often difficult to find all the systems owners, that have this knowledge." (project 8)*	**Moderate** (both parallel and sequential) *"We develop an API connection [together] with them. We can also install it in their environment, which would make it very easy for them to [connect to our system]." (project 8)* *"...we don't have [the required certification] yet. So it's like a security standard for the network architecture of our integration. And so it's just waiting to hear back if [our network architecture] is sufficient" (project 6)* *"that they understand how our technology works, and how we got there. So from my experience it cannot be a black box to them, Especially, because for each customer, we have to develop this customized interface which we we call "shipper" from their legacy systems to our new system. (project 9)* .

Table 3.3 Continued.

Case 3	**Network-Device Interface** *"Device deployment concerns, issues with construction. Cyber-security constraints" (project 14)* *"Technical discussion about how to introduce the [startup's] device in [utility's] network" (project 12)* *Challenges: ... technical device support, installation, commissioning" (project 11)* *"Technical modifications [to hardware], capital requirement, compliance & regulation, 2nd onsite demo & testing" (project 13)*	***Situating to resolve interdependencies*** **Definition:** integrating knowledge by situating the knowledge provided by the external partner in the new (utility) environment, which allows to test and resolve emerging interdependencies between the external knowledge and the internal environment. **Illustrative Example:** In project 13, the utility situates the startup's knowledge about a smart micro-battery to resolve interdependencies between the battery and other smart home networks and devices operated by the utility, finally allowing them to offer a solution that prevents power outages.	**Moderate** (physical and digital, 2-3 domains) *"There are many people that really want to get trained on what these things [the external devices] do and what they look like. The physical system which has physical buttons on it, like off and an on button, things like this. And then there's also the installation personnel [that needs to be involved] who will need to know the power supply situation, the ethernet and the networking situation [in this new environment]." (project 14)* *"So, our side is easy. So, it is myself, CEO, I've been involved in most of this process, working with utilities, it's also my background, but then we have mechanical and electrical engineers [physical domain] and the firmware engineers [digital domain]" (project 13)*	**Moderate** (both explicit and tacit) *"In the first part [before the installation] we need to train the technicians from the company, okay, so the idea is they can move it and since they do it the first time, we will supervise and getting them certified to do it. So, the second time they can do it by themselves." (project 15)* *... basically, there is at least one person ... one person you need to supervise, and the other staff may be involved remotely... Basically to start the system. (project 12)* *"And how should [the device] reach this [internal network]? They don't want to connect to the public Internet because that's risky. These are complete computing [devices], they're installed at the home level. But if someone tries to enter the [device network] as employed, it's a big problem" (project 14)*	**High** (sequential) *"And because after you install the equipment, you still need to tune the equipment with the machine. So that takes some time. Two weeks or even one month to tune the machine. And then you take two months to make the operation stabilized and you can get the measurement result." (project 12)* *"[We have to decide on] which [and] how many customer households we are going to install the equipment and set the timeline and the deliverables. And also, we can check the installation timeline for that. (project 13)* *"With [this utility], it's heavily around the technical feasibility. Okay, so we're doing lab tests or in the certification process, or working with, technical engineers to assess our technological capabilities, and make sure it's delivering as promised" (project 11)*

3.4.1 Case 1: Connecting back-and-forth to integrate knowledge at the application-data interface

At the application-data interface (case 1) startups and utilities employed a knowledge integration mechanism that we label *connecting back-and-forth.* That is, they integrated knowledge by iteratively connecting their respective knowledge. As indicated by our data, this entails (a) connecting experts from the utility and startup that have knowledge in the same or similar knowledge domain ("low" heterogeneity) (b) iteratively connecting mostly explicit information ("low" tacitness) and (c) rather independently developing and optimizing the digital solution ("low" interdependencies) (see also table 3.3).

We use project 1 (within case 1) to illustrate the *connecting back-and-forth* knowledge integration mechanism. In this project, the startup provided a machine learning application that predicts energy prices. Because of transformative changes in energy supply (e.g., intermittent supply from solar and wind) and increases in demand (e.g., electrification of transport), prices are becoming much more volatile. The utility scouted and selected this startup into the program, because its machine learning models would allow the utility to leverage its existing data to cope with this volatility. On the one hand, engineers at the startup possessed in-depth knowledge about their machine learning models (application layer) and the required input related to energy prices. The utility, on the other hand, had access to extensive data streams (data layer) related to energy prices. Knowledge about these data streams resided in a utility data science team within the energy trading department. Both, the startup's machine learning engineers and the utility's data science team had specialized knowledge regarding energy prices. While the startup team focused more on the application and the utility team more on the data, there is a significant knowledge overlap between the two and the knowledge resided in few, rather homogenous actors, as illustrated in the following quote:

"We just need a typical subject matter expert on our side to make sure we can understand what data exactly they [the startup] need to deliver their service" (project 1, Manager from the utility)

This knowledge overlap could be leveraged to *connect* the knowledge about application and data. To achieve this connection, the startup shared specifications about the type and format of data that is needed for full functionality. These specifications were rather straightforward (e.g., "*we require energy consumption data at a high sampling rate, e.g., 10 data points per hour"*) and could be communicated via email. The utility in turn, shared datasets with descriptions about included variables. Jointly, the datasets

and descriptions provided a common lexicon which utility and startup representatives could rely on in their interactions. Given the limited number of people that could rely on this common lexicon, knowledge was integrated through the back-and-forth connection of (mostly) explicit knowledge. This approach enabled clarifications to be resolved rather quickly, as illustrated below:

"They sent a lot of data. I clarified a lot of questions. Really good … So, we would get the data back, [would] start looking at it. And then you go—ah, wait; I did not quite understand this. So, let me make sure I understand it. Then you send an email back and say—okay, are you sure you mean this? Are you sure this is everything?" (project 1, Startup project manager)

Through this connection of knowledge across the application and data layer, the utility and the startup could quickly and fully understand the needs of the other. This understanding facilitated by the back-and-forth connection of knowledge enabled each party to independently leverage their existing knowledge at the respective layer to optimize the solution. For instance, the startup could train the models rather independently from the utility's efforts to access larger datasets and streams in the right format and at the right frequency. This independence is also illustrated below:

"They [utilities] need to understand the use case but that is not difficult [...] and they need to identify the right contact person [...] besides that they only need to give us the data they already have [...] then we can start training our models" (project 1, Startup project manager)

Similar patterns of this knowledge integration mechanism could be detected across all other projects clustered at the application-data interface, as also shown in table 3.3. For instance, in project 5, startup and utility connected their knowledge about data from a large-scale hydro-power-plant (data layer) and a physics-based model to build a digital twin (application layer) that estimated potential life-time extensions of the power plant.

Having understood the knowledge integration mechanism and its underlying dimensions of heterogeneity, tacitness and interdependencies, we were looking for more detailed explanations of how and why such knowledge integration was shaped by the characteristics of the specific digital interface. Based on our case analysis and by iterating with literature, we further theorize *how and why* the application-data interface shapes the nature of *connecting back-and-forth*. First, the "low" heterogeneity of knowledge that characterizes this mechanism can be traced back to the specific affordance at the application-data interface. Affordance at the application layer is specific because it is positioned at the digital periphery of the digital architecture (Yoo

et al., 2010). Put differently, the startup applications (e.g., energy price prediction) have a rather specific business purpose. Because of this specific purpose, knowledge about the application and about relevant data tends to reside within relatively few experts inside the startup and the utility (i.e., heterogeneity is "low").

Second, the "low" need to uncover and interpret tacit knowledge during *connecting back-and-forth* can be explained by both the homogenization of data and the specific affordances at the application-data interface (Yoo et al., 2010). Given the homogenization and standardization of data in a digital (binary) format, the data layer offers a basic set of rules and standards for how to interpret datasets that are relevant for an application. These datasets are artifacts that contain information related to the specific affordance of an application, thus providing actors with a common lexicon that they can rely on in their communication. For instance, in their effort to connect knowledge about application and data layers, actors can send datasets back and forth and refer to the descriptive meta-data when seeking interpretation clarifications. Put simply, this common lexicon allows the exchange of explicit knowledge.

Third, the "low" knowledge interdependencies that characterize *connecting back-and-forth* can be traced back to the intangibility and re-programmability that characterizes the application-data interface. Applications are re-programmable (Kallinikos et al., 2013). That is, they can be edited, and functionalities can be added, while they are in use. Therefore, external application providers (e.g., startups) can repeatedly update and improve their applications (e.g., by training machine learning models) "on the go" as new data from the utility becomes available. This reduces interdependencies between actors involved in the integration of knowledge. Furthermore, data is intangible, meaning that it is not bound by location (e.g., Autio et al., 2021). As such the transfer of data is associated with low cost, time, and effort. This implies that actors can send datasets back-and-forth without needing to assess resource constraints.

3.4.2 Case 2: Fusing from heterogenous sources to integrate knowledge at the data-network interface

At the data-network interface (case 2), knowledge was integrated across firm boundaries by what we refer to as *fusing from heterogenous sources*. That is, startups and utilities integrated knowledge by leveraging knowledge from multiple domains and fusing them into a novel combination. As indicated by our data analysis this entails (a) finding experts from the utility and startup with knowledge in multiple different knowledge domains ("high" heterogeneity) (b) uncovering and converting tacit

knowledge in these domains ("high" tacitness) (c) jointly developing new and customized linkages ("moderate" interdependencies) (see also table 3.3).

We illustrate the nature of this knowledge integration mechanism with the example of project 7 (within case 2). In this project, the startup provided a grid data management system. Managing electricity grids is becoming more challenging as, for instance, many decentralized generation (e.g., residential solar) and demand (e.g., EV chargers) sources need to be connected to the grid and their activities coordinated. Grid data management infrastructures hold the promise of developing and using applications that increase efficiency of such grid management processes. The startup possessed knowledge about how to combine, aggregate and visualize data related to grids (data layer). However, to apply such data management capabilities, it needed to connect to internal utility systems such as customer relationship management, billing, and grid asset information systems. The need to connect to multiple systems meant that various operational knowledge domains and departments within the utility needed to be tapped. Furthermore, the startup solution needed to run on the utility's cloud computing environment, the repository and processing hub for sensitive operational data. Given this sensitivity, the related enterprise-spanning units within the utility concerned with data privacy, customer management, cyber-security, and network governance (network layer) also needed to be engaged. This knowledge heterogeneity is also illustrated in the following:

"For the system integration we pulled in the commercial people. But then also technical people, the data science team … and then the next piece will be the CRM, the customer relationship people. That's the next piece of the puzzle… that will be around 5 or 6 different teams" (project 7, Manager from the utility)

Not only did this knowledge stem from multiple heterogenous domains, but it also was primarily tacit. For example, how employees practically coordinate maintenance and operation of all the systems across the utility may not be fully codified or exist in a form that is easily interpretable by an outside party. Instead, it is more deeply embedded within the utility's routines. Therefore, intensive workshops and personal meetings were required to uncover and interpret tacit knowledge about all relevant systems. Hence, knowledge integration at the data-network interface was not only about connecting related knowledge within one domain, but about *fusing* more tacit knowledge from multiple and more diverse domains. This entailed the co-creation of customized linkages between systems which required the input from heterogenous system owners, as also illustrated below:

"This is actually the manual work we have to do. So that's not [just] data, it's more operations. That's more like a, we call it onboarding process, together we have to develop these customized interfaces for each legacy system... So, for this we really have to understand the legacy systems and how they're using them and so that we connect them and can convert into our platform" (project 7, CTO of the startup)

As both parties had to fuse their knowledge to co-develop these customized linkages, they could often not work independently from each other. During the co-developing process, actors from the startup and utility could develop parts on their own but often had to wait for feedback from internal system owners. These interdependencies are illustrated below:

"So, it is their [internal system] that was already in production for like 35 years or so, there was one person, one person who knew all about the [system]. This person had a holiday... for three weeks. So, and then we had to stop our projects [until he's back]." (project 7, CTO of the Startup)

Similar patterns of this knowledge integration mechanism could be detected across all other projects clustered at the data-network interface, as also shown in table 3.3. For instance, in project 9, startup and utility fused their heterogenous knowledge about internet-of-things (IoT) data management and existing internal utility systems to bundle diverse IoT initiatives.

In a next step, we iterated between case analysis and literature to explain how and why the nature of *fusing from heterogenous sources* is shaped by the data-network interface. First, the "high" need to involve heterogenous knowledge sources can be explained by the general affordance of this interface. The affordance of the data-network interface is rather general because it constitutes the core of the digital architecture from which it enables the downstream connections to multiple devices at the physical periphery and upstream connections to applications at the digital periphery (Gawer, 2014; Nambisan et al., 2017; Tilson, 2010; Yoo et al., 2012). These potential upstream and downstream interactions – often spanning multiple business units – require the involvement of a larger number of – and more differentiated - knowledge domains (i.e., "high" heterogeneity) (Lee and Berente, 2012).

Second, the "high" need to uncover and interpret tacit knowledge can be traced back to the constrained re-programmability of legacy systems at the data-network interface. Legacy systems are less re-programmable because they are subject to organizational rules and regulations that have emerged over long periods of time

(Faulkner and Runde, 2019; Lee and Berente, 2012; Tilson, 2010). As such, adding new functionalities that enable the connection to a new data management system (e.g., grid data management) requires knowledge often embedded in individuals, roles, and relationships (i.e., tacit knowledge) (Nonaka, 1994; Szulanski, 1996).

Third, the "moderate" interdependencies can be explained by the constrained re-programmability coupled with the general affordance at the data-network interface. Both require a more coordinated development process because functionalities are more difficult to add "on the go" and multiple stakeholders need to agree on potentially new functionalities as it may have implications for many downstream and upstream connections. Because of these coordination requirements, involved actors cannot easily decompose their activities and thus are more dependent on each other.

3.4.3 Case 3: Knowledge integration by situating to resolve interdependencies at the network-device interface

At the network-device interface (case 3), we distilled a knowledge integration mechanism that can be described as *situating to resolve interdependencies*. That is, knowledge gets integrated by situating the knowledge provided by the external partner in the new (utility) environment, which allows to test and resolve emerging interdependencies between the external device and the internal environment. As indicated by our data this entails (a) involving individuals with digital and physical domain knowledge ("moderate" heterogeneity), (b) sharing explicit device information and understanding tacit knowledge about the new environment in which the device will be placed ("moderate" tacitness), (c) sequentially verifying the device ("high" interdependencies) (see also table 3.3).

We use project 10 (within case 3) to illustrate how knowledge gets integrated at the network-device interface via *situating to resolve interdependencies*. In this project, the startup provided a smart air conditioning device. If connected to and controlled through the utility's network, the smart air conditioner can temporarily reduce the temperature (and thus the energy consumption) of users in such a way that they are unlikely to notice it. The utility scouted and selected this startup because, on a large scale, this would allow the utility to balance demand in peak-times, for instance, in the evening when everyone gets home and turns on the air conditioner at the same time. This reduces the need for costly and potentially high carbon emitting additional energy sources. While the startup possessed knowledge about the device and its functionalities, the utility possessed knowledge about the environment in which the device must be installed and connected to the network. Inside the utility, this knowledge resided mostly in field engineers familiar with connecting devices at end-customers (i.e., physical

domain) and experts familiar with cybersecurity concerns and network settings (i.e., digital domain). This moderate heterogeneity is also illustrated in the following quote:
"So, we are talking to technical or field engineers, that's kind of like the team we have any time anyway. And then they're going to bring over the team from the CIO [chief information officer]." (project 10, Startup CTO)

The startup knew how the device functions in their own labs and within the environment of their existing customers. Its performance in these well-known contexts is often recorded in rather explicit forms such as device specifications. However, within the purview of the project, the device acts in a new environment within the utility with potentially unique interdependencies. These interdependencies may stem from other devices installed at the utility's customers, utility's network connections, and country, industry, or company-specific regulations. Knowledge of how to manage these interdependencies, especially for the first time, is often tacit, and embedded in individuals – often the utility's field engineers. As such the field engineers and digital experts needed to situate the startup's existing knowledge about the device within a new environment. The tacit elements of this knowledge situating are illustrated below:
"Our engineers need to have some intuition on what it looks like to be there, what it feels like to be there, and to see the assets connected to each other … And that's really important for just building intuition and speeding up the technical process" (project 10, Startup CTO)

Situating knowledge about the device enabled the project partners to test and resolve the interdependencies between the external device and the new internal environment. This took place in a sequential chain of validation tests. First, the startup had to ensure that it meets the country-specific regulations. Second, the smart air conditioner got validated in the utility's internal test labs. Third, it got installed in an operational test set-up at the customer to validate its performance under real-world conditions, being connected to other devices and the utility's network. As each step could only start once the previous one had been successfully completed, the involved actors were highly dependent on each other, as illustrated in the following quote:
"There is a deployment of equipment necessary. That's taking a lot of time. I think it makes it expensive and more complicated. And also, it makes it more difficult to do iterations. You cannot say, after one or two months, I do it a little bit differently. Yeah, and let's do something new. So, iterations would be like, six months." (project 10, Manager from the utility)

We detected similar patterns across all projects at the network-device interface, as also shown in table 3.3. In project 12, for instance, a utility situated a startup's knowledge about a transformer sensing device to resolve interdependencies between the device and the internal machine set-up, allowing them to perform predictive maintenance on their own assets.

The following arguments help to explain *how and why* the device-network interface shapes the nature of the knowledge integration mechanism *situating to resolve interdependencies*. First, the "moderate" heterogeneity of knowledge can be traced to the interfaces' position at the physical periphery. This position implies a specific affordance because the startup devices connect to internal networks with the purpose of collecting new data (sensing) or enabling a new functionality (acting). As such, new devices open up specific use cases through their functionalities (Teece, 2018; Yoo et al., 2010). However, the device-network interface also builds the bridge from the physical and tangible (physical periphery) to the digital and intangible world (Faulkner and Runde, 2019; Autio et al., 2021). Thus, knowledge from both the digital and the physical domain is required, making the involved knowledge somewhat more heterogenous (Pershina et al., 2019).

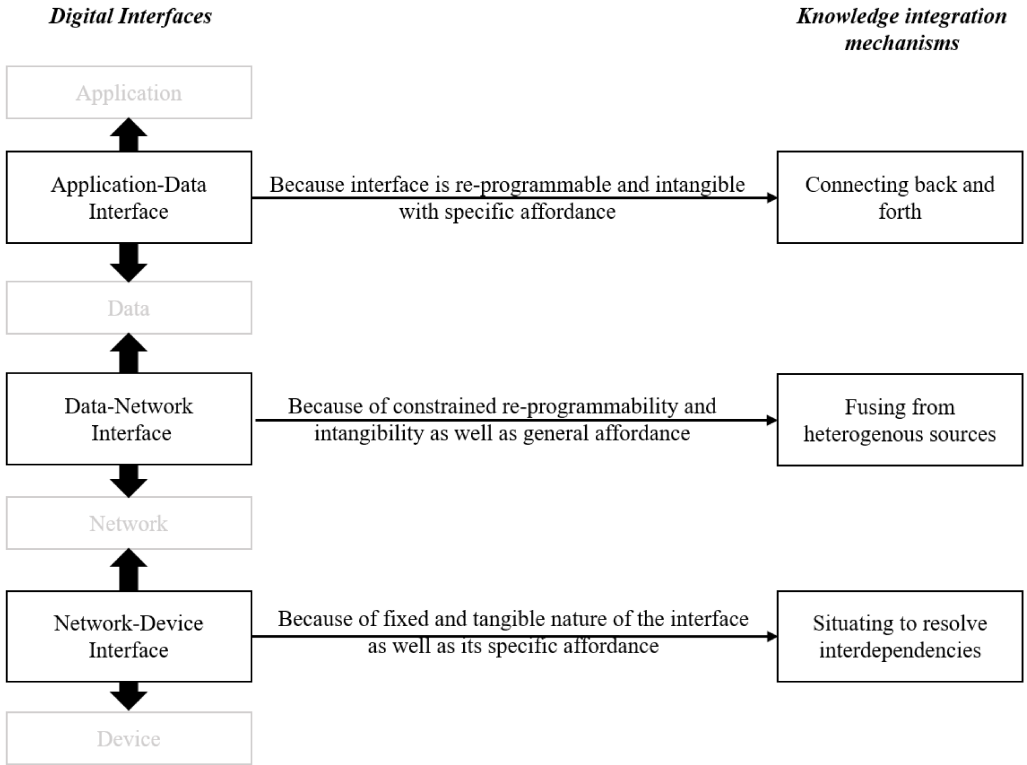
Second, the "moderate" need to uncover and interpret tacit knowledge can be traced back to the tangibility of devices. Devices are tangible which makes them location-bound and intertwined with the physical world (Autio et al., 2021; Yoo et al., 2010). While device specifications are usually codified within manuals (i.e., explicit knowledge), knowledge about the real-world conditions of the physical environment within which the device is placed entails tacit knowledge. Consequently, when integrating knowledge at the network-device interface, both tacit and explicit knowledge are important (i.e., "moderate" tacitness).

Third, the "high" need to manage knowledge interdependencies is another consequence of device tangibility as there are various established safety standards that need to be met. These standards have been established over many years to prevent physical harm to the environment that interacts with the device. However, sharing and testing a new device is associated with more resources (e.g., money and time). For instance, instead of simply sending new data, devices must be shipped and set up in a testing environment (Autio et al., 2021). Beyond this, while certain functionalities of a device could be unlocked via software, there are others that are not re-programmable (Yoo et al., 2010, 2012). In that sense, the product boundaries of a device are less fluid (Kallinikos et al., 2013; Nambisan et al., 2017; Yoo et al., 2012), further complicating independently working on sub-tasks and customizing on the go.

3.5 Discussion

While firms are increasingly becoming more open to external knowledge (e.g., Laursen and Salter, 2006; 2014; Garriga et al., 2013; Hagedoorn et al., 2018), the benefits of such openness are often limited, as it is only through the integration of external and internal knowledge (i.e., the open innovation back-end) that value is unlocked (West and Bogers, 2014). Prior work often neglects these later phases of knowledge integration (Zahra et al., 2020) and has not yet fully uncovered the mechanisms of how the integration of external and internal knowledge takes place. As firms increasingly acquire external knowledge to keep up with rapid developments in digital solutions (Nambisan et al., 2019; Yoo et al., 2012; Dahlander et al., 2021), the issue of knowledge integration becomes particularly pressing in this context. By studying 15 open innovation projects concerned with the adoption of external digital solutions, we develop a theoretical framework that is summarized in figure 3.5. In the following, we describe our two key contributions to the open innovation and knowledge integration literature along this framework. First, we identify three knowledge integration mechanisms (see righthand side of figure 3.5), thereby illuminating the open innovation back-end. Second, we theorize how and why these knowledge integration mechanisms are shaped by digital interfaces (see arrows in figure 3.5), thereby advancing our understanding of digital interfaces as antecedents to knowledge integration mechanisms.

Figure 3.5 Theoretical framework: knowledge integration and digital interfaces.



3.5.1 Illuminating the open innovation back-end: knowledge integration mechanisms

We follow recent calls for more research on the mechanisms of how knowledge gets integrated across firm boundaries (West and Bogers, 2014; Zahra et al., 2020) and identify three novel knowledge integration mechanisms (see figure 3.5): (1) *connecting back-and-forth,* which entails iteratively connecting knowledge from both sides of the boundary, (2) *fusing from heterogenous sources,* which entails the leveraging of knowledge from multiple heterogenous domains and fusing them into a novel combination, and (3) *situating to resolve interdependencies*, which entails situating external knowledge in the internal environment to test and resolve emerging interdependencies between the external digital solution and the internal environment. These mechanisms are both novel and distinct. On the former, they offer explanations for how external and internal knowledge is integrated in the context of adopting external digital solutions, complementing prior work on knowledge integration (e.g., Grant, 1996; Iansiti and Clark, 1994; Zahra et al., 2020). On the latter, they differ across three underlying dimensions: heterogeneity, tacitness, and interdependencies of knowledge. While these underlying dimensions are related to prior literature, their unique combination in a set of knowledge integration mechanisms shed new light on the open innovation back-end (Chesbrough, 2019; West and Bogers, 2014).

By iterating our identified mechanisms with prior work on knowledge integration, we offer a tighter theoretical connection between the open innovation literature and prior theorizing around the knowledge-based view. First, regarding the dimension of knowledge heterogeneity (Iansiti and Clark, 1994; Kogut and Zander, 1992), *fusing from heterogenous sources* draws from a larger number of different knowledge domains. In contrast, *situating to resolve interdependencies* mainly involves the physical and digital knowledge domains (Pershina et al., 2019), while *connecting back-and-forth,* deals with rather homogenous knowledge. Second, regarding the tacitness of knowledge (Polanyi 1966; Nonaka, 1994; Nonaka and von Krogh, 2009), *connecting back-and-forth* strongly relies on the channeling of explicit knowledge (Monteiro and Birkinshaw, 2017), while *fusing from heterogenous sources* and *situating to resolve interdependencies* require more translation (Carlile, 2004) and interpretation of tacit knowledge (Nonaka and von Krogh, 2009). Third, regarding the knowledge interdependencies dimension, *situating to resolve interdependencies* makes more use of sequencing to deal with high knowledge interdependencies (Grant, 1996; Wallin and von Krogh, 2010). The other two knowledge integration mechanisms,

however, allow for more parallelization of activities (Nonaka, 1994), given lower levels of interdependencies.

To conclude, while prior work already highlighted the importance of knowledge integration for open innovation (Wallin and von Krogh, 2010; West and Bogers, 2014; Zobel, 2017), we extend the open innovation and knowledge integration literatures by uncovering detailed mechanisms of how this integration takes place. The tighter integration of the open innovation literature and prior work on the knowledge-based view provides us with a much-needed understanding of the open innovation back-end, offering a new lens to understand why open innovation can fail (Chesbrough, 2019; Lhuillery and Pfister, 2009, Un et al., 2010). For instance, while we do not compare successful vs. failure cases, our mechanisms indicate that failure may be caused by firms' inability to connect, fuse, or situate the externally acquired knowledge to/with/within internal knowledge.

3.5.2 A digital interface – knowledge integration framework

Firms are increasingly using open innovation to adopt specifically digital solutions from external partners (Dahlander et al., 2021; Nambisan et al., 2019), requiring them to integrate knowledge at digital interfaces (Yoo et al., 2010; 2012 Henfridsson et al., 2018). As it is difficult to capture *how* knowledge integration is taking place without understanding *what* is being integrated – i.e., the raw material of knowledge integration (Zahra et al., 2020), neglecting these digital interfaces is heretofore a shortcoming of prior literature. We fill this gap with a theoretical framework that clarifies how and why digital interfaces shape knowledge integration mechanisms (see also figure 3.5).

First, knowledge at the *application-data interface* can be integrated by connecting back-and-forth, because the application-data interface is re-programmable, intangible and has specific affordance (Kallinikos et al., 2013; Autio et al., 2021). Second, constrained re-programmability, intangibility, and the general affordance of the *data-network interface* (Tilson et al., 2010; Yoo et al. 2010) explain why knowledge at this interface can be integrated by fusing from heterogenous sources. Third, knowledge at the *network-device interface* gets integrated by situating to resolve interdependencies. This can be explained by the fixed and tangible nature as well as the specific affordance of the network-device interface. In sum, our theoretical framework explicates how the re-programmability, tangibility, and specificity of affordances at different digital interfaces shape knowledge integration mechanisms.

Based on our cross-case comparison and the theoretical arguments outlined in the results section (section 4), we establish a more explicit link between the digital

architecture (Yoo et al., 2010; Henfridsson et al., 2018) and prior work on the knowledge-based view (e.g., Grant 1996; Iansiti and Clark 1994; Kogut and Zander, 1992). First, we reveal that re-programmability and intangibility are associated with lower tacitness and interdependencies of knowledge. For instance, re-programmability and intangibility at the application-data interface relates to low tacitness and interdependencies of knowledge for the respective knowledge integration mechanism. In contrast, at the network-device interface, which is tangible and not re-programmable, tacitness and interdependencies are moderate and high.

Second, we find that more general (rather than specific) affordances are associated with high knowledge heterogeneity. For instance, affordances of the data-network interface are general, and the corresponding knowledge integration mechanism deals with high heterogeneity of knowledge. In contrast, the two remaining interfaces with specific affordances imply lower heterogeneity of knowledge.

Finally, our theoretical framework extends prior literature on open innovation that has often treated digital solutions uniformly, not carefully considering their digital architecture and its affordances. Notably, prior literature introduced important technology-driven contingencies to the benefits of openness such as absorptive capacity (e.g., Cohen and Levinthal 1990; Zahra and George, 2002) or the complexity or modularity of physical products (e.g., Baldwin and Clark 2000, Schilling 2000, Singh 1997, Cabigiosu et al. 2013; Tee et al. 2019; Ulrich, 1995). However, these existing frameworks primarily build upon the traditional modular architecture of physical products, neglecting the considerably different architecture and affordances of digital solutions (e.g., Henfridsson et al. 2018; Yoo et al. 2010, 2012). While we do not compare physical with digital solutions, we fill this gap by incorporating the architecture of digital solutions and its affordances at the core of our theoretical framework. As such, we offer a new lens to theorize about contingencies to the benefits of openness (e.g., Dahlander et al., 2021; Chesbrough 2019). For instance, when theorizing about open innovation, it is unlikely that the relationship between openness and innovation performance is the same when companies are adopting external applications (which requires integration at the application-data interface) vs. external devices (which requires integration at the network-device interface). While prior frameworks would only look at the complexity or modularity of such applications or devices, our framework suggests that it is particularly the position in the digital architecture – the digital interface – that matters.

3.5.3 Limitations and future research

In this section, we outline the limitations of our findings, describe the boundary conditions of our emerging theoretical framework, and lay out corresponding avenues for future research. First, our study is situated in the energy sector, which is marked by institutional constraints and dominated by incumbent energy utilities that have retained large market-shares. This indicates that our framework might be particularly generalizable to other sectors with similar characteristics (e.g., healthcare sector, transportation sector, minerals and resource extraction sectors). However, the underlying digital technologies (e.g., machine learning, big data management, cloud technology, Internet-of-Things) that enable new digital solutions in the energy industry are the same as those that are transforming most other industries (e.g., manufacturing, agriculture). As our theorizing draws from the underlying digital architecture that applies to digital solutions across sectors, our main theoretical arguments are likely to hold to a certain extent. Applying and empirically validating our framework across other sectors, specifically drilling down on the role of institutional constraints could be a promising avenue for future research.

Another potential boundary condition of our framework is the type of firms that engage in external digital solution adoption. In our case, these are incumbents that are non-digital natives and that are adopting digital solutions from mature technology startups. As such, the generalizability of our findings is likely to be high in similar settings, where (e.g.) manufacturing incumbents adopt digital solutions from late-stage startups. However, there might be other relevant digital interface - knowledge integration cases, such as when digital natives (Amazon, Facebook, Google, Apple, Microsoft) are either the provider or the adopter of new digital solutions. While future research must validate to what extent our framework holds in these different settings, it might be a good starting point for investigating knowledge integration in such settings. For instance, when Microsoft is adopting new devices for the Azure IoT Suite (e.g., device-network interface), it has a device certification process that is likely to contain elements of *situating to resolve interdependencies* (esp. high interdependencies because of device tangibility). Instead, when Microsoft is adopting new applications for the Azure IoT App-Store, the process is likely to contain elements of *connecting back-and forth* as they use software development kits and application programming interfaces that provide a common language for external app developers. As such, they connect their knowledge about data (Microsoft) and applications (external app developers), which is possible due to the re-programmability and intangibility of the application-data interface.

Finally, one potential boundary condition relates to the size of the projects that we investigated. While the rather small and homogenous project size allowed us to investigate entire projects and to compare integration mechanisms across projects, our findings might be less replicable in the context of larger projects. For instance, very large application adoption projects, for instance in the case of acquisitions, might require more tacit and heterogenous knowledge when compared to smaller projects. Yet, our theorizing would suggest that if there are two larger projects – one at the application-data interface and one at the data-network interface – *ceteris paribus*, integration at the application-data interface follows more the nature of *connecting back-and-forth* and integration at the data-network interface follows more the nature of *fusing from heterogenous sources* with more heterogeneity and knowledge tacitness.

3.5.4 Managerial and policy implications

Our findings provide several takeaways for managers and policymakers. For managers, an understanding of digital interfaces is critical in the design of the open innovation process. Not fully considering these interfaces and related challenges may lead to unrealistic expectations, misallocation of resources and potentially a "false-negative" (Chesbrough, 2019) assessment of an externally provided digital solution. Further, the knowledge integration mechanisms – connecting back-and-forth, fusing from heterogenous sources, situating to resolve interdependencies – provide a framework for how to think about project resourcing, task sequencing, communication tools and collaboration modes as well as schedule updating. Adapting these knowledge integration mechanisms to adopt different types of digital solutions may help focal firms to accelerate their digital transformation.

For policymakers concerned with supporting digital solution adoption within industries of concern, it may be useful to think about ways to accelerate knowledge integration between digital solution providers and those firms seeking to understand and adopt them. Industry specific testbeds, "sandboxes" and demonstration facilities could act as an augmenting bridge between such firms, while also providing exchange of best practices on how to efficiently setup and manage processes for adopting digital solutions.

Chapter 4

Online Networking at Virtual Conferences: Feature Usage and Relational vs. Structural Social Capital

4.1 Introduction

Nowadays, online networking takes place not only on Social Media Networks (SMNs) (e.g., Weiler et al., 2021) but also at virtual events or conferences (Hacker et al., 2020) - preliminary versions of a 'metaverse', recently introduced as the future of making social connections by Mark Zuckerberg (CEO of Meta). But how can individuals effectively network at these virtual events or conferences and build trusted relationships that go beyond new LinkedIn connections?

Networking – the strategic behavior to accumulate social capital (SC) (Forret and Dougherty 2001; Porter and Woo 2015) – is important as SC is a valuable resource for individuals (Kwon & Adler, 2014). For instance, having more SC facilitates the acquisition of new knowledge (Tortoriello et al., 2012), hiring outcomes (Gee et al., 2017) and career advancement (Bapna and Funk, 2020). Accordingly, networking has been investigated in both offline contexts, when individuals make new relationships at physical conferences (Chai & Freeman, 2019; Bapna and Funk, 2020) and online contexts when individuals connect on SMNs (e.g., Hinz et al., 2011; Lanz et al., 2019; Weiler et al., 2020). However, the benefits of SC not only depend on the number of new relationships – the structural dimension of SC – but also on the reciprocity and trust embedded in these relationships – the relational dimension of SC (Bourdieu 1986; Nahapiet & Ghoshal, 1998). More specifically, structural SC increases the access to partners with valuable resources. However, it is relational SC that increases both the motivation to share these resources and the capability to use them effectively (Nahapiet and Ghoshal 1998). Yet particularly the research on online networking has often focused on structural SC and neglected the relational dimension of SC, partly due to its focus on SMNs (e.g., Weiler et al., 2021).

Focusing on both dimensions of SC is a relevant research opportunity with the promise to improve our understanding of online networking, especially given the recent rise of virtual conferences. Virtual conferences are enabled by developments in digital technology tools and features and the pervasive adoption thereof. Compared to physical ones, virtual conferences have smaller carbon footprints (Arsenault et al., 2019; Fraser et al., 2017) and enable more inclusiveness and participation because of lower costs and less travel time (Gichora et al., 2010). In addition to these benefits, it is primarily the Covid-19 pandemic that has exponentially accelerated their popularity (Hacker et al., 2020). Compared to SMNs, they represent temporary endeavours that provide a more extensive set of features that afford networking inspired by both SMNs (e.g., booths/profiles) and physical conferences (e.g., web conferencing) (Hacker et al., 2020). Therefore, they promise to facilitate the accumulation of both structural and relational

SC. However, to what extent this promise holds is unclear. This is also indicated by one of the informants of this study, a participant of a virtual conference: "W*e didn't really have the opportunity to network in this virtual format of the conference. So, getting to know people or making new connections was difficult."* For another participant of the very same conference, however, the promise seems to hold: *"In spite of it being virtual, I got to know a lot of new people [structural SC], and build good relationships with many other participants [relational SC]."* So far, we have very few insights into this puzzle of how and why individuals are more or less successful in networking at virtual conferences.

Following prior research on online networking and the theory of purposeful feature utilization (e.g., Hinz et al., 2011; Lanz et al., 2019; Weiler et al., 2021), this heterogeneity in networking outcomes likely depends on the active usage of the different features provided to participants at virtual conferences. Consequently, this study aims to answer the research question: *How and why does the active usage of different digital technology features at virtual conferences facilitate the accumulation of structural and relational social capital?*

This question is timely and relevant for information systems (IS) research as it allows to improve our understanding of online networking by incorporating both a relational and structural dimension of SC and shedding light on virtual conferences as a novel phenomenon. For practitioners, these questions are important as nowadays, every professional – including academics – has to question her-/him-self of how to engage in effective online networking behavior at virtual conferences. Hosts of conferences or industry events need to consider which digital technology features to provide for virtual conferences to allow participants to network effectively.

To address this research question, I first synthesize insights from prior research on social capital theory (e.g., Nahapiet and Ghoshal, 1998), online networking in SMNs (e.g., Weiler et al., 2021), offline networking at physical conferences (e.g., Bapna and Funk, 2020) and digital technology features and affordances (e.g., Hacker et al., 2020) to develop a theoretical framework of online networking at virtual conferences. I argue that visiting online booths/profiles, using direct messaging, and multi-lateral web conferencing facilitates the accumulation of *structural* SC because it allows individuals to identify and contact networking targets. Direct messaging, bi-lateral and multi-lateral web conferencing facilitate the accumulation of *relational* SC because it enables individuals to experience a sense of virtual togetherness.

To substantiate this framework, I conducted a longitudinal mixed-methods study in the setting of a virtual conference series in the energy industry. I collected longitudinal

digital trace (i.e., feature usage) and survey data of 74 individuals collected at four sequential virtual conference events spread across 6 months (233 observations). Based on this dataset, I test the association between feature usage (e.g., # of multi-lateral web conferencing calls) during an event and increases in structural SC (# of new LinkedIn connections with other participants after each event) as well as relational SC (increase in RC assessed via survey scale after each event). Second, I complement the quantitative with a qualitative analysis based on 19 semi-interviews, 120 hours of observations, 4700 chat messages and other non-public documents.

I find that, as theorized, visiting booths/profiles of other conference participants is significantly positively associated with an increase in *structural* SC. However, direct messaging and multi-lateral web conferencing during the conference has no significant association with increases in structural SC. Similarly, as theorized, using bi-lateral and multi-lateral web conferencing and direct messaging during a conference is significantly associated with relational SC increases. The qualitative insights substantiate and detail the theorized mechanisms of identifying and contacting targets and creating a sense of virtual togetherness. Furthermore, they shed light on the discrepancies between theoretical framework and empirical results. Finally, they allow me to derive important contingency factors that are likely to moderate the relationship between feature usage and SC accumulation. More specifically, the results point toward factors such as feature design, number of participants, as well as an individual's language proficiency, perceived similarity, gender, and time zone. In a post-hoc quantitative analysis, I can partly confirm the role of gender and time zones.

This study makes several contributions to prior literature in IS. Taking an individual's agency for networking seriously (Borgatti & Halgin, 2011; Leonardi, 2013), I confirm the general proposition of the theory of purposeful feature utilization (Weiler et al., 2021) - that active feature usage relates to the accumulation of SC - in the context of virtual conferences. Furthermore, the comprehensive framework of online networking at virtual conferences extends prior research by (1) differentiating between structural and relational SC, (2) expanding the set of investigated features, and (3) introducing potential contingency factors. Jointly, these findings also shed light on virtual conferences as a relevant and novel yet poorly understood online networking phenomenon.

Finally, this study offers several practical implications. For the organizers of virtual conferences or online networking events, the findings provide practical insights about which features to offer to facilitate effective networking. Online booths and profiles help facilitate finding new contacts, particularly if they are well-designed and

contain high-quality information. To enable participants to build trusted and reciprocal relationships, one should offer multi-lateral and bi-lateral web conferencing and complementary messaging features. For multi-lateral web conferencing, however, one should limit the number of participants or use break-out room features. Participants of virtual conferences can use these guidelines to increase their networking effectiveness. However, they should think about customizing their feature usage depending on their language proficiency, time zone, and gender.

4.2 Theoretical background and framework

4.2.1 Social capital theory

Drawing from social network theory, the fundamental proposition of social capital theory poses that SC is a valuable resource that results from the relationships among actors in a social network (Burt, 1983; Coleman, 1988). While the literature on social capital is a broad field drawing from several social theories, in the field of management and information systems, it has been conceptualized as a multi-dimensional construct with, primarily, a structural and a relational dimension (Nahapiet and Ghoshal 1998). The structural dimension mainly draws from social network theory and contains the number of dyadic ties an actor has in a network (Burt, 1983; Granovetter, 1973). The relational dimension captures the quality, reciprocity and trust embedded in the set of relationships in a network - beyond the pure existence of a single dyadic tie or the network's structure (Bourdieu, 1986; Nahapiet & Ghoshal, 1998; Blutt, 2009).

A large body of literature revealed the beneficial outcomes of SC but also point to the differential consequences of structural and relational SC (see Kwon and Adler, 2014 for an overview). For instance, while structural SC relates to higher career success (Seibert, et al., 2001; Bapna and Funk, 2020; Gee et al., 2017), the positive association between SC and knowledge acquisition is primarily driven by the relational dimension of SC (Yli-Renko, Autio and Sapienza, 2001). More specifically, while structural SC (e.g., a higher number of relationships) increases the access to partners for knowledge exchange, it is relational SC (e.g., the trust and reciprocity embedded in a network of relationships) that increases both the motivation to exchange knowledge and the capability to combine the exchanged knowledge (Nahapiet and Ghoshal 1998).

Accordingly, prior research investigated antecedents of relational and structural SC at different levels of analysis. For instance, at an inter-organizational level, in the context of supply chain networks, formal and informal socialization mechanisms increase relational SC (Cousins et al., 2006). At an organizational level, employment practices in the firm, namely stable relationships, strong norms and specified roles, increase relational SC in the form of associability and trust (Leana & van Buren, 1999).

Similarly, in the context of innovation outposts of multi-national enterprises, physical co-location increases both relational and structural SC (Monteiro & Birkinshaw, 2017). At a team level, relational SC (in the form of trust, identification and obligations) is reduced by novelty but facilitated by communal schemas and contracting practices (Blutt, 2009). However, instead of looking at an inter-organizational, organizational or team level, this study focuses on individuals and how their behavior can facilitate the accumulation of their structural and relational SC, as elaborated in the following.

4.2.2 Networking offline and online

Individuals engage in networking – strategic behavior to accumulate SC (Forret and Dougherty 2001; Porter and Woo 2015). One stream of literature has mainly focused on the context of (physical) conferences and investigated how individuals network at conferences and how they benefit from such networking (e.g. Feld, 1981). Conferences are temporary endeavors that bring together individuals of a particular profession or industry with a common interest or that are associated with the same ecosystem. For instance, Bapna and Funk (2020) showed that participants of an IT industry conference could accumulate SC, operationalized as meeting new contacts and making new LinkedIn connections, and benefitted from that SC in terms of career advancement. However, they also find that women accumulate less SC than men because of social and search barriers that can be overcome with interventions. More specifically, their findings indicate that, while individuals can network by spending time talking to individual contacts (i.e., bi-lateral), a social intervention that facilitates group meetings (i.e., multi-lateral) further facilitates SC accumulation in the setting of physical conferences. Related literature showed that making new connections by participating in conferences also relates to higher productivity in the context of academic conferences and paper publishing (Chai & Freeman, 2019). The same association holds in the context of developer conferences (e.g., AppleWorld) and coding activity in platform ecosystems (Foerderer, 2020).

While literature in the information systems field has long acknowledged the importance of SC in the context of virtual teams (e.g., Robert et al., 2008, Cummings and Dennis, 2018) or online communities (Constant et al., 1996; Hinz et al., 2015), the strategic behavior of individuals to accumulate SC (i.e., networking) has been predominantly investigated in the context of Social Media Networks (SMNs) such as LinkedIn (Gee et al., 2017; Kane et al., 2014). To manage SC online, SMNs provide individuals with some features that are free to use and other features that can be unlocked by paying a premium fee (Voigt & Hinz, 2016). For instance, there are passive and active features that afford the accumulation of structural SC (Weiler et al., 2021).

Passive features include, for instance, badges and facilitate the accumulation of structural SC through saliency, as they increase an individual's visibility in an SMN. Active features, instead, include browsing through profiles of other members of the SMNs to find new and often distant contacts and sending messages to existing contacts (Bapna et al., 2018). They facilitate the accumulation of structural SC through activity - searching actively for or actively contacting new targets (Weiler et al., 2021). For instance, in the context of entrepreneurial networks, digital user profiles, digital search, digital relations, and social network transparency can drive the accumulation of SC through network broadening mechanisms and network deepening mechanisms (Smith et al., 2017).

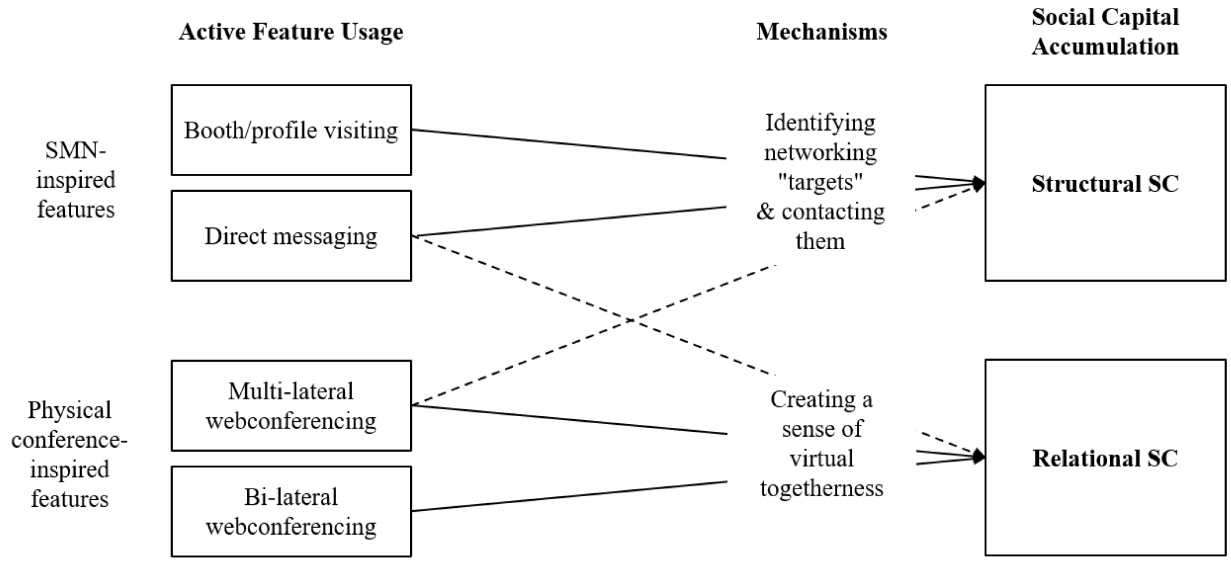
Recent research on online networking in SMNs has established the theory of purposeful feature utilization, showing that heterogeneity in the actual usage (and not just the availability) of features (e.g., sending of messages) explains heterogeneity in the accumulation of structural SC (Weiler et al., 2021). This relationship can be explained by the affordances of these features, describing the action potential– i.e., what a user can do with that technology or feature (Gibson, 1977; Leonardi, 2013; Majchrzak & Markus, 2013). However, in the context of online networking, we only know how active feature utilization influences the accumulation of structural SC but not the accumulation of relational SC. Given the beforementioned differential implications of relational vs structural SC, this is a relevant gap that warrants further investigation. In addition, prior research has focused on online networking in the context of SMNs (Hinz et al., 2011; Lanz et al., 2019; Weiler et al., 2021) or offline networking at physical conferences (Chai & Freeman, 2019; Bapna & Funk, 2021) but has so far neglected online networking at virtual conferences. To fill these gaps, in the following section, I develop a theoretical framework that aims to make sense of online networking at virtual conferences by synthesizing and combining prior insights from (1) social capital theory, (2) online networking in SMNs, (3) offline networking at physical conferences and (4) digital technology features and affordances.

4.2.3 A theoretical framework for online networking at virtual conferences

The theoretical framework (see figure 4.1) for online networking at virtual conferences distinguishes between two types of features and two dimensions of SC. First, there are features that afford networking behavior inspired by online networking in SMNs. I argue that, at virtual conferences, they primarily afford the accumulation of structural SC. Prior research has identified features that afford (1) searching for and visiting profiles and (1) direct messaging (to contacts and non-contacts) as two of the most important networking features in SMNs (Smith et al., 2017; Weiler et al., 2021). I argue that also

at virtual conferences, using these features allows individuals to accumulate structural SC by identifying attractive networking targets and actively contacting them (Bapna et al., 2016; Weiler et al., 2021), as also visualized in figure 4.1.

Figure 4.1. Theoretical framework for online networking at virtual conferences



Second, there are features that afford networking behavior inspired by offline networking at physical conferences. I argue that, at virtual conferences, they primarily afford the accumulation of relational SC. Prior research on physical conferences highlighted that both the participation in group sessions as well as one-on-one conversations facilitate the accumulation of SC (Bapna & Funk, 2020). Analogously, prior research has established that web conferencing features can provide these networking affordances at virtual events (Hacker et al., 2020). More specifically, web conferencing features allow one-on-one conversations (i.e., bi-lateral) as well as group conversations (i.e., multi-lateral). Combining arguments from both literature streams, I argue that the usage of bi-lateral and multi-lateral web conferencing facilitates a sense of 'virtual togetherness' (Hacker et al., 2020), which translates into the accumulation of relational SC, as also visualized in figure 4.1.

Third, I argue that there are cross-relationships between SMN-inspired features and the accumulation of relational SC as well as between physical conference-inspired features and the accumulation of structural SC. More specifically, direct messaging can also facilitate a sense of virtual togetherness as it not only allows to contact formerly unknown participants but also to manage and maintain relationships with existing or new contacts in a continuous conversation (e.g., Kane et al., 2014; Smith et al., 2017). Thus, I argue that the usage of direct messaging is positively related to the accumulation of relational SC, as also visualized with dashed lines in figure 4.1. Analogously, I argue

that multi-lateral web conferencing can also help individuals identify new networking targets (and contact them). This is because the participants in multi-lateral web conferencing sessions at virtual conferences can include formerly unknown yet potentially interesting individuals. Web conferencing features afford first social interaction between potentially new contacts (Hacker et al., 2020). Thus, I argue that the usage of multi-lateral web conferencing is positively related to the accumulation of structural SC (visualized with dashed lines in figure 4.1.

4.3 Methods

4.3.1 Context

This study was conducted in the setting of a series of a virtual industry conference in the energy sector. The virtual conference series is financed by 10 international energy utilities that are headquartered in 9 different countries and operate in 40 countries with a joint revenue of more than 170 billion US dollars. A team of conference hosts manages it. The four conferences bring together individuals from key players in the energy transition, including individuals from large global energy utilities and late-stage clean-tech startups. The startup participants were jointly selected and invited to the conference series by the utilities. The goal of the series is to enable the exchange of knowledge, build relationships, and explore potential collaborations among the participants. The purpose is also demonstrated in the following quote by one of the startup participants: *"The greatest benefit for us in [this conference series] was the chance to build relationships, also on a personal level with some of the most relevant people in the energy sector all over the world. Because it opens ups options for our international expansion and large-scale collaborations in the future."*

As such, the conference series at hand provides an ideal setting to investigate individuals' networking behaviour at virtual conferences and offers similarities in size and setup to physical conference settings chosen in prior studies (e.g., Bapna and Funk, 2020; Chai & Freeman, 2019). Given the global spread of its participants (spread over 40 countries and five continents) and its focus on a clean energy future, the conference hosts have for a long time discussed moving some or all of the conference events online to enable more individuals from the different firms to participate and to reduce the carbon footprint of the conference series, as also illustrated in the following quote: *"We could save an enormous amount of co2 by not travelling. It's a crazy program. I mean, I love to travel. But thinking about it, it's ridiculous to take 100s of people and fly them to Sao Paulo to Dubai, to Singapore, when you can also do it digitally. The other good thing is that by doing things digitally, you can have more people participating."* (Conference Host).

However, as the study was set in 2020, the Covid-19 pandemic forced the decision to move the conference series to exclusively take place in a virtual conference environment. Given that the organizers have looked into hosting a virtual conference before, they were able to offer a rather smooth virtual conference experience. Accordingly, one participant reflects: *"I think even now, six months later, having taken part in other virtual settings as well, I think this one has been the best one of any kind of conference or another type of online event. So, I think the whole kind of framework has been good."* While another adds: *"But in general, yeah, I mean, we've been, again, I can't remember the names of the other tools, but we've been involved in many other online conferences and so on, for months. And this [the conference series at hand] was by far the best experience"* This ability to provide a rather smooth virtual conference experience makes this setting particularly well suited to investigate networking in a virtual conference setting. First, it increases the likelihood that I can trace back findings to the actual usage of features and that they are less influenced by bad organizing or technical glitches. Second, the setting represents an instance of a conference series that is likely to keep some virtual elements in the future, increasing the generalizability of the findings beyond extreme cases of one-time virtual conferences in response to the Covid-19 pandemic. For instance, in the following edition, 2021, the conference series took place in a virtual format and is set to continue so in 2022 and will probably alternate between physical and virtual conference events in the future (initial discussion for 2023 suggested 2 virtual and 2 physical conference events).

The virtual environment in which the conference took place was designed by an external vendor that is specialized in offering high-end virtual conference environments. Like other market tools, the environment graphically imitates a physical conference where users can enter different rooms, see other participants, and access different features. More specifically, the virtual conference at hand provided four primary features to its participants. First, users could enter a room that entailed company information booths of all companies from which members participated in the conference. Each company information booth entailed information about the company, such as product, size, or strategy and information about all its individual members participating in the conference - including names, pictures, and functions. Second, users could enter the main auditorium with an embedded multi-lateral web conferencing tool. The auditorium further provided a timetable with an overview of networking sessions and their starting time and date. Third, each company had a meeting booth, where users could book and enter bi-lateral web conferencing meetings. Fourth, the conference organizers invited all conference participants to participate in different chat groups of a

direct messaging application, also giving the participants the option to contact other participants directly. The following quote by one of the conference hosts also illustrates the available features: *"The [virtual conference platform] brings all participants to a central point and brings a physical metaphor for meeting other participants and for retrieving information from the booths. And there are multiple means of interaction, which are the meeting booths where people actually interact [through web conferencing]. The auditorium, where we host our group sessions and [the messaging application] where the continuous conversation happens."* As I were able to closely track the usage of these different features through different means, this setting allowed me to investigate the role of feature usage in the accumulation of structural and relational SC.

4.3.2 Sample

Throughout the 4 virtual events, 150 individuals participated in the virtual conference series. Out of these 150 individuals, 114 gave their consent to (1) access and analyze their usage of digital technology features, (2) answer surveys at the end of each of the virtual conference events, and (3) analyze messages in the messaging application groups, (4) manually collect data from their LinkedIn profiles and (5) to combine all that data. I ensured that results would only be presented in an aggregated and anonymized format so that neither quotes nor quantitative results could be traced back to individuals or companies. Out of the 114 participants that gave me consent, 40 only responded to one of the four online surveys and were thus excluded from the longitudinal panel, which requires multiple data points over time. Thus, the remaining sample consists of 74 individuals. 40 individuals in the sample responded to all four surveys (complete), 23 responded to three surveys, and 17 responded to two surveys. Thus, on average, the 74 individuals in the sample answered 3.15 out of 4 surveys. 5 of the 74 individuals did not have a LinkedIn account and were thus excluded from the analysis for structural SC.

4.3.3 Research design and measures

Dependent Variables (DVs). To measure the change in structural SC (ΔSSC) from before to after each virtual conference event, I draw from LinkedIn data. For each individual, I manually assessed the number of LinkedIn connections to other participants of the conference before each event and after the conclusion of each event. The dependent variable was then constructed as the number of LinkedIn connections to other conference participants after each event subtracted by the number of LinkedIn connections to other conference participants before each event (as also shown in figure 4.2). An individual's total number of LinkedIn connections was collected as a control

variable. Collecting this data was possible because the conference hosts provided me with a list of conference participants well before the start of the conference. Using the change in the number of LinkedIn connections as a measure for structural SC accumulation is common practice in the field of IS (see also Bapna and Funk, 2020; Weiler et al., 2021).

Furthermore, I used a 5-item survey scale adapted from Kale et al. (2000) to measure relational SC after each virtual conference event. Sample items include: *"[The conference] is characterized by high reciprocity among the participants"* or *"[The conference] is characterized by mutual trust among its participants".* I then constructed the change in relational SC (ΔRSC) as the difference between two measurement points (as also shown in figure 4.2). Cronbach's alpha for the relational SC scale was 0.86. Confirming the operationalization of structural vs relational SC as two very different forms of SC, participants also commented: "*Yeah. I mean, I may be connected with a couple of new people on LinkedIn. Well, that is helpful but it's different from a long term personal relationship."* More generally, in designing the survey, I followed Dillman' Tailored Design Method (2007) and collected several relevant control variables.

Independent Variables (IVs). Following prior work (e.g., Weiler et al., 2021) I measured the active feature utilization of individuals for four different features. For each individual that gave me consent the conference hosts provided me with detailed activity reports downloaded from the central virtual conference platform. The activity reports entail the extent to which each individual used a certain feature (e.g., number of booth visits).

The measure for the usage of *multi-lateral web conferencing* captures the number of multi-lateral web conferencing sessions an individual participated in during each conference event.

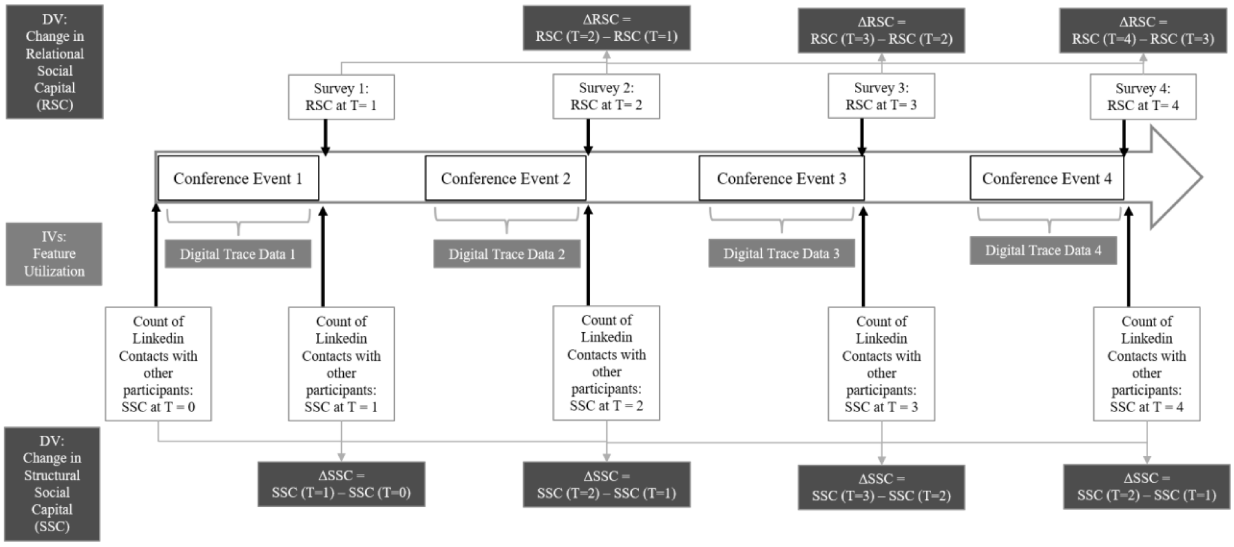
The measure for the usage of the *booth visiting* feature captures the number of times an individual entered a company information booth on the platform during each conference event.

The measure for the usage of the *bi-lateral web conferencing* feature captures the number of bi-lateral web conferencing meetings each individual participated in during each conference event. This number was assessed from a survey question, as some individuals were not allowed to use the embedded web conferencing tool because of firm-internal regulations. Thus, in the survey, I asked: *"In how many 1:1 meetings did you participate during [the last conference event]?"*

The measure for the usage of the *direct messaging* application was captured with a 7-item Likert scale assessing the extent of usage (not at all (1) - to a great extent (7)):

"During [the last conference event], to what extent did you rely on direct messaging applications to communicate with other participants?"

Figure 4.2 Research design



In addition to the quantitative data, throughout the series of virtual conference events, I observed 120 hours of bi-lateral or multi-lateral web-conferencing sessions (detailed notes totaling 43 documents with each 2-3 pages of notes, i.e. 97 pages of detailed notes), explored all booths of the platform, analyzed 4700 messages sent on the direct messaging application and conducted 19 complementary interviews with startup participants (11), utility participants (5) and conference hosts (3) (45-70 minutes each).

4.3.4 Analysis

Since I rely on observational data, I cannot determine causal relationships. However, to contribute to the research on online networking, I derive meaningful associations in a relevant real-world context and substantiate the underlying mechanisms of these associations with an in-depth qualitative analysis of interviews, documents and complementary observations collected in this context. To increase the likelihood of deriving meaningful associations, I addressed important issues related to endogeneity. First, I overcome common method bias by using three different data sources for independent and dependent variables: digital trace data from the virtual conference environment, self-reported survey data, and data manually sourced from LinkedIn. Second, I address selection bias by conducting mean comparisons between survey responders and non-responders, revealing no significant differences. Furthermore, I address issues related to simultaneity (i.e., does a change in x precede a change in y or vice versa?) and omitted variable bias (uncontrolled confounding variables). First, I set up the research design such that it minimizes simultaneity concerns. As shown in figure

4.2, the dependent variables are constructed as *the change from the previous to the current measurement occasion* (i.e., ΔSSC and ΔRSC). The models do not estimate associations between feature usage and the overall structural or relational SC level but instead with the change that occurred precisely in the period of feature usage. While one could argue that the overall level of SSC or RSC would drive feature usage, it is less likely that a change in SSC or RSC from the beginning to the end of one event would predict feature usage during that event (i.e., reverse causality). This is also supported by prior research that established the same direction of causality between feature usage and ΔSSC (i.e., feature usage predicts ΔSSC and not vice versa) (Weiler et al., 2021). Second, collecting longitudinal data offers me the advantage of addressing concerns related to omitted variables (other than in cross-sectional designs) by estimating a fixed-effects panel model (Woolridge, 2002). The within transformation used in fixed-effects models rules out that time-invariant covariates (e.g., the total number of previous LinkedIn connections, Age, Education etc.) bias the estimated coefficients (time-invariant control variables are thus excluded from the model estimation). While I cannot rule out that the fixed-effects model estimations are biased by other time-varying confounders, the well-defined setting and the research design reduce the potential risk of such biases. This is because the feature usage that I track provides me with a decently complete picture of each individual's behaviour during each conference event. Furthermore, the DVs are also directly related to these activities as I only track changes in SC with other participants of the conference (not overall levels of SC).

However, I acknowledge that given the observational nature of the data, I cannot entirely rule out selection bias and time-varying confounders and cannot prove the theorized direction of causality. Thus, the results offer meaningful associations rather than causal relationships. To further substantiate these meaningful associations, I analyzed interview, document, and observational data to confirm the theorized mechanisms and identify contingency factors of the presented associations between feature usages and structural vs relational SC changes.

In the qualitative analysis, I followed best practices in qualitative research (e.g., Bluhm et al., 2011; Gioia et al., 2013; Yin, 2018). First, I started with a first round of coding inspired by the theoretical framework (see figure 4.1). Accordingly, I coded the documents for instances where individuals talked about using one of the four focal features of the research interest. Furthermore, I coded for instances where individuals talked about how they could or could not make new LinkedIn connections (accumulation of structural SC) and how they could or could not build up trusted and

reciprocal relationships (accumulation of relational SC). Based on this initial set of coding, I could look for patterns at the intersection of a feature (e.g., booths/profile visiting) and one of the SC dimensions (e.g., LinkedIn connections). That allowed me to distil the mechanism that led from feature usage to SC accumulation and compare it to the initial theoretical framework (Figure 4.1). In the second coding round, I adopted an open coding approach to capture any factors that could influence the quantitative results that I did not consider in the theoretical framework and the research design. Based on this initial round of open coding, I iteratively aggregated first-order codes into second-order codes. I summarized the emerging codes under the higher-level category of contingency factors. Investigating the intersection of emerging codes (contingency factors) with the theory-inspired codes (four features, 2 dimensions of SC) allowed me to match contingency factors to the relationships in the theoretical framework.

Having this precise matching of contingency factors to hypothesized relationships allowed me to test moderator variables (if available in the dataset) in a post-hoc quantitative analysis.

4.4 Results

4.4.1 Results of the quantitative analysis

Table 4.1 presents the results of the quantitative analysis. To compare coefficient sizes, all IVs were standardized. Model 1 (see Table 4.1) shows the results of the fixed-effects panel model for change in structural SC (ΔSSC). The results show that the usage of feature 1, visiting profiles/booths of other conference participants during a conference event, is significantly positively associated with an increase in LinkedIn connections (ΔSSC) after the conference event (b = 0.914; p-value = 0.023; Model 1; Table 4.1). This implies that using this feature more by 1 s.d. during a conference is associated with about one more novel LinkedIn connection to another participant after the conclusion of this conference event. Thus, the findings support the hypothesized relationship in the framework (see figure 4.1). Interestingly, in contrast to the theoretical framework, the usage of feature 2, direct messaging application (b = -0.255; p-value = 0.377; Model 1; Table 4.1), and feature 3, multi-lateral web conferencing (b = -0.096; p-value = 0.720; Model 1; Table 4.1) is not significantly associated with increases in structural SC. As hypothesized in the framework, the usage of feature 4, bi-lateral web conferencing, has no significant association with increases in structural SC (b = 0.365; p-value = 0.257; Model 1; Table 4.1).

Table 4.1 Results of the fixed-effects panel estimation

	Analysis of theorized framework (fixed effects)		Post-hoc analysis of contingency factors (fixed effects)	
Usage of	**Model 1. Change in Structural Social Capital (ΔSSC)**	**Model 2. Change in Relational Social Capital (ΔRSC)**	**Model 3. Change in Structural Social Capital (ΔSSC)**	**Model 4. Change in Relational Social Capital (ΔRSC)**
	Coefficient (S.E.) p-value	Coefficient (S.E.) p-value	Coefficient (S.E.) p-value	Coefficient (S.E.) p-value
feature 1: Profile visiting	0.914** (0.392) 0.023	-0.221 (0.093) 0.246	0.895*** (0.394) 0.000	-0.205 (0.176) 0.250
feature 2: Sending messages	-0.255 (0.286) 0.377	0.422** (0.187) 0.027	-0.272 (0.287) 0.348	0.103 (0.131) 0.431
feature 3: Multi-lateral web conferencing	-0.096 (0.265) 0.720	0.177* (0.095) 0.067	-0.295 (0.331) 0.375	0.183** (0.091) 0.049
feature 4: Bi-lateral web conferencing	0.365 (0.319) 0.257	0.324* (0.170) 0.061	0.416 (0.316) 0.193	0.273* (0.131) 0.093
feature 3: Multi-lateral web conferencing * Gender			0.636* (0.349) 0.073	
feature 2: Sending messages * Time Difference				0.540** (0.236) 0.025
Observations	214	159	214	159
Number of individuals	69	74	69	74
R^2	0.167	0.110	0.177	0.153
Adjusted R^2	0.151	0.086	0.157	0.125

Note. All IVs are standardized. The number of individuals is 69 instead of 74 for SSC models because 5 individuals were not on LinkedIn. The number of observations is lower for RSC models because the baseline measure for RC was measured after the first conference event 1, while LinkedIn connections could be assessed before conference event 1 (see also figure 4.2). * p-value < .10; ** p-value < .05; *** p-value < .01.

Model 2 (see Table 4.1) shows the results of the fixed-effects panel model for change in relational SC (ΔRSC). The results show that the usage of feature 1, profile visiting, has no signification association with increases in relational SC, thereby confirming the theorized framework (b = -0.221; p-value = 0.246; Model 2; Table 4.1). Furthermore, the results show that the usage of feature 2, sending messages during a

conference event, is significantly positively associated with an increase in relational (ΔRSC) after the conference event (b = 0.422; p-value = 0.027; Model 2; Table 4.1). This implies that using this feature more by 1 s.d. during a conference is associated with an increase of 0.422 in relational SC (scale from 1-7) after the conclusion of this conference event. Similarly, the results show that the usage of feature 3, multi-lateral web conferencing during a conference event, is significantly positively associated with an increase in relational (ΔRSC) after the conference event (b = 0.177; p-value = 0.067; Model 2; Table 4.1). This implies that using this feature more by 1 s.d. during a conference is associated with an increase of 0.177 in relational SC (scale from 1-7) after the conclusion of this conference event. Finally, the results show that the usage of feature 4, bi-lateral web conferencing during a conference event, is significantly positively associated with an increase in relational (ΔRSC) after the conference event (b = 0.324; p-value = 0.061; Model 2; Table 4.1). This implies that using this feature more by 1 s.d. during a conference is associated with an increase of 0.324 in relational SC (scale from 1-7) after the conclusion of this conference event. In sum, the associations between feature usage of features 1-3 and the accumulation of relational SC confirm the theoretical framework (see figure 4.1).

4.4.2 Qualitative insights: substantiated mechanisms and explanations for discrepancies between theoretical framework and quantitative results

In the framework, I argue that (1) using features 1-3 drives the accumulation of structural SC because it allows individuals to identify interesting networking targets and contact them and (2) using features 2-4 drives the accumulation of relational SC because it allows individuals to experience a sense of virtual togetherness. The qualitative analysis substantiates and qualifies these theorized mechanisms as illustrated in the following.

Feature 1. Profile/Booth visiting. The quantitative analysis confirmed that, as theorized, profile/booth visiting is related to the accumulation of structural but not relational SC. The qualitative analysis confirms and substantiates the underlying mechanism. More specifically, visiting booths/profiles of other participants indeed allows individuals to gather information about other participants outside of their existing network. They can identify networking targets for sending out LinkedIn requests based on this information. However, there is an additional mechanism at play as the individuals can also use the information from the booths to customize the LinkedIn connection request message to their targets. Such customization increases the likelihood of acceptance and thus further facilitates the accumulation of structural SC, also illustrated in the following quote:

"I browsed through all the booths of the companies and their participants. Also, to know, it helps me to identify who would be interesting to connect with on LinkedIn – so let's say targets […]. That's one and the other way around, to make sure that what I have to tell is most interesting for them. So, it [the booth visiting] helps both on the sending and receiving end."

Feature 2. Direct messaging. The quantitative results indicate that using a direct messaging application during the conference is positively associated with the accumulation of relation SC but not with structural SC. First, the qualitative analysis helps shed light on the non-intuitive finding that, in contrast to the initial framework, direct messaging did not facilitate the accumulation of structural SC (new LinkedIn connections). One potential mechanism that could explain this result is that users felt a social barrier to reaching out to individuals outside their existing social network in the direct messaging application, as also illustrated in the following quote:

"In a non-virtual setting, we would have probably been better placed to mingle and speak with new people in their free time to get in touch. I think we didn't do as much of that. Because it was virtual, you had to reach out to somebody new in a random part of the to chat on [the direct messaging application], so there was a natural obstacle in doing that."

Similarly, as increases in structural SC are operationalized as new LinkedIn connections, individuals could naturally also rely on LinkedIn connection requests and LinkedIn messaging features to contact individuals after identifying them as attractive networking targets.

Second, the qualitative results confirm the mechanism that explains the association between messaging and the accumulation of relational SC. While direct messaging does not afford oral communication and visually seeing other participants, it affords a constant communication with other participants, which instils a feeling of virtual togetherness, as also illustrated below:

"And then the other form of communication that I think was useful was like [the direct messaging application]. And I think it worked pretty well because there was constant communication. And it was really easy because everybody used it and you could interact with others. It's almost like having professional relationships, sometimes in a group, sometimes privately. So, I think the whole setup was good, the communication flow was excellent."

"I'm not really one for chatting a lot on those things, personally, but actually, in reflection, I found it quite good. Because, you kind of feel connected with other people."

Feature 3. Multi-lateral web conferencing. The quantitative results indicate that using multi-lateral web conferencing is positively associated with the accumulation of relational SC but, in contrast to my theorizing, not with structural SC. Clarifying the mechanisms that explain the former, the qualitative analysis confirms that using multi-lateral web conferencing facilitated a sense of virtual togetherness, translating into the accumulation of relational SC. More specifically, this sense of virtual togetherness stems from the feature's ability to support the visual appearance and oral communication, as well as an option to diverge into private topics, not necessarily business-related, enables by its multi-lateral nature. This is also illustrated below:

"I think the closest we got to building personal relationships was in a [web conferencing] session where we were with like 15 participants, and that were all startup people. And there was a lot of bonding going on. So, there was the first time we really had like, open discussions about wine about electric vehicles about it was like, having a beer together at seven o'clock. Like it was a relaxed everyone felt relaxed and started to talk and that was a good moment."

Furthermore, the qualitative analysis sheds more light on the contradicting finding that multi-lateral web conferencing did not facilitate new LinkedIn connections. More specifically, my findings reveal that the multi-lateral aspect of the feature sometimes constraints individual's ability to interact with potential new contacts (i.e., "strangers") because other participants in the sessions are naturally always listening and watching:

"So, I have the feeling that in a meeting with more than five or six people, it becomes difficult to interact, especially if they're strangers. Because imagine, you're in a room with 10, or 15, or 20 strangers, and then there are like three people talking and you know, like 10, other people you don't know, are listening. So, it sort of changes the social dynamics a little bit, which makes it weird. It's like, imagine if you met someone at a networking event in person. And then you have like, 10 people standing behind you that you didn't know, and they're just listening, but not talking"

Feature 4. Bi-lateral web conferencing. The quantitative results indicate that, as theorized, using bi-lateral web conferencing is positively associated with the accumulation of relation SC but not with structural SC. On the former, and in addition to the above-mentioned affordances of web conferencing, the bilateral nature of the feature enables a more intimate sense of togetherness with other individual participants (rather than a group feeling of togetherness). This especially drives the depth of trust

and reciprocity experienced in some relationships, as also illustrated in the quote below:

"I think the best parallel to draw not only with this but also any other Energy Conference, is that conversations are never in depth if there is more than two people, I find. So, I had my two best conversations during this conference, when I was e reaching out to one utility members over the platform at a really, really late time in the evening. And we just had a chat. After five minutes, we discussed it, there's probably no business between us. But then the next 45 minutes, we just discussed about what they're doing what we're doing. And that was just really great and actually that kind of led to some real connection"

4.4.3 Qualitative insights: contingency factors

From the qualitative analysis, I derived contingency factors that further qualify the quantitative findings. These contingency factors moderate the relationships between feature usage and SC accumulation and operate at two levels, the individual level, and the conference/host level, as also summarized in the updated theoretical framework of online networking at virtual conferences (see figure 4.3). I start to present individual-level contingency factors.

Language Proficiency. Some participants revealed that their lack of language proficiency in English, other than in non-virtual settings, limits their ability to benefit from the oral communication affordances of web conferencing, particularly in multi-lateral sessions:

"So, I am not an English native, I am not so much proficient in English. So sometimes I am hesitant about making an English chatting, actually. Especially when you are talking in front of a larger group. And if I could attend a physical party is it's much easier for me, because I can use, for example, body language rather than oral communication. So, when it comes to relying only on oral communication it is more difficult for me."

Accordingly, I argue that lower language proficiency is less likely to lead to a sense of virtual togetherness and therefore acts as a contingency factor to the relationship between bi-lateral and multi-lateral web conferencing and the accumulation of relational SC, visualized in figure 4.3.

Time Zones: Another relevant contingency factor relates to the time zone from which an individual participates, or more precisely, the difference in time zones between individual participants. This contingency factor operates on both the web conferencing and the direct messaging features in reverse manners. While the communication afforded by direct messaging can overcome time differences, the nature of web

conferencing makes it difficult for individuals located in very distant time zones to benefit from the web conferencing affordances:

"So, these tools have a problem, because one of the things that we when we all are together in a physical place, okay we will have jetlag, but at least we are all in the same time zone at a certain point. And that doesn't happen in a virtual setting, because everybody's still in their own time zone. So, it is very uncomfortable to join the web conferences for someone at some time. […] so basically, the only convenient tool remains the [direct messaging]"

Accordingly, I argue that a large time difference positively moderates the relationship between direct messaging and SC accumulation, as it becomes the primary means to experience a sense of virtual togetherness. It negatively moderates the relationship between web conferencing and SC accumulation, as the time difference deteriorates the sense of virtual togetherness if individuals have to join meetings in the middle of the night (see figure 4.3). As I were able to track participants' time zones, I could test this contingency moderator in a post-hoc analysis (see Model 4, Table 4.1). I find that, indeed, higher time distance positively moderates (b = 0.540, p-value = 0.025) the relationship between direct messaging and the accumulation of relational SC (see the bold black line in figure 4.3). However, I could not confirm that it moderates the associations for web conferencing.

Perceived Similarity: Furthermore, I derived perceived similarity (e.g., through, for instance, the same nationality) as a factor that positively moderates the relationship between the usage of direct messaging apps or web conferencing and the accumulation of relational SC. This is because it offers a common base based on which individuals can experience a heightened sense of virtual togetherness. This potential moderator is also illustrated in the following quote:

"Well, yeah. I chatted a bit with [Yve] but that's more because we're both from [the same country]. And I'm sure when I'm [back in my country], we'll meet up. It's just easier to feel connected, also in this virtual world, if you know that he is also from [your country]"

Gender*:* Finally, while prior research established that women generally have to overcome more barriers in networking (Bapna & Funk, 2021), the qualitative insights indicate that interacting digitally could reduce these barriers because virtual communication facilitates a focus on content and less on other social dimensions of interaction. This is likely to moderate the established relationships: It can increase the motivation of other (male) participants to contact women after they identified them as

interesting networking targets (structural SC). Further, it can reduce inappropriate behaviour by men in their interactions with women, increasing a positive feeling of virtual togetherness for women (relational SC). This is also illustrated in the quote below:

"So, in this industry [the energy industry] you are always a minority [as a woman] and there are moments where it still seems difficult for some [men], but I think in this setting this is less, well, think about the [multi-lateral web conferencing] sessions, there the discussion was really about content and if you have interesting stuff to say about the future of energy, it [gender] just doesn't' matter".

As I were able to track participants' gender, I could test this contingency factor in a post-hoc analysis (see Model 3, Table 4.1). I find that, indeed, a female gender positively moderates (b = 0.636; p-value = 0.073) the relationship between multi-lateral web conferencing and the accumulation of structural SC (see the bold black line in figure 4.3). However, I could not confirm other moderating effects of gender. I now move to present factors that do not act on the individual level but can instead be influenced by the conference hosts.

Feature Design: The interviews reveal that the design and the information quality of the online booths/profiles could be another contingency factor that moderates the association between feature usage and structural SC accumulation (see also figure 4.3). It limits an individual's ability to assess a new networking target's potential relevance and customize the first message. This is also illustrated in the following quote:

"How well it works depends a lot on the design and quality of the booth. Some were just very generic and didn't really add any value and some were a bit more specific, and that helps a lot to understand what another person is about and to tune your message."

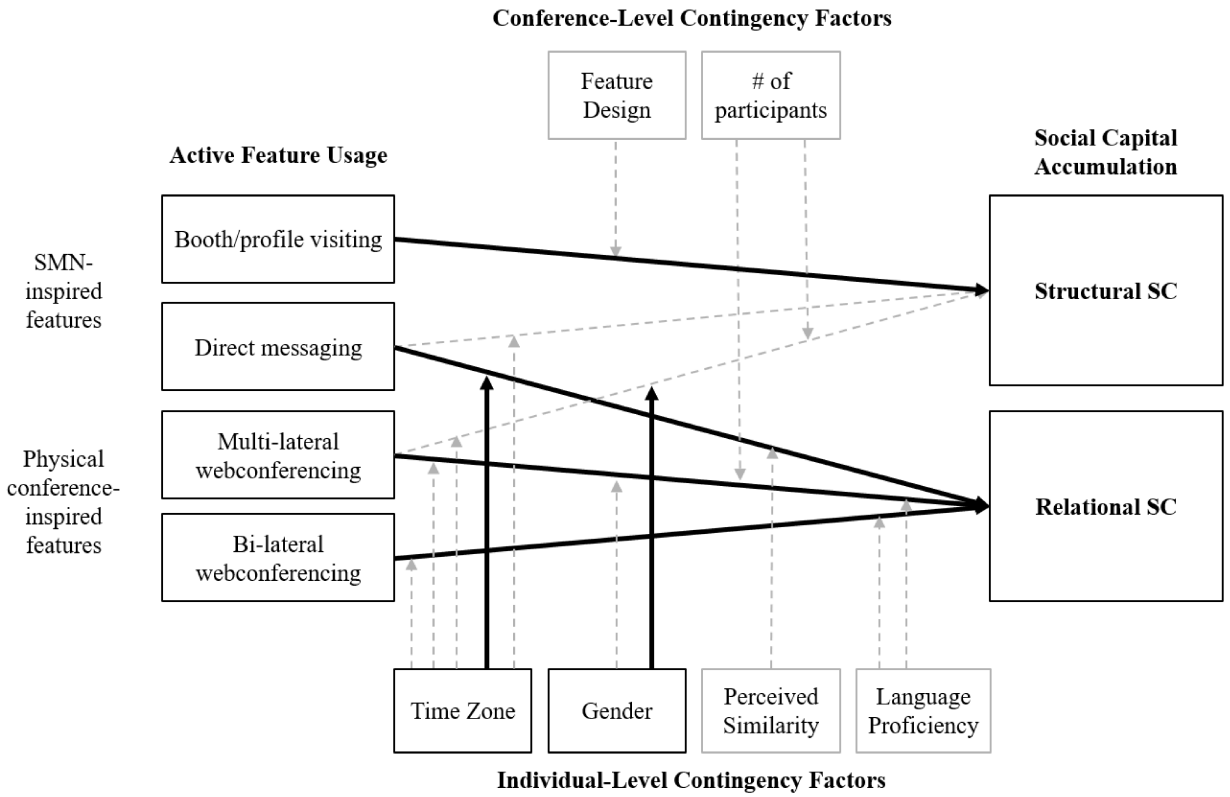
Number of Participants: Finally, the qualitative insights point to the number of participants in multi-lateral web conferencing sessions as a contingency factor to the association between feature usage and the accumulation of structural and relational SC (see figure 4.3). More specifically, a smaller number of participants would facilitate better conversations which allow for better assessing the fit of potential networking targets (structural SC) and a sense of virtual togetherness (relational SC), as illustrated in the following quotes:

"What I really liked for the tools was the virtual breakouts they would create, which was like, you know, like you do in zoom in a little breakout. So there I had very

good chats with other startup and utility people. So it was really in these smaller groups it was much more personal and much easier to talk and connect to new people."

All identified contingency factors are also visualized in figure 4.3. Dashed vertical lines indicate potential moderating relationships identified from the qualitative analysis that could not be validated in quantitative analysis (either because the variable could not be captured or the result was insignificant). Bold black vertical lines indicate the contingency factors that I could validate in quantitative analysis.

Figure 4.3 Theoretical framework for online networking at virtual conferences qualified with empirically supported relationships and contingency factors



4.5 Discussion

4.5.1 Short summary of results

Prior research on online networking has developed a decent understanding of how individuals accumulate structural SC in SMNs (e.g., LinkedIn) by using features such as direct messaging or visiting profiles (Hinz et al., 2011; Lanz et al., 2019; Smith et al., 2017; Weiler et al., 2021). However, we lack an understanding of how individuals network in novel digital formats such as virtual conferences and how their usage of an extended set of features relates to the accumulation of both structural and relational SC. In response, this study synthesizes insights from social capital theory (e.g., Nahapiet and

Ghoshal, 1998), online networking (e.g., Weiler et al., 2021), offline networking (e.g., Bapna and Funk, 2020) and digital technology features and affordances (e.g., Hacker et al., 2020) to develop a theoretical framework of online networking at virtual conferences (see figure 4.1). I test and extend this framework based on a longitudinal survey (e.g., relational SC), and digital trace data (e.g., feature usage, #of new LinkedIn connections) collected on 74 individuals in the context of a virtual conference series in the energy industry.

First, I argue that visiting online booths/profiles, direct messaging and multi-lateral web conferencing is positively related to the accumulation of *structural* SC because it enables individuals to identify networking targets and contact them. While I find that visiting online booths/profiles facilitates the accumulation of SC, I find no significant association between direct messaging and multi-lateral web conferencing. Furthermore, I argue and find that the usage of direct messaging, as well as bilateral and multi-lateral web conferencing is positively associated with the accumulation of *relational* SC at virtual conferences because it facilitates a sense of virtual togetherness. Finally, I present qualitative insights that substantiate the theorized mechanisms and shed light on the discrepancies between theoretical framework and empirical results. Further building upon these qualitative insights, I derive 6 contingency factors that are likely to moderate the relationships between feature usage and SC accumulation: time difference, language proficiency, gender, and perceived similarity – at the individual level – and feature design and the number of participants – at the conference level. In a post-hoc quantitative analysis, I confirm the moderating role of gender and time differences. In sum, I present an empirically substantiated and extended theoretical framework of online networking at virtual conferences (see figure 4.3).

4.5.2 Theoretical implications

My theorizing and empirical insights make several theoretical contributions to the literature on online networking. Prior research established the relationship between active feature usage and SC accumulation in the context of SMNs (Weiler et al., 2021), thereby highlighting the importance of an individual's agency for networking outcomes (Borgatti & Halgin, 2011; Leonardi, 2013). Taking this agency seriously, I confirm the general proposition of this theory of purposeful feature utilization (Weiler et al., 2021) in the context of virtual conferences and extend it by (1) differentiating between structural and relational SC, (2) expanding the set of investigated features, and (3) introducing potential contingency factors. Jointly, these findings not only connect to and

extend received knowledge but also shed light on virtual conferences as a relevant and novel online networking phenomenon.

First, I theorize and show that different features have different implications for accumulating structural vs relational SC. The distinction between SC's structural and relational dimensions is vital as both have differential consequences (Bapna & Funk, 2020; Nahapiet & Ghoshal, 1998; Yli-Renko, Autio and Sapienza, 2001). More specifically, structural SC increases the breadth of access to individuals with valuable resources. However, it is the relational dimensions of SC that increase the willingness to share valuable resources (e.g., Nahapiet and Ghoshal, 1998). As such neglecting one of these dimensions in research on online networking might lead to incomplete conclusions. While prior research on SC in virtual teams has made this important distinction (e.g., Cummings and Dennis, 2018), I introduce it to the research on online networking (e.g., Weiler et al., 2021). I thus propose the accumulation of relational SC as a relevant outcome of an individual's networking behaviour that complements structural SC outcomes. This might be particularly relevant for research on SMNs (e.g., Kane et al., 2014; Bapna et al., 2016) as I find that SMN-inspired features at virtual conferences have differential implications. While booth/profile visiting is positively related to the accumulation of structural but not relational SC, direct messaging is positively related to relational but not structural SC.

Second, by merging insights from social capital theory (e.g., Nahapiet and Ghoshal, 1998), online networking (Weiler et al., 2021), offline networking (Bapna & Funk, 2020) and digital technology features and affordances (Hacker et al., 2020), this study introduces bi-lateral and multi-lateral web conferencing as features that individuals use to online network at virtual conferences, mirroring interactions at physical conferences. More specifically, this study shows that the usage of bi-lateral and multi-lateral web conferencing is positively associated with the accumulation of relational SC. As such, this study confirms the affordance of web conferencing to create a sense of virtual togetherness (Hacker et al., 2020) and introduces it as a mechanism that explains the relationship between feature usage and relational SC accumulation. While we derive this finding in the specific setting of virtual conferences, it provides insights into the broader online networking literature (e.g., Hinz et al., 2011; Lanz et al., 2019), as web conferencing features might be integrated into SMNs or other online networking contexts at some point. More specifically, the findings suggest that the integration of web conferencing would potentially improve an individual's ability to use SMNs to accumulate relational SC (Bapna et al., 2016). By looking at bilateral and multi-lateral web conferencing in addition to profile visiting and direct messaging, this

study extends the set of features for the theory of purposeful feature utilization (Weiler et al., 2021). This is an important contribution as technology rapidly develops and online networking increasingly rests on the usage of more and more different features. For instance, nowadays, online networking not only includes the sending of messages and visiting profiles in SMNs, but also interaction via web conferencing at virtual conferences and in the future probably interaction via VR (virtual reality) features in the "metaverse".

Third, this study introduces contingency factors to the relationship between feature usage and SC accumulation. For instance, the findings suggest that the number of participants, language proficiency, or time differences are contingency factors that limit an individual's ability to accumulate relational SC via web conferencing. While I derive this finding in the context of virtual conferences, it provides more nuanced insights on the more general affordance of web conferencing to create a sense of virtual togetherness (Hacker et al., 2020), which might very well depend on the above-mentioned factors. Furthermore, the findings point toward the design of online booths/profiles as a contingency factor. This not only improves our understanding of virtual conferences but also complements similar findings from other settings such as internal SMNs and virtual teams (e.g., Cummings & Dennis, 2018). In addition, introducing individual-level factors such as perceived similarity or gender as contingency factors suggests that there is some additional heterogeneity in the extent to which individuals benefit from feature usage that might be traced back to differences in characteristics or demographics of individuals. This also has implications for research on online networking in other settings and, for instance, complements received knowledge on online networking in SMNs (Hinz et al., 2011; Lanz et al., 2019; Smith et al., 2017; Weiler et al., 2020). Finally, deriving gender as a contingency factor and confirming its role in a post-hoc analysis adds to prior research on networking barriers for women at offline conferences (Bapna & Funk, 2020). More specifically, Bapna and Funk (2020) theorize and show that women can overcome disproportionate social networking barriers through interventions that facilitate group meetings at physical conferences. My findings add to this by suggesting that multi-lateral (i.e., group) web conferencing is particularly beneficial for women in terms of structural SC accumulation at virtual conferences.

Finally, the comprehensive framework (see figure 4.1 and figure 4.3) sheds light on an increasingly relevant online networking phenomenon: virtual conferences. So far, it has primarily been the Covid-19 pandemic that has forced professionals and academics around the globe to move events and conferences to a virtual format (Hacker

et al., 2020). While there has been much frustration with virtual conferences, many have also acknowledged their advantages, such as lower costs and carbon footprints (Arsenault et al., 2019; Fraser et al., 2017) as well as more inclusiveness (Gichora et al., 2010). Depending on the global reach, goal and structure of a conference, these factors might be more or less critical. However, in many cases, hosting a virtual conference or event might likely make more sense, making virtual conferences a permanent alternative to physical conferences. This trend is accelerated by the development of cutting-edge digital conference tools/environments that can be seen as preliminary versions of a "metaverse". The "metaverse" has long been discussed in crypto, gamer and coder communities and has recently reached the mainstream when it was introduced by Mark Zuckerberg as the future of making social connections, even prompting his firm to rename from Facebook Inc. to Meta Platforms Inc. Considering these developments, for IS researchers, virtual events and conferences are likely to continue to be relevant online networking phenomena. This study contributes to the literature on IS by providing IS researchers with a first framework of online networking at virtual conferences that can help to make sense of this phenomenon and structure future research.

4.5.3 Practical Implications

Networking is vital for any professional or academic. The findings of this study have important and actionable implications for both participants and organizers/hosts of virtual conferences. On the former, participants can use my insights to optimize their strategic networking behaviour. First, to make new connections, they should take the time to browse through and visit booths and profiles that are provided at virtual conferences. This will help them identify interesting networking targets that they can contact via direct messaging apps provided by the virtual conference or directly via LinkedIn. To increase the likelihood of successful connection requests and fruitful relationships, they should use the information from the online booths/profiles to customize their first message to people outside of their existing network. To build trusted and reciprocal relationships at virtual conferences, individuals should interact with other participants via direct messaging applications as well as via bi-lateral and multi-lateral web conferencing. For individuals that prefer offline conferences, it might be tough to motivate themselves to use these features. However, my findings are a reminder that the usage of these features can indeed facilitate a sense of virtual togetherness and thereby facilitate the formation of relationships. These relationships can be a valuable resource that often translates into tangible benefits such as career advancement (Bapna & Funk, 2020).

Finally, participants should customize their networking behaviour (i.e., feature usage) depending on their language proficiency, gender or time zone. Individuals from distant time zones and with lower language proficiency should mainly use direct messaging apps. Individuals that identify as women should particularly make use of multi-lateral web conferencing.

Conference hosts/organizers can use the same guidelines to create effective and efficient networking opportunities for their participants. In particular, they should pay attention to the design of online booths/profiles. The higher the design quality and the included information, the higher the benefits for their participants. Furthermore, they should consider limiting the number of participants in multi-lateral web conferencing sessions or using the break-out room function to facilitate a sense of virtual togetherness. In sum, my findings might help organize effective virtual conferences that might also decrease the global carbon footprint in the long term.

4.5.4 Limitations

My study is subject to several limitations. First, as I investigate a real-world context in real-time, I rely on observational (instead of experimental) data, which limits my ability to draw causal conclusions. However, through my research design and the mix of quantitative and qualitative data, I can provide first relevant insights and a comprehensive theoretical framework. Future work ought to confirm and extend these insights with experimental studies. Second, while I have longitudinal data that allows me to reduce the influence of uncontrolled time-invariant characteristics, the sample size (74 individuals) is still relatively small. While it is difficult to get access to larger numbers of individuals who agree to comprehensively track their behaviour in real-world contexts, future research should try to investigate larger virtual conferences. Third, my study is situated in the setting of a virtual conference series in the energy sector that is structured via 4 temporally separated conference events. Future research ought to validate and extend my insights by investigating virtual conferences in other industries or professions (e.g., IT, science) and with other structures (e.g., one-time / one-day events). Fourth, while the focal virtual conference in this study uses a high-end virtual conference solution, virtual conferencing platforms are becoming more advanced and are constantly adding additional features that individuals could use to network (e.g., virtual reality). Future research could look at the additional networking affordances of novel features and extend the presented framework by expanding the set of investigated features. Fifth, this research focuses on a relational and structural dimension of SC. However, a related stream of literature has also conceptualized a cognitive dimension of SC (see also Nahapiet and Ghoshal, 1998), which could further complement the

insights presented in this study. Sixth, while this study combines data from LinkedIn (# of new LinkedIn connections) it was not set up to comprehensively investigate cross-platform networking (e.g., by tracking feature usage on a professional SMN and at a virtual conference) which provides another promising avenue for future research.

Chapter 5

Conclusion

This dissertation investigates collaborative innovation in the context of the grand challenges of climate change and emerging digital technologies. This chapter summarizes the theoretical and practical implications of the three studies of the dissertation. Furthermore, it aggregates implications and reflects on how this dissertation contributes to a more comprehensive and transdisciplinary understanding of collaborative innovation, emerging digital technologies, climate change mitigation, and the interplay of the three.

5.1 Summary of results and theoretical implications

Chapter 2 reports a study that uses QCA and a multiple case analysis to identify three ecosystem realignments that contribute highly to climate-related SDGs. The study further reveals why these ecosystem realignments are important for climate change mitigation. The first ecosystem realignment explicates how incumbents leverage digitalized infrastructure through a digital platform and new software complementors to increase resource efficiency. The second ecosystem realignment reveals how incumbents and new device complementors enable the customer to contribute to more resilient and flexible infrastructure. Ecosystem realignment 3 captures how new entrants connect customers with a digital platform to enable the sharing and leveraging of resources and information. The study also presents incumbents' ability to attract third-party complementors and the incumbent's strategic resistance as boundary conditions to the scaling of the climate impact of these ecosystem realignments. These findings contribute to the literature by elaborating on how and why ecosystem realignments may help to tackle the inherent interdependencies of a grand challenge like climate change (e.g. Adner, 2017; Adner & Kapoor, 2010; Gawer, 2014; Kapoor, 2018; Jacobides et al., 2018). They further contribute to a better understanding of the emergence and scaling of ecosystems, adding more nuance to the well-known platform ecosystem disruption story (e.g. Ansari et al., 2016; Khanagha et al., 2022; Dattee et al., 2018). As such, this study brings together theoretical perspectives from digital technologies and platforms (e.g., Nambisan et al., 2017), innovation ecosystems (e.g., Adner, 2017) and grand challenges (e.g., George et al., 2016) to illuminate the interplay of digital technologies, collaborative innovation and tackling climate change.

Chapter 3 presents a study that entails an in-depth multiple case study of 15 pilots between startups offering digital solutions and electric utilities seeking to integrate them to navigate the energy transition. The study reveals that digital interfaces shape three knowledge integration mechanisms: connecting back-and-forth at the application-data layer, fusing from heterogeneous sources at the data-network layer, and situating to resolve interdependencies at the network-device layer. The knowledge integration

mechanisms contribute to a better understanding of the open innovation back-end (West & Bogers, 2014; Zahra et al., 2020). The resulting digital interface-knowledge integration framework tightly integrates the knowledge-based view (e.g. Grant, 1996) with the theoretical toolkit of layers, interfaces and affordances (Yoo et al., 2010; Henfridsson et al., 2018). This integration helps open the 'black box' of digital technologies in prior research on collaborative innovation (e.g., Dahlander et al., 2021). Thereby it offers a new lens to theorize about contingencies to the benefits of openness (Chesbrough, 2019). More broadly, it thus contributes to a better understanding of the interplay of collaborative and digital innovation at the organizational level in the context of firms tackling climate change.

The fourth chapter of this dissertation presents a longitudinal survey and digital trace study that hypothesizes, tests, and qualifies a framework of social capital accumulation at virtual conferences. It contributes to the literature on digital technologies and information systems by extending prior insights on online networking (e.g., Hinz et al., 2011; Lanz et al., 2019; Weiler et al., 2021). More specifically, it adds to prior work by investigating virtual conferences as a new context for online networking, differentiating between relational and structural social capital, and introducing new features and contingency factors. More broadly, by introducing feature usage as antecedents to an individual's accumulation of social capital, it contributes to the literature on social capital as a critical enabler of collaborative innovation (Monteiro & Birkinshaw, 2017; Tortoriello et al., 2012; Kale et al., 2000; Yli-Renko et al., 2001). The study combines the theoretical perspectives of digital technology features and affordances with social capital theory to investigate virtual open innovation in the context of tackling climate change. Thus, it is another step toward better understanding the interplay of collaborative innovation, digital technologies, and climate change.

5.2 Contributions to our understanding of collaborative innovation, emerging digital technologies and climate change

This section aims to aggregate the insights from the three studies of the dissertation to reflect on our understanding of collaborative innovation, emerging digital technologies and climate change. Jointly, the presented insights primarily contribute to the field of collaborative innovation (e.g., Chesbrough, 2003; Bogers et al., 2017). While prior literature focused on innovation and financial performance (e.g., Laursen and Salter, 2006; Lu & Chesbrough, 2022), this dissertation adopts a broader lens by illuminating the role of collaborative innovation in tackling grand challenges. While prior work already suggested that collaborative innovation might be essential to tackle grand challenges (e.g., McGahan et al., 2021), this dissertation provides a first framework for

better understanding its important role. More specifically, the framework explicates how co-innovation and coordination in ecosystems allow firms to unlock the climate mitigation impact of digital technologies. Furthermore, it dives deeper into the underlying processes and mechanisms across different levels of analysis. It presents three knowledge integration mechanisms that firms employ to co-innovate and adopt different kinds of digital solutions. These knowledge integration mechanisms are important for firms to deal with emerging digital technologies and are it is likely that they support the implementation of ecosystems with climate mitigation impact. Finally, it shows how individuals can accumulate social capital in the context of emerging digital technologies and climate innovation. Individuals' social capital is likely to be a crucial enabler for knowledge integration and ecosystems concerned with climate change mitigation. As such, it provides a comprehensive multi-level framework for understanding collaborative innovation in the context of emerging digital technologies and climate change.

In addition, the framework shows how theory development in the field of collaborative innovation can benefit from combining different theoretical perspectives. For instance, innovation ecosystems and grand challenges proved to be a powerful combination. The concepts of complementarities and interdependencies from the ecosystems lens (Jacobides et al., 2018) help to make sense of the uncertainty and complexity central to the theories around grand challenges (Ferraro et al., 2015; George et al., 2017). Similarly, combining the layered architecture with digital layers and interfaces (Henfridsson et al., 2018; Yoo et al., 2012) with the knowledge-based view of the firms (Grant, 1996; Zahra et al., 2020) allows for a better understanding of collaborative innovation concerned with digital technologies at the organizational level. Finally, marrying social capital theory (e.g., Nahapiet & Ghoshal, 1998) with a features-affordances lens (Leonardi, 2013) proved to be fruitful in investigating collaborative innovation in a world of virtual collaboration. Overall, this powerfully illustrates how the field of collaborative innovation could benefit by taking novel contexts like grand challenges seriously. They not only provide opportunities to investigate collaborative innovation but are also a breeding ground for novel transdisciplinary theorizing based on theoretical perspectives relevant to contexts like emerging digital technologies and climate change.

In addition to contributing to a better understanding of collaborative innovation, the aggregated findings of this dissertation might also provide some implications for research on digital technologies and climate change mitigation. The literature on information systems aims to understand better developments in and implications of

digital technologies for individuals, organizations, and the economy (see Nambisan et al., 2017 and Yoo et al., 2010 for an overview). This dissertation investigates the intersection of digital technologies, collaborative innovation and climate change and reveals interesting insights that add to prior work on information systems. First, it develops theory on how and why different combinations of digital technologies can unlock climate impact – in combination with an appropriate ecosystem strategy. Thus, it contributes to recently emerging work on digital sustainability that aims to understand the role of digital technologies for sustainability (Bonina et al., 2019; George et al., 2021). While previous work remained mainly conceptual or focused on single product innovation, this dissertation introduces an (eco-)systems perspective that reveals how multiple firms can coordinate to realize digital sustainability. Second, it shows how the layered-modular architecture (Henfridsson et al., 2018) is useful for classifying different types of digital solutions and to determine the interfaces at which inter-firm integration takes place. While prior work classified different types of digital innovations (Appio et al., 2020), this dissertation pays specific attention to the classification at inter-firm digital interfaces which provides a better and more nuanced understanding of digital innovation in the context of collaborative innovation. Thus, it complements recent calls to theorize about digital technology and its implications for different forms of organizing across firm boundaries (e.g., Dahlander et al., 2021; Nambisan et al., 2019; von Krogh, 2018). Finally, this dissertation introduces virtual conferences as a novel and relevant phenomenon to the information systems field, complementing prior work on social media networks (Weiler et al., 2019) and adding to recent work on the future of collaboration (Hacker et al., 2020). Overall, this dissertation's empirical investigation of digital technologies and their implications at the individual, organizational, and inter-organizational levels adds to a better and more theoretically grounded understanding of ubiquitous digitalization – one of the grand challenges of our times.

Finally, this dissertation also contributes to a better understanding of how to address climate change. Research on global climate change builds upon a solid basis of science, and the profound and catastrophic implications of climate change are well understood (e.g., IPCC, 2021). Similarly, there is a large body of research on how to tackle climate change by decarbonizing the global economy (e.g., Rogelj et al., 2021), on the kinds of technological innovations required to achieve that decarbonization (e.g., Bumpus & Comello, 2017; Inderwildi et al., 2020), and the cost and innovation rates of such technologies (Comello & Reichelstein, 2019). However, while there are rich insights on climate innovation policies and national or regional innovation systems (e.g., Rogelj et al., 2018), the implications of collaborative climate innovation efforts of firms

has often been neglected when simulating climate change mitigation pathways. While it does not offer large quantitative datasets on carbon emissions, this dissertation provides in-depth quantitative and qualitative insights that highlight the role that collaborative innovation could play in accelerating the development and deployment of low carbon solutions. Consequently, it might be worthwhile to further reflect on the role that collaborative innovation could play in climate change mitigation pathways. One careful proposition could be that integrating novel parameters on collaborative innovation activities that facilitate learning rates and innovation diffusion could improve the accuracy of simulated climate change mitigation pathways. For instance, the timing and extent of emission savings realized by battery storage solutions (Comello & Reichelstein, 2019) might very well depend on collaborative innovation activities, as suggested by the framework presented in chapter 2. More (less) coordinated innovation activities might lead to earlier (later) realized emission savings because of accelerated diffusion and higher resource efficiency.

In addition to reflecting on the role of collaborative innovation, this dissertation also pays specific attention to the role of digital technologies in tackling climate change. It thus adds to prior work suggesting that digital technologies are a core part of climate change mitigation (e.g., Inderwildi et al., 2020) by providing a more detailed understanding of the kinds of digital technologies and under which conditions they can unlock climate change mitigation impact. For instance, coming back to the example of battery storage solutions (Comello & Reichelstein, 2019), the findings of this study further elaborate on how the introduction of novel innovations at the device and application layers that is likely to facilitate the realization of climate mitigation impact of such solutions. For instance, chapter 2 suggests that it is the combination of digitalized infrastructure and third-party device innovations that enables climate mitigation impact by improving resource efficiency.

To conclude, this dissertation illuminates the role of collaborative innovation in the context of emerging digital technologies and climate change. Thus, it directly provides several theoretical implications for different literature streams in management research. Furthermore, it contributes to a more comprehensive understanding of the interplay of collaborative innovation, digital technologies and climate change mitigation. Consequently, it also provides insights and reflections for the fields of research on information systems and research on climate change mitigation.

5.3 Implications for managers

In addition to theoretical implications, this dissertation offers several practical insights for managers on how to conduct collaborative innovation in times of the digitalization

of everything and the required decarbonization of our economy. First, the theoretical framework of ecosystem realignment and climate change mitigation, presented in chapter 2, could also serve as a comprehensive practical playbook for managers that explicates how they can leverage ecosystem strategies to contribute to climate change mitigation. This playbook helps climate-tech startups unlock the climate impact of their novel digital innovations. Similarly, it allows managers of incumbent firms to strategize in a world of ecosystems while navigating trade-offs between business demands and climate change mitigation. Incumbents can leverage their access to critical infrastructure to lead climate mitigating innovation ecosystems. They can facilitate climate impact by sharing customer access and coordinating with third-party complementors. Eventually, they can also drive climate impact in complementary positions when joining the dominant platform of a new orchestrator. For determining the right strategy for the right technology (and time), they might be well advised to pay attention to their ability to attract third-party complementors. Another critical concern is determining whether and if they can and should leverage their incumbent position to facilitate or hinder climate change mitigating digital innovations.

Second, the knowledge integration mechanisms outlined in chapter 3 give managers guidance on how to think about resourcing, scheduling, and modes of knowledge exchange in collaborative innovation projects that aim at integrating external digital solutions. More importantly, it advises managers to customize the collaborative innovation process towards the desired external digital solution type. When integrating external machine learning applications, they might be well advised to facilitate a fast and efficient process with multiple iterations and remote collaboration. For working on novel systems and platforms at the core of their digital infrastructure, they are likely to be better off when planning with significantly more resources and more intense in-person workshops. Finally, more upfront planning is required when working on external device innovations, as iterations take more time and resources. Following this advice to design efficient collaborative innovation projects is also likely to enable the above-described ecosystem strategies for mitigating climate change.

Third, moving to the individual level, the framework of social capital accumulation presented in chapter 4 illuminates how managers can set up virtual open innovation conferences. Similarly, it provides guidelines for navigating these conferences to maximize networking outcomes. Using bi- and multi-lateral web conferencing seems to be particularly promising for building trust in relationships. Accessing online booths and profiles of collaboration partners might be particularly relevant to broaden one's social network and identify potential 'champions' for future

collaborations. That being said, the benefits of using the respective features should be customized to each user's time zone or gender and further depend on the design of the respective feature. Following these guidelines might help realize the above-mentioned knowledge integration mechanisms and ecosystem strategies for climate change mitigation. This is because they rely on collaboration not only across firm but also across spatial boundaries that can only be bridged with carbon intensive travel or virtual collaboration tools.

5.4 Implications for policymakers

Finally, this dissertation provides some insights for policymakers. Digital technologies and climate change mitigation are at the core of many challenges policymakers currently face. Thus, a better understanding of the interplay of digital technologies and collaborative innovation processes may help design effective policies. More specifically, the findings in chapter 2 suggest that policymakers might think about incentivizing climate innovations with research grants. Similarly, policymakers might be well advised to re-think current subsidies that preserve the incumbent's position and business models that are not necessarily aligned with climate mitigation. Based on the findings presented in chapter 3, policymakers may think about programs and incentives that facilitate the exchange of knowledge between digital solution providers and incumbent firms with the required resources to scale them, especially when concerned with climate mitigation. This could take place in the form of demonstration facilities, industry-specific testbeds and "sandboxes".

5.5 Limitations and future research

While each chapter provides a detailed description of study-specific limitations and suggestions for future research, this section links back to the broader motivation of this study. It briefly describes the limitation of the dissertation setup and suggests broad directions for future research.

First, the dissertation is situated in the electricity industry. Given the critical role of the electricity sector for climate change and the importance and breadth of digital technologies for achieving climate change mitigation, it provides a premier setting for investigating collaborative innovation in the context of emerging digital technologies and climate change mitigation. However, the focus on one industry poses limitations to the generalizability of the presented findings. Future research might bring the developed theoretical arguments to the test in other industries facing digitalization and decarbonization (e.g., manufacturing, mobility, construction).

Second, only the first study, presented in chapter 2, directly investigates implications for climate change mitigation. Chapters 3 and 4, instead, are situated in the

context of firms tackling climate change. However, they do not entail variables or theoretical arguments related to climate change mitigation. While the overarching framework of this dissertation explicates the links between the different chapters, future research should specifically focus on climate change implications of collaborative innovation at the individual and organizational levels. More specifically, future research might investigate an optimal strategy of physical co-location vs virtual collaboration for realizing collaborative innovation projects while optimizing their carbon footprint. Similarly, connecting the findings of chapter 3 closer to the grand challenge of climate change, future research could track the carbon emission savings of digital technologies developed and deployed in closed vs collaborative innovation.

Third, this dissertation aims to contribute toward a comprehensive understanding of collaborative innovation in the context of emerging digital technologies and the fight against climate change across multiple levels of analysis. This comes at the cost of further exploring the different levels of analysis in more detail. For instance, at the inter-organizational level, future studies could shed more light on the role of inter-organizational partnerships for realizing net-zero strategies. At the organizational level, future research might focus on developing and implementing said net-zero strategies. At the individual level, future research might particularly focus on individuals in their function as boundary spanners that transfer knowledge from the external environment to the firm and how they can maximize such knowledge transfer.

To conclude, this dissertation makes a first step towards understanding collaborative innovation in the context of emerging digital technologies and climate change. As such, it paves the way for a more comprehensive research agenda on the interplay of collaborative innovation, emerging digital technologies, and climate change mitigation.

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