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ORIGINAL ARTICLE

Paradoxes of implementing digital manufacturing systems: A longitudinal study of digital innovation projects for disruptive change

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Abstract

Digital manufacturing technologies offer many opportunities for established companies to innovate. They promote data-driven gains in operational efficiency and enable the transformation of current business models or the creation of entirely new differentiation opportunities. However, many digital innovation projects in manufacturing fall short of their initial ambitions and result in incremental improvements to an existing manufacturing system, if at all. To understand the reasons for the discrepancy between initial ambitions and achieved outcomes, we conduct a longitudinal qualitative study based on a collaborative research project with eight companies and additional expert interviews. Applying a paradox lens, we identify three tensional knots that reveal interrelated, multiple tensions of digital innovation management projects in established manufacturing firms: (1) amalgamating physical and digital assets, (2) innovating in an existing *modus operandi*, and (3) integrating internal and external stakeholders. These tensions result in the simultaneous occurrence of dynamic and conflicting forces that turn digital innovation projects in manufacturing away from their high initial ambitions. Our findings explain why digitizing the manufacturing system is a non-trivial endeavor for established firms, which need to balance the complexities inherent in digitization efforts and manage conflicting goals. For managers, the findings provide ways to manage the interrelated tensions in their digital innovation efforts, enabling them to better capitalize on disruptive innovation ambitions.

KEYWORDS

digital innovation management, digital manufacturing, digital transformation, Industry 4.0, paradox theory

1 | INTRODUCTION

For more than a decade, phrases such as Industry 4.0 or the Fourth Industrial Revolution have promised a radical

transformation of industrial manufacturing (Meindl et al., 2021). In turn, many manufacturing companies have embraced digitization to benefit from new digital business models or to radically change the value

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proposition of their production systems (Holmström et al., 2019; Rindfleisch et al., 2019). Integrating digital technologies such as the Internet of Things, additive manufacturing, artificial intelligence, and cloud-based analytics services into an existing production system creates connectivity along the entire value chain (Benitez et al., 2020; Frank et al., 2019). This connectivity makes it possible to respond to heterogeneous, rapidly changing customer demands in novel ways, to better leverage the specialized competencies of external partners, or to position a company as a sustainability leader by not only reducing resource consumption but also radically changing the production process, for example by incorporating biologically inspired designs for lightweight construction. All of these options offer great opportunities for manufacturing-based business model innovation (BMI) (Paiola & Gebauer, 2020). However, the reality of many digital manufacturing projects in practice is more modest. Instead of benefiting from new digital business models, many industrial incumbents often end up with incremental optimizations (efficiency gains and cost reductions) of existing operations and processes (Gregory et al., 2015; Helo & Hao, 2017)—despite higher ambitions at the start of their projects.

These divergent realities have motivated our research. We investigate why firms often fail to achieve their initial ambitions of realizing disruptive business model innovation through digital transformation of the manufacturing system. With this focus, we complement previous research that has examined the digital transformation paradigm (e.g., Appio et al., 2021; Hanelt et al., 2021; Vial, 2019), the impact of digital technologies on innovation networks (e.g., Benitez et al., 2020; Brunswicker & Schechter, 2019), and multi-stakeholder aspects of digital business model innovation (Rindfleisch et al., 2017). However, limited research has examined more radical innovation efforts in the context of digital manufacturing in established firms (e.g., Appio et al., 2021). Such innovation initiatives are not trivial, as digitization involves high levels of uncertainty due to the high degree of novelty and broad application possibilities of digital technologies. Thus, digital innovation projects are often considered fuzzy as they involve heterogeneous actors and competing demands (Nambisan et al., 2017). As a result, managers perceive tensions in how to position digital manufacturing within existing and new business models to manage transformation (Appio et al., 2021; Aversa et al., 2021; Brenk et al., 2019).

An illustration of this struggle is the adoption of additive manufacturing, a typical example of a digital innovation in manufacturing. Despite high expectations a decade ago, to date we observe a rather limited adoption of additive manufacturing for new business models in

Practitioner points

- While the application of digital technologies in manufacturing systems offers promising innovation opportunities, such as disruptive business model innovations, they often cannot be realized by established industrial companies.
- These implementation challenges may lie in paradoxical tensions that are interwoven in so-called tensional knots, which show the intricate complexities for the involved stakeholders.
- These tensional knots appear especially when physical and digital assets are combined, when digital innovation projects are executed in a conventional *modus operandi*, and when internal and external stakeholders are integrated.
- Untangling these knots—if possible—is by no means trivial, but an awareness of their presence and paradoxical nature can help managers deal with them better than just through simple pragmatic downsizing of project objectives.

established firms (Proff & Staffen, 2020). Previous research has shown that additive manufacturing affects several dimensions of innovation simultaneously, such as providing new capabilities in the design process, changing established supply chain infrastructures, and placing a firm in new technological ecosystems with new collaboration requirements (Jiang et al., 2017; Stanko & Rindfleisch, 2020). It also provides many opportunities for business model innovation (Rindfleisch et al., 2017, 2019). To derive greater value from a digital innovation such as additive manufacturing, companies need to view these dimensions as intertwined (Sawhney et al., 2006). Managers need to address these dimensions holistically. This includes being aware of how additive manufacturing could innovate their company's business model (Rindfleisch et al., 2017, 2019). This example shows that combining the different dimensions of digital innovation is not an easy task, and can be a source of many tensions.

Our study examines the digitization of manufacturing systems in a related context of a disruptive digital innovation: pooling data from connected manufacturing assets across various independent companies on a shared data platform. This pooled data can become the origin of new digital business models around prediction and prescription services that can help manufacturers optimize their operations. Similar to additive manufacturing, such a data platform is a digital manufacturing innovation that

needs to cope with different, but interrelated innovation dimensions on different levels (e.g., organization and networking of manufacturing infrastructures, adaptation of process structures for innovation and operations, establishment of collaborations in an ecosystem). These dimensions and their interrelationships can cause tensions that challenge the realization of the initial ambitious innovation objective. Thus, we pose the research question whether managers in established manufacturing firms experience tensions in their digital innovation projects, how these tensions manifest, and how they are interrelated.

To answer this question, we turn to paradox theory, which is well suited to researching conflicting goals and competing demands in intricate and complex environments (Hahn & Knight, 2021; Lewis & Smith, 2014; Schad et al., 2016; Schad & Bansal, 2018). Paradoxes are “contradictory yet interrelated elements that exist simultaneously and persist over time” (Smith & Lewis, 2011, p. 382). Previously studied paradoxes include learning, organizing, performing, and belonging paradoxes (Smith & Lewis, 2011), the paradox of success (Cunha & Putnam, 2019), ambidexterity (Andriopoulos & Lewis, 2009), and the openness paradox (Lauritzen & Karafyllia, 2019). These paradoxes cause actors to experience tensions, “defined as stress, anxiety, discomfort, or tightness in making choices and moving forward in organizational situations” (Putnam et al., 2016, p. 68). For managers, tensions are problematic trade-offs that need to be resolved or avoided. These tensions are caused by the contravening poles of a paradox that pull actors and their decisions in opposing directions (Smith & Lewis, 2022). For example, the focal manufacturing firm needs data openness for the shared data platform to deliver value. However, opening up calls for more control over the data as a key resource. This control demand would not have been as prominent without the call for openness in the first place. Hence, actors are in a situation with opposing demands and face tensions of how to deal with these. Especially when firms pursue multiple conflicting goals simultaneously, several paradoxes can be at play and thus are interwoven. Hence, they can co-occur (Jarzabkowski et al., 2013). For example, in addition to the data openness-control paradox, the manufacturing firm needs to incorporate more adaptive innovation processes to work with multiple actors on the shared data platform, while at the same time the higher degree of uncertainty calls for more stable instead of more flexible operations. Attempts to address one of these paradoxes often creates others, causing so called knotted paradoxes (Smith & Lewis, 2022). Also the tensions resulting from these paradoxes can be nested on different levels—from the individual to the organization to

the society (Gilbert et al., 2018). In this context, the notion of (knotted) paradoxes and, as the result, tensional knots can help managers to shift their conceptual frames to better understand the complexity and interdependent dynamics of situations where several tensions co-exist and interrelate with each other. Hence, developing a paradox mindset could support managers to reach for more disruptive transformations (like BMI).

However, research on the co-occurrence of paradoxes and tensions is rather nascent. So far, research has mainly zoomed in on single paradoxes or tensions, despite earlier calls to examine how multiple tensions emerge and interrelate (Cunha & Putnam, 2019; Hahn & Knight, 2021). Moreover, previous paradox research in innovation management has mainly focused on the organizational level (for an exception, see Miron-Spektor et al., 2011). In practice, companies have increasingly organized tasks in the form of projects (“projectification”), especially in the context of innovation and research and development (R&D), which distinguishes project work from regular and recurring tasks in day-to-day activities (Schoper et al., 2018). This also applies to incumbents, which typically organize their digital manufacturing initiatives in the form of innovation projects. We therefore chose the project as the object of analysis, as this is how established organizations typically address digital opportunities. Digital innovation projects provide the interface between individual actors and their organizational context. Analyzing the project allows us to assess the multiple dimensions that characterize digital innovation initiatives without limiting our findings to the individual or organizational level. This allows for a more systemic and holistic perspective, which is particularly valuable in the business-to-business environment of manufacturing companies (Lievens & Blazevic, 2021).

Our study is based on a longitudinal, qualitative analysis of a collaborative research project and additional expert interviews on the perceived challenges of digitizing manufacturing systems in collaboration with external stakeholders. We used an abductive approach to discover three tensional knots showing the interrelatedness of multiple tensions. We observe and explain how these tensions led to a downgrading of initially ambitious innovation goals that altered (disruptive) digital manufacturing business models into rather incremental efficiency optimizations. These tensional knots do not happen in isolation, but influence each other, which further increases the entangled complexity of digital transformation in manufacturing.

The contributions of our study are threefold. First, by providing empirical insights into the interrelatedness of multiple tensions that emerge in innovation projects to digitize manufacturing systems, we explain specific

challenges that manufacturing incumbents face in their digital innovation efforts. These insights contribute to the literature on BMI by raising awareness of the intractability of interrelated tensions in the pursuit of disruptive ambitions. This literature has argued that the architecture of a firm's value creation, delivery, and appropriation mechanisms and the underlying complementarities between these elements are central to the success of a BMI (Foss & Saebi, 2018; Sorescu, 2017). We propose that a paradox view of these interrelated BMI elements can help to better understand the implementation tensions that arise due to the complex architecture of these BMI activities. Therefore, an awareness of the paradoxes that cause these tensions can help manufacturers drive more transformative change through digital manufacturing.

Second, we contribute to paradox theory by providing empirical insights into the co-occurrence of paradoxes (as requested in research calls by, e.g., Cunha & Putnam, 2019; Jarzabkowski et al., 2013; Sheep et al., 2017) and their relationships with tensions perceived by managers in the context of (radical) change. This will increase the level of specificity and understanding for future research investigating paradoxes in different contexts.

Third, by demonstrating the complexities and interrelated elements across multiple levels—individual, project, organization, and external stakeholders—we provide a more nuanced understanding of the dynamic evolution of digital manufacturing systems. These complexities must be recognized through a systemic view, as interdependent elements cannot be changed in isolation. Such a multilevel perspective could also benefit the BMI literature, which has so far mainly examined the organizational level, focusing on performance implications, cognitive schemas, and organizational activities (e.g., Foss & Saebi, 2018). We complement this research with our findings at the project level. In addition, a multilevel understanding of the interrelated tensions can generate coping strategies that better balance the complexity inherent in digitization efforts.

2 | THEORETICAL BACKGROUND

2.1 | Digitizing manufacturing systems and digital BMI in manufacturing

Research refers to digital transformation as the substitution of current business operations based on analogue or manual processes with digital (computer structure) operations (Lanzolla et al., 2020). This transition entails a transformative process by enabling significant improvements to organizations through combinations of digital

technologies, such as information, computing, communication, and connectivity technologies (Vial, 2019). Correspondingly, manufacturers engage in digital innovation to achieve operational improvements on the one hand and to generate new revenue and value-producing opportunities on the other (Rindfleisch et al., 2017). Therefore, they use digital technologies to optimize the efficiency of their manufacturing processes and to enable new value propositions, such as customized products, digital product-service systems, or manufacturing as a service (Helo & Hao, 2017). Digital manufacturing technologies build on the Internet of Things, a set of protocols and standards to integrate smart devices with sensing, communication, network, and autonomous acting capabilities into a holistic cyber-physical system (Meindl et al., 2021). Data from connected devices are aggregated in data spaces (cloud computing) and analyzed with artificial intelligence and machine learning algorithms. The result is a transformation of the existing manufacturing infrastructure into an interconnected and integrated Industry 4.0 (Frank et al., 2019; Meindl et al., 2021). This fourth industrial evolution not only reshapes producing industries with significant opportunities for the design of manufacturing, work structure, and supply chains but also increases the solution space for product and service innovation enabled by such intelligent cyber-physical systems (Frank et al., 2019). Consequently, digitization technologies inspire digital innovations of manufacturing systems, which we define as novel data-driven and connected applications and services offered to manufacturers to improve the performance or strategic differentiation of their operations. The focus of our research is on their management, that is, “practices, processes and principles that underlie the effective orchestration of digital innovation” (Nambisan et al., 2017, p. 224).

When investigating digital innovation, a solely intra-organizational perspective is often not sufficient (Benitez et al., 2020); it requires a simultaneous consideration of external stakeholder relationships, either because incumbents lack required resources and competences to conduct such projects on their own or because creating new value through digital technologies requires new partnerships and collaborations (Nambisan et al., 2017; Vial, 2019). Thus, many digital innovation projects are executed in rather complex ecosystems (Adner, 2017), in which established manufacturers must co-create with new stakeholders, such as specialized, often powerful IT suppliers or digital start-ups (Benitez et al., 2020). These projects' importance have increased with the growing use of digital technologies due to new interdependencies and collaborations to jointly operate digitized manufacturing systems (Benitez et al., 2020). Finally, relevant external stakeholders include customers, who become more active

participants in organizational relationships through increased information and communication capabilities (Lucas Jr. & Goh, 2009). Closer relationships lead to increased exchanges, which raise customers' expectations. At the same time, connected products also provide manufacturers novel insights into the usage of their products and the outcomes of their manufacturing processes (Vial, 2019). These novel customer insights support the optimization of existing production setups and process interconnectivity in a firm's manufacturing ecosystem (Frank et al., 2019) and also enable a better design of new product generations.

These opportunities of enhanced external stakeholder involvement offers digital innovation projects to strive for disruptive change (Mithas et al., 2013; Vial, 2019). Examples are the development and launch of entirely new digital offerings that facilitate entry into new markets or provide new opportunities through servitization (Frank et al., 2019; Paiola & Gebauer, 2020). To leverage this transition, digital innovation managers adapt a BMI mindset, though companies may differ in how they approach their digital innovation projects: while some perceive BMI as an existential threat, others regard it as major opportunity (Brenk et al., 2019; Sjödin et al., 2020). In both cases, BMI activities require a search for new institutional logics and new ways to create and capture value for stakeholders (Casadesus-Masanell & Zhu, 2013). Therefore, BMI can be disruptive (Markides, 2006), as it implies an elementary variation of the current business model, changing existing value propositions, value chain architectures, and revenue models. As a result, digital innovation managers driving BMI must often overcome organizational inertia and path dependences. Especially when opportunities of new business ideas involve great uncertainties, managers prefer to avoid risks and radical change, such that BMI initiatives are often impeded from the beginning (Markides, 2006). Furthermore, managers willing to seize new business opportunities often lack hierarchical power or available resources to induce a BMI process (Bock et al., 2012).

Prior research on BMI in a digital context has focused on digital ventures and start-ups, service sectors (e.g., health care, finance, entertainment), or consumer industries, often applying single case studies as a research method (e.g., Lucas Jr. & Goh, 2009; Srivastava & Shainesh, 2015). We contribute a complementary perspective by examining digital innovation activities in industrial manufacturing companies and by examining on a project level how companies carry out such activities (Nambisan et al., 2017; Vial, 2019). We chose to analyze projects because they represent the working mode where organizations usually address digital opportunities and where digitization challenges arise. Digital innovation

projects provide the interface between individual actors and their organizational context.

2.2 | Paradox theory in the context of digitization

While the BMI literature emphasizes exploratory innovation, where digitalization is used to create new processes and value propositions, most industrial companies in the past decade have used digital technologies to improve the operational efficiency of existing processes, thereby strengthening the competitiveness of their current business (Aversa et al., 2021). According to ambidexterity literature (e.g., Andriopoulos & Lewis, 2009; Smith & Beretta, 2021), many firms struggle to engage simultaneously in such conflicting ambitions between exploitation and exploration. Additional complexity results from the multifaceted constellations of external stakeholders, which are typical for digital innovation. Investigating these issues requires a holistic and dynamic research perspective (Reypens et al., 2021). To address this demand, we adopt paradox theory as a meta-theory (Smith & Lewis, 2011). According to Lewis and Smith (2014), paradox theory is especially helpful when organizations pursue multiple goals in complex conditions. Schad and Bansal (2018, p. 1491) propose that digitization is a "wicked" problem, that is, "system problems characterized by complex dynamics exposing multiple tensions across levels of analysis." Digitizing manufacturing systems is a complex endeavor characterized by many interactions between internal and external stakeholders with different needs, requirements, and obligations that provoke multiple and often contrary objectives (Smith & Beretta, 2021).

Paradox theory provides an analytical lens to examine digital innovation projects spanning between the organization and individuals. On the organizational level, paradox theory assumes (in contrast with contingency approaches) the presence of ubiquitous forces that can both challenge and fuel the success of organizations in the long run. These competing forces co-constitute a repertoire of multiple, interrelated tensions that develop over time (Cunha & Putnam, 2019; Sheep et al., 2017). Therefore, we expect contradictions to arise because digitizing manufacturing systems involve multiple goals (Nambisan et al., 2017). Digital innovation managers search for new value-creating opportunities through digital innovation projects while simultaneously exploiting existing production processes and infrastructure. This contradiction is often amplified, as the current operational business must finance the digitization projects with different degrees of innovation. Prior research calls for

investigation on the specific interconnections of tensions and paradoxes that stimulate or amplify each other and result in tangled knots (Cunha & Putnam, 2019; Sheep et al., 2017).

On the individual level, paradox theory is especially suited to study how actors respond to contradictions in “contextually embedded, ongoing processes of organizing” (Cunha & Putnam, 2019, p. 100). In digitizing their manufacturing systems, managers must adapt for the future and confront renewals, changes, adjustments, and innovations. Doing so, however, may lead to a contradiction of the past and present states (Smith & Lewis, 2011). Therefore, contradictory but interdependent challenges emerge and evolve, as digitizing manufacturing systems may transform the value and role of innovation managers. Paradoxes might arise when desired outcomes in systems must be achieved by opposing means (e.g., control vs. flexibility, collaboration vs. competition, or empowerment vs. direction). When innovating for digital manufacturing, managers need to balance their perceptions of profiling digital innovations as a disruptive opportunity, which may raise doubts about the current operative business, and an opportunity to improve the existing business, which may lead to a lack of awareness of disruptive opportunities (Nambisan et al., 2017). At the same time, digital innovations require optimizing a current state and facilitating the transition to something new. Gregory et al. (2015) describe such tensions in the context of the ambidextrous role of IT management, which both ensures operability and continuous improvement of IT and participates in transformation initiatives.

Paradox theory provides an approach to overcome “either/or” thinking by using “both/and” (Lewis & Smith, 2014; Putnam et al., 2016). For example, in the context of open innovation, Lauritzen and Karafyllia (2019) propose a both/and approach to the control versus openness paradox. Either/or approaches usually propose weighing the cost–benefit trade-off of openness to make a choice for either control or openness, instead a both/and approach suggests that firms can be both open and under control. Only a few studies have applied paradox as a meta-theory to innovation research on an organizational level to examine ambidexterity (e.g., Andriopoulos & Lewis, 2009; Hargrave & Van de Ven, 2017), openness (e.g., Lauritzen & Karafyllia, 2019), innovation intermediaries (e.g., Lauritzen, 2017), or knowledge leveraging (Ritala & Stefan, 2021). On an individual level, Miron-Spektor et al. (2018) show that a paradox mindset fosters both in-role job performance and innovation when resource scarcity causes tensions.

In practice, established organizations typically address digital opportunities in form of (innovation) projects (Schoper et al., 2018). We therefore chose the project as the object of analysis. Digital innovation projects in

manufacturing provide the interface between individual actors and their organizational context. Analyzing the project allows us to assess the multiple dimensions that characterize digital innovation initiatives without limiting our findings to the individual or organizational level. In summary, we aim to use paradox theory to answer why innovation managers experience interrelated tensions in digital innovation projects and what the outcomes of these tensions are.

3 | RESEARCH METHOD

To understand the complex situation of incumbent manufacturing firms undertaking innovation projects to digitize their manufacturing systems, we conducted an exploratory, qualitative case study that followed a longitudinal collaborative project and collected data from additional incumbent manufacturing firms and digital transformation experts. We followed Goffin et al.'s (2019) case study evaluation template to report how we conducted our case study (see Table 1). We adopted an abductive qualitative research design (Bamberger, 2018; Dubois & Gadde, 2002; Sætre & Van de Ven, 2021) because our main goal was to discover interdependent elements in how these incumbents organize their digital transformation. Therefore, we were primarily interested in generating plausible explanations (Bamberger, 2018; Sætre & Van de Ven, 2021).

3.1 | Research context and data collection

We collected data in real time and retrospectively over the course of 3 years from a collaborative research project, which we term Digmasy (digitizing manufacturing systems). Digmasy aimed to systematically develop innovative business models based on digital transformation of existing manufacturing systems and operating models of manufacturers. In addition, the project served as a replication of a multi-stakeholder digitalization environment, which allowed us to consider external partnerships and ecosystem dynamics in digital manufacturing projects. We attended all project meetings and conducted expert interviews with members of Digmasy. Qualitative data included project workshop and meeting minutes, interim and final reports, observation logs, and formal and informal exchanges with project partners. Although we did not have a pilot study, we began with a longitudinal research project that helped us develop and refine our research protocols, interview questions, and observation guides. We also critically reflected on the interview guide

TABLE 1 Case study evaluation template overview.

Evaluation criteria	Application in this study
Theoretical foundation	An abductive qualitative research design is most appropriate, as our main goal was to discover interdependent elements in how manufacturing incumbents organize their innovation projects to digitize their manufacturing systems. We therefore were mainly interested in generating plausible, conjecturable explanations.
Pilot study	Our longitudinal research project helped us develop and sharpen our research protocols, interview questions, and observation guides. We also critically reflected on the interview guide after the first interviews and slightly revised them, when necessary.
Theoretical sampling	We selected both our longitudinal project and our interview partners from other cases on the basis of theoretical purposes; they had to come from established manufacturers that engaged in digital innovation projects that entailed collaboration with external stakeholders.
Triangulation	Our research is based on more than one source of data, including interviews, Digmasy workshop and meeting minutes, the initial project proposal, interim and final reports, observation logs, and formal and informal exchanges with project partners.
Review and validation of evidence	We reviewed and validated our evidence during feedback sessions with project participants and interviewees. The second and third author also remained distant from the data collection.
Transparency of data collection	Interviews were semi-structured and inquired about interviewees' general attitude toward digital innovation in manufacturing and were then dived into particular topics of innovation project management, partnerships and collaboration, and business models in this context. The interview guideline was also inspired by a paradox approach but avoided the terms "contradiction," "paradox," "tension," and "dilemma." We rather used terms such as "challenges," "problems," "dynamic and/or conflicting forces," and "areas for improvement." The interviews began with open questions, such as the description of own function and position or current projects and initiatives to create an open atmosphere. All interviews were digitally recorded and transcribed verbatim. Our interview protocol is available on request.
Inter-coder agreement	We did not calculate inter-coder agreement, as we engaged in several rounds of coding, including several iterations between the emerging data insights and theory, as is common in abductive approaches. Furthermore, quantifying inter-coder agreement represents a rather quantitative approach that might not fit all qualitative studies. However, we included comparisons between individual team members' impressions of the data and engaged in intense group discussions of overlaps and divergences.
Case presentation	We explicitly demonstrate how the empirical data enabled us to come to our results, as we provide a "trail of evidence" through ample quotes in the results section, additional quotes for our challenges and tensional knots, and visual aids in showing our results.
Case interpretation	We moved beyond description and conceptual ordering by systematically discussing our empirical results in relation to paradox literature. We iteratively moved between our empirical findings and theoretical insights, where after several rounds of discussion and abstraction, we finally zoomed in on tensional knots. Our figures show our conceptualizations of the identified tensional knots.
Reflecting on validity and reliability	We discuss these quality criteria throughout our Research Method section to detail the rigor of our qualitative approach and reflect on the validity and reliability. Furthermore, in our Limitations section we address the problem of generalizability of our findings.

after the first interviews and revised it slightly when necessary. Throughout the project, we also contacted additional interviewees from digital innovation projects in other established manufacturing companies, as well as specialists in digital transformation in industrial settings. Our purposive sampling criteria included that interviewees come from manufacturers that (1) are engaged in digital innovation projects that (2) collaborate with external stakeholders. The selected firms are established organizations that have existed for several decades, have a workforce that has grown over the years, and sell their

products to largely constant (industrial) customer segments. All companies had an existing business model focused on the development, production, and sale of physical goods, based on operational processes that have been continuously improved over years or even decades.

3.1.1 | Longitudinal project data

Digmasy was tasked with bringing significant innovation to the partners' manufacturing systems by collecting and

TABLE 2 Companies participating in the collaborative research project.

Company	Size	Description
MiningCor	Medium	This company manufactures heavy-duty systems for the mining industry that are used worldwide. These systems have a long operating lifespan of decades, they are usually custom-made, and their purpose of use is often very different. MiningCor's focus for the project was on operating machines while ensuring outcome quality for its customers, as well as improving machine availability and longevity.
MaterialsCor	Medium	The company produces parts with high precision from high-tech materials. The production process of this company ranges from raw materials, to manufacturing and machining, to just before the final product. A multi-stage distribution via various channels and partners then follows through to the end customer. Quality and precision are of importance for the final products. The focus in the project was on the quality-related process control in production and on the integration of measuring stations with capability for predictive maintenance in the different stages of the manufacturing process.
AutoCor	Large	The company manufactures assemblies for vehicles with combustion engines from semi-finished products. These are precision parts that are manufactured in large quantities worldwide on various production lines. At the same time, AutoCor has homologated production processes that must meet the strict regulations of the automotive industry. AutoCor also acts as supplier and original equipment manufacturer for automobile companies. In the project, it focused on the control of process parameters to ensure quality for assembly and its machined components, which were built in combustion engines.
QualCor	Large	The company has been supplying MaterialsCor with high-precision measuring systems for quality control for many years. To ensure the accuracy of the measurements, the systems must be maintained several times a year and repaired if necessary.
DataCor	Medium	This internationally active software company offers software and services in various areas, such as the digitization of IT and customer services. In the project, its main contribution as an enabler company was the preparation of big data analyses and development of artificial intelligence algorithms to analyze data from the manufacturing environment of the user companies.
NetCor	Small	NetCor has been involved in process automation in manufacturing companies for several decades, and as an enabler company in data acquisition, it supports the production environment and data transmission with network and gateway technologies.
NetTech	Medium	The company has a similar profile to NetCor and already worked before the research project with AutoCor in digitization activities in manufacturing.
SensCor	Large	The globally active producer of sensor and measurement technology supplies multiple industrial companies and aims to develop into a solution provider for automation in the manufacturing environment. Thus, it participated in the project as an enabler company.

analyzing process and product data in new ways. Some of the data was already available but not systematically analyzed, and some had to be collected by adding new sensors and connectivity to existing machines. The project partners wanted data-driven manufacturing decision support solutions, such as predictive maintenance algorithms to reduce unplanned machine downtime, algorithms to predict and improve production quality, and approaches to monitor and reduce energy consumption. They used digital technologies such as sensor and measurement technology, connectivity and gateway solutions, and sophisticated data science applications (e.g., big data analytics and algorithms based on machine learning and artificial intelligence). Beyond these use cases, which focused on improving the operational efficiency of the participating companies, the project partners had a particular ambition to develop new business models. The written goal at the beginning of the project was to jointly develop digital manufacturing solutions and to make these offerings

available to other companies. The data-driven decision support solutions developed to improve their own factories were to be monetized by selling them in the form of data-driven products and digital services to others, using the insights from optimizing their own manufacturing as benchmarks and training data for the algorithms. Part of the Digmasy project was therefore to implement concrete demonstrators to ensure the sustainable use of the results obtained and to present them to the public.

Digmasy consisted of 11 partner organizations, which can be subdivided into user companies, enabler companies, and research institutions (see Table 2 for an overview). The data-driven digital manufacturing innovations were to be applied in the three user companies (MiningCor, MaterialsCor, and AutoCor) that selected suitable production processes. In addition to the user companies, five enabler companies participated in the project to provide complementary resources such as hardware (e.g., sensors, actuators), software, and analytical capabilities to implement the

TABLE 3 Expert interviews.

Company	Size	Expert	Position	Duration (min:sec)
<i>Experts actively participating in digital transformation projects</i>				
A ^a (MiningCor)	SME	a1	Middle management	59:11
		a2	Senior management	38:48
		a3	Sales manager	39:19
B ^a (MaterialCor)	SME	b1	Shopfloor management	38:03
		b2	Middle management IT	32:04
		b3	Shopfloor management	54:02
C ^b	SME	c1	Middle management	46:49
		c2	Middle management	47:07
D	Large	d1	Middle management	70:42
		d2	Purchasing management	48:47
E ^b	SME	e1	Middle management	41:15
		e2	Middle management IT	35:36
F	Large	f1	Middle management	66:25
		f2	Data scientist	41:41
		f3	Middle management IT	48:30
		f4	Senior management IT	71:35
		f5	Senior technical leader	35:42
<i>Specialists for digitization and transformational activities</i>				
F	Large	f6	Senior technical leader	54:54
G ^a (AutoCor)	Large	g1	Local chief technology officer	35:23
H	Large	h1	VP technology management	68:00
I	Business-to-business platform	i1	Chief executive officer	65:20

^aProject partner of the Digmasys project.

^bProject partner in a similar collaborative research project.

intended digital innovations. MaterialsCor introduced QualCor to the project, its supplier of measuring equipment also interested in implementing predictive maintenance in practice. SensCor, another supplier of sensor and measurement technology, provided the hardware to collect additional data in the production processes. A major task of the project was to connect different machines in the production processes to collect and aggregate the resulting data. Therefore, two suppliers of networking, gateway, and automation technology (NetCor and NetTech) participated to contribute their solutions and knowledge. Finally, DataCor, a company specializing in data analytics and data science, evaluated the data from the production processes, derived cause-and-effect relationships between different variables and parameters, and generated algorithms and models. DataCor contributed not only its software but also knowledge in this field.

The three research institutions came from the fields of computer science, production engineering, and innovation management. They not only participated as advisers to the

companies but also contributed academic expertise and ensured the further exploitation of the project results. A funding institution supported the research consortium; the German Ministry of Education and Research evaluated the mission and objectives of the collaborative research project and its participating members and ensured funding to the participating organizations to support the project over a period of 3 years. The funding was to help ensure the diffusion of the project results into a wider industry environment and to recognize the leading role of the manufacturers. As such, these firms, even though they were already established, were also leading initiatives in their industries to engage in digital transformation.

3.1.2 | Qualitative data from expert interviews

In total, we held 21 interviews (see Table 3). We conducted 17 interviews with experts from six industrial

companies, speaking to two to five experts from different management levels of each company independently. We held interviews with participating members of Digmasy as well as with other experts involved in similar digitization projects to gain further insights into the challenges faced. The interviewed companies were incumbents that had already initiated digitization activities. The interviewees came from different hierarchical levels (operative shop floor management up to senior management) and different functions, such as manufacturing, R&D, IT and technology management. In addition, we conducted four expert interviews with dedicated specialists for digitization and transformational activities who hold leadership positions, to comprehend overall perspectives and underlying mechanisms in their organizations. These experts had a high level of cross-project understanding of ongoing activities within and outside their organizations. One of the specialists worked as a chief technology officer for AutoCor but did not participate actively at regular project meetings.

All interviews were semi-structured and inquired about the interviewees' general attitude toward digital innovation in manufacturing, before diving into particular topics of innovation project management, business models, and partnerships in this context. The interview guideline was also inspired by a paradox approach, but it avoided the terms "contradiction," "paradox," "tension," and "dilemma" (Andriopoulos & Lewis, 2009). Instead, it used terms such as "challenges," "problems," "dynamic/conflicting forces," or "areas for improvement." The interviews began with open questions, such as the description of interviewees' own function and position or of current projects and initiatives, to create an open atmosphere (Spradley, 2016). All interviews were digitally recorded and transcribed verbatim.

3.2 | Data analysis

For data analysis, we followed an abductive approach by triangulating the perspectives of informants, project documents, and our own project observations. By taking the project as our unit of analysis, we were able to analyze both individual and organizational activities and interdependencies that interacted as the projects unfolded. We assured respondents of confidentiality and anonymity, and all received access to our verbatim transcripts to mitigate bias. We also sought informant validation by presenting our findings to the project participants. Thus, we took several measures to ensure credibility and conformability of our findings (Gioia et al., 2013).

Informed by prior research (Gregory et al., 2015; Mithas et al., 2013), we engaged in the research project

from the idea that digital innovation entails challenges and, in particular, tensions. Thus, to some extent, we already had a paradox approach in mind. However, our first "hunch" (Sætre & Van de Ven, 2021) was the observation that, despite the ambitious and disruptive initial project objectives, the Digmasy project members tended to downgrade their innovation goals throughout the project. The first author, who participated in all Digmasy meetings, continued to challenge the participating firms with their original project vision; however, this did not change their path to pare down the initial disruptive goals into small, individual optimizations of the existing manufacturing systems. The second and third authors did not participate in the meetings and therefore could better judge the tensions from afar (Sætre & Van de Ven, 2021).

Our data analysis proceeded in two stages. In the first stage, we openly coded and examined the project activities and the members involved from the user companies to gain a deeper understanding of the context. When it became clear that the projects would result in more incremental process innovations despite their initial radical goals, we identified and categorized challenges and barriers that arose during the innovation activities to discover the reasons. The identified challenges resulted in our first-order codes. In a second step, we incorporated cross-project, cross-functional, and cross-company perspectives to systematically uncover explicit and implicit contradictions and paradoxical tensions. We then further abstracted our data and compared the positions of different companies and the statements of digitization specialists to deepen our empirical insights. While we adopted a general paradox approach, it was only by systematically combining the empirical fieldwork with recent discussions in paradox theory that we were able to engage in theoretical development (following Dubois & Gadde, 2002). Thus, we moved iteratively between our empirical findings and theoretical insights and, after several rounds of discussion and abstraction, finally focused on tensional knots. We settled on the notion of tensional knots because it was able to explain the interrelationship and dynamics between the salient tensions that co-occurred and reinforced each other.

3.3 | Validity and reliability

We took several measures to ensure validity and reliability. First, we followed the criteria outlined by Goffin et al. (2019) and as reported in Table 1. Second, our assurances of anonymity and confidentiality allowed interviewees to speak freely, which increased confidence in our findings. Third, all authors extensively discussed the empirical

findings and went through several rounds of abstraction and conceptualization, synthesizing the empirical data with theoretical insights to uncover the interrelated, knotted tensions. Because our empirical data include a longitudinal project and additional, multiple retrospective cases, we mitigated potential observer and retrospective sensemaking biases (Eisenhardt & Graebner, 2007).

4 | RESULTS

We present a narrative of how the longitudinal, collaborative research project unfolded to highlight how project members continuously and systematically turned the initially ambitious goal of developing disruptive digital innovation into more incremental, short-term-oriented solutions. The narrative provides first insights and experiences to show the identified challenges and resultant tensions of digital innovation management in manufacturing systems. During our analysis, we realized that project members experienced multiple tensions as interwoven knots, such that they could not easily separate these tensions (Sheep et al., 2017). In particular, we discuss three tensional knots: (1) amalgamating physical and digital assets in a manufacturing system, (2) innovating the manufacturing system in an existing *modus operandi*, and (3) integrating internal and external stakeholders. We report how the project members encountered these entanglements and dynamic complexities when digitizing their manufacturing systems.

4.1 | Experiences and insights from DigmaSys

During the planning of DigmaSys, the project partners jointly defined precise objectives to be achieved through digital BMI (development of digital analytic services and their external provision). These ambitious but well-defined goals were the reason the consortium received public funding. From the outset, however, the project members repeatedly revised their initial ambitions downward. It quickly became clear that the data-driven solutions to be developed were constrained by the contingencies of individual use cases. With all activities taking place in live production environments, it was critical that the technical solutions fit within the existing manufacturing infrastructure. For example, MaterialsCor initially wanted to autonomously adjust production process parameters based on real-time data analysis to improve the quality of parts produced, reduce waste, and enable more efficient customization. Instead, it switched to a system that suggested parameter adjustments to

operators, who could then choose to implement them or not. Similarly, MiningCor initially wanted to develop an automated control and operation system for customers of its heavy equipment, but ended up with suggestion algorithms for initial commissioning. AutoCor originally envisioned an automated setup system for an entire assembly line and the machining of its components. Instead, it ended up trying to find better process settings for just two of the components. MaterialsCor and QualCor also had an initial idea to jointly install an automated condition monitoring and predictive maintenance system for measuring stations to avoid unplanned downtime, but instead agreed to transmit machine data on demand so that a technician could plan regular maintenance in advance based on manual data analysis. Thus, despite their initial interest in developing autonomous digital solutions, the companies were reluctant to give the automated system any decision control; instead, an operator always had the final say. It is important to note that the initial application ideas were ambitious in terms of the state of the art, but were still deemed technically feasible and achievable within the project timeframe by a committee of Industry 4.0 experts from the funding organization.

Goal downgrading also occurred because the involved project members of the user companies, who were embedded in work environments with a strong technical background, had little awareness of the business-related issues and little knowledge of the current business models of their companies. In MaterialsCor and AutoCor they worked for the production department and in MiningCor for the development department. They had more operational responsibilities than project work, such as maintaining and improving their respective production processes. Thus, although they had technical domain-relevant knowledge in their work environments, they never had to consider strategic BMI. In addition, they often did not have the hierarchical power to initiate and/or implement more radical changes in their organizations due to their position in shop floor management. For example, at MaterialsCor, the value of smaller and more flexible batch sizes could not be appreciated, so this opportunity could not be pursued. Finally, the employees involved typically had a limited understanding of industrial equipment connectivity or data transfer and processing. As a result, each project member company had to involve its respective IT department, which added to the complexity of the project. Accordingly, the involved employees had to manage the knowledge exchange between the internal requirements of their IT colleagues and the external project stakeholders.

Getting the data they needed was also a challenge in some cases. For example, MaterialsCor and AutoCor

wanted to export data to separate machines in production, but the supplier of those machines was unwilling to provide the necessary support. In another case, installing additional sensor technology was not an option because the machine would have to be re-certified, and the company was not willing to go to that expense. The enabler companies repeatedly suggested installing existing measurement, gateway, and data processing solutions, but these were rejected due to lack of compatibility with the existing manufacturing infrastructure of the user companies. This led to the time-consuming development of small, custom technical solutions. AutoCor itself also had strict data exchange rules and administrative requirements before the project partners could begin joint data analysis. MiningCor first had to convince customers to provide data from machines in operation, and then organize data transfer despite the lack of an Internet connection in the factory. MaterialsCor had to adjust its goals for collaborative development of predictive maintenance because of hurdles in arranging continuous data transfers with QualCor.

Furthermore, all user companies had already engaged extensively in continuous improvement programs in the past, resulting in well-balanced and proven manufacturing setups. Therefore, project members were careful with modifications of single production steps to prevent (unwanted) effects elsewhere in the process or uncertainties about again needing regulatory approval of the entire production process. The stability of the considered production processes always evolved as a necessary condition. Interventions were mostly considered undesirable and had to be well prepared, planned, and verified in advance.

The aforementioned complexities intertwined and amplified each other. Combined, they led to more pragmatic solutions with lower levels of innovation, even though the collaborative environment and government funding would have allowed for more innovative (risky) endeavors. The originally planned development of new data-driven digital products and services offering new business model opportunities was continuously downgraded. In addition to the reduction of data-driven applications from autonomous system-level solutions (prescriptions) to simple component-level predictions, the ambitions to monetize the new applications in the form of digital solutions sold to third parties also diminished. All partners remained focused on improving the efficiency of their own production, but did not engage in BMI activities. Some of the results were controversial, such as data-driven maintenance planning at MaterialsCor. The company worked with QualCor to reduce machine downtime for maintenance based on manual data analysis for individual measuring stations. However,

this maintenance only took place during the holiday shutdown, so MaterialsCor was not able to increase its machine availability to gain a greater advantage.

4.2 | Tensional knots in innovation projects for digitizing manufacturing systems

As described earlier, the Digmasys partners faced several challenges that hindered their ambitious digital innovation goals. We therefore analyzed the interrelated tensions that emerged throughout the collaborative research project. In addition to analyzing project activities and conducting in-depth interviews with project members, we used insights from additional expert interviews. Once we realized that the tensions were interwoven, we sought to identify tensional knots. There are conditions in which multiple tensions interact with each other, resulting in a multifaceted co-presence of tensions (Sheep et al., 2017). This multifaceted nature contributed to a high level of complexity and uncertainty for the project members. Figure 1 summarizes the perceived challenges and the three tension knots, which illustrate the dynamic nature of the complexities behind the incidents. These knots do not occur in isolation, but can occur simultaneously.

4.2.1 | Tensional knot of amalgamating physical and digital assets

The first tensional knot combines goal ambiguity, lack of strategic vision and BMI awareness, inability to see the value of data leveraging, and constraints by the legacy of existing and continuously optimized manufacturing systems into an interwoven set of tensions that amplified each other. All digital innovation projects centered on combining physical and digital aspects of manufacturing into innovative solutions. For most of the companies involved, this digitization terrain was a new endeavor in which the objectives for the digital innovation projects remained ambiguous. On the one hand, senior management provided vague goals (e.g., “but nobody has yet considered how this...is feasible” and “how it can be realized in the end” – a2). On the other hand, inadequate or missing definitions of goals led to new offerings that did not meet market demand (e.g., “In the end, one has introduced a system or developed something that does not quite meet the requirements and wishes of the users or, in this case, customers” – a3). In general, respondents observed that project planning was often deliberately approached inaccurately or too optimistically, because “sometimes you see things in a naive way and think that

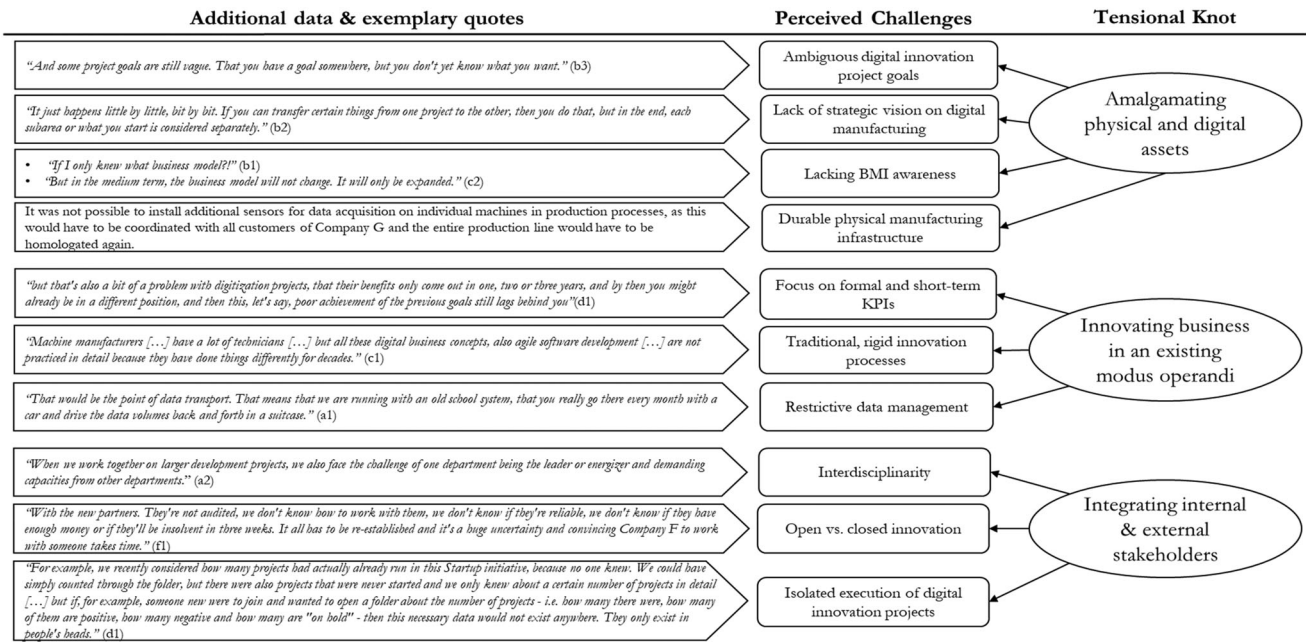


FIGURE 1 Tensional knots from the perceived challenges of digital manufacturing transformation.

it will be finished earlier, but afterwards you have to postpone the deadline repeatedly. You tend to specify a shorter time period and then say that it is postponed for a reason. Then it's more likely to go through than if you realistically estimate it from the beginning" (b3). Given this goal ambiguity, the development efforts went into different directions and resulted in conflicting sub-projects. In turn, project members felt discomfort and arranged only to incrementally optimize the existing physical assets, without considering more ambitious digitization opportunities.

Along with goal ambiguity, respondents indicated a lack of strategic vision on digitizing their manufacturing. Their digital innovation projects were rather isolated efforts toward digital manufacturing (e.g., "I haven't found anywhere that we have a digital strategy" and "some things are still fuzzy there. Like you have a goal somewhere, but you don't know what you want" – b3). When asked about his corporate digital manufacturing strategy, one project member answered, "We should really ask the board about this. I'd be very interested in that myself. The overarching strategy may be a problem for [MiningCor]" (a1). His colleague also stated, "I don't think we're the right industry for this [digitization]" (a2). Thus, goal ambiguity and lack of strategic vision for digital manufacturing opportunities reduced project members' motivation to grasp the full innovative potential of digitizing their manufacturing systems.

This entanglement was further complicated by the project members' deep technical background in manufacturing, in which they were trained to search for

quick solutions. Their tasks commonly focused on technical optimization to achieve efficiency in their current manufacturing systems. We observed a lack of awareness of and knowledge on BMI. Project members hardly thought about disruptive new solutions and offerings from a user-centric perspective. Most interviewees instead preferred a gradual approach to digital opportunities, taking one step at a time: "As I said, of course Industry 4.0 means also innovation, new and hip stuff, like apps. But for AutoCor it is of importance to achieve our goals, like cost, quality, and delivery targets. That's why... we keep looking at how we can improve our production accordingly" (g1). Furthermore, respondents indicated that combining physical with digital assets demanded expertise in handling data-driven applications, because "the tendency is of course moving towards employees who have an affinity for software and who have completely different educational backgrounds than what we find in manufacturing today" (g1). They often did not think about the value of leveraging data beyond their own manufacturing systems to, for example, obtain better training data for machine learning algorithms or achieve an inter-organizational process optimization or more flexibility. Thus, they were in constant conflict when trying to utilize the full potential of amalgamating physical and digital assets, while being embedded in technical practices and optimization goals.

Restrictions in the existing manufacturing setup further amplified this conflict. Over decades, all firms had optimized their manufacturing processes, which they then chose as their primary application area for the

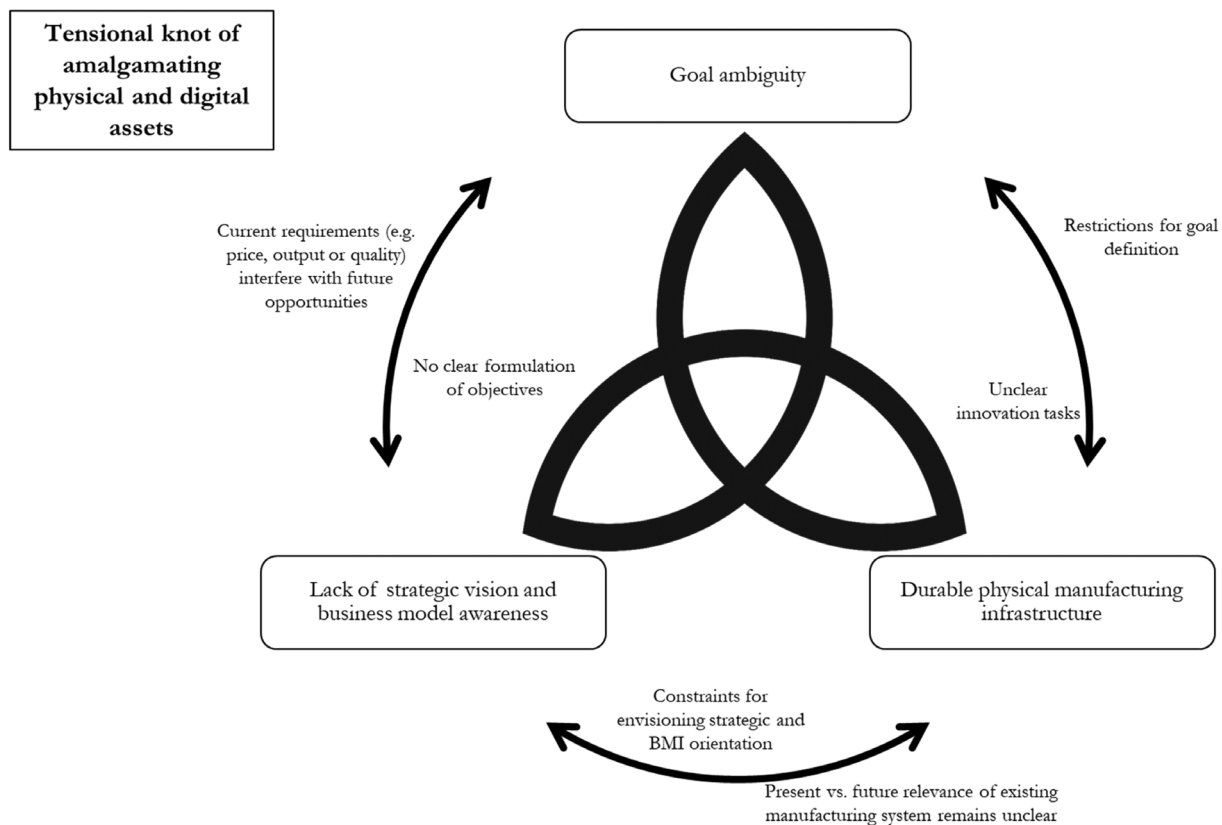


FIGURE 2 Tensional knot of amalgamating physical and digital assets.

digital innovation projects, so any new innovation had to fit. “No new business model or anything like that has been developed, but digitization is then simply able to save costs by simplifying processes” (f3). Because production employees were responsible for the digital innovation projects, their primary objective was to solve current concrete problems, without wanting to consider the entire manufacturing system. At the same time, these companies had durable machines as infrastructure and, therefore, also long investment cycles. Their manufacturing systems were strongly oriented toward quality and efficiency. This legacy of the past provided the pressure to first and foremost ensure the stability of the manufacturing system. The companies feared that digital innovations could jeopardize their manufacturing reputation: “So I think that [Company D] simply has a super strong brand recognition and you expect certain quality... and this is not only an opportunity, but perhaps also a risk...if the digital services do not offer the same quality that the customer expects” (d2). Thus, even small changes, such as attaching an additional sensor or reading data already recorded from a machine, were deemed impossible because they would require complicated internal company approvals or the installation would lose its certification and need to be re-homologated as a result.

Figure 2 summarizes the distinct challenges and their interrelated effects forming the tensional knot of amalgamating physical and digital assets. Due to goal ambiguity, the innovation tasks remained unclear and therefore did not provide the impetus to engage in more data applications or to deviate much from the existing manufacturing system and current business model. Similarly, the focus on the existing manufacturing system constrained goals and repeatedly contributed to goal ambiguity. While all project members were aware that data-driven digital applications were important, they lacked the vision and expertise to create value from the use of data, contributing to further goal ambiguity. As a result, project members focused on short-term goals and current requirements (e.g., price, quality, production stability), which hindered their ability to understand what was needed for future opportunities and to develop better data leveraging expertise. A lack of strategic vision and BMI awareness exacerbated this situation, as more ambitious digital innovation goals were not specifically articulated in the companies. This suppressed the vision of more forward-looking, data-leveraging, and flexible manufacturing systems and reinforced the focus on the status quo, which further constrained the vision of a strategic BMI orientation. Overall, these tensions resulted in

a justification for continuing to focus primarily on optimizing current physical assets rather than taking innovative actions toward more disruptive and flexible cyber-physical manufacturing systems.

4.2.2 | Tensional knot of innovating the manufacturing system in an existing *modus operandi*

The second tensional knot encompasses a focus on short-term key performance indicators (KPIs), a lack of agile innovation process skills, and restrictive data management procedures. As a result, companies attempted to manage ambitious, disruptive change with current skills and processes. They wanted to take advantage of the change opportunities presented by the digitization of their manufacturing systems and were aware that they needed more exploratory activities. As this involved more complexity and uncertainty, they felt the urge to hold on to their proven traditional innovation methods to reduce complexity. As such, they perceived a simultaneous need to explore business model opportunities and follow formalized traditions, and thus sought to innovate their business within their existing *modus operandi*.

Project members were aware that digitizing their manufacturing system was important; they perceived it as a necessity because “if you don’t play along as a company, you will be passed over” (d2) and miss “an important business opportunity” (h1). Even with seemingly incremental innovations, it was important to consider possible far-reaching changes in these projects. “Many people think that [digitizing, note from the authors] only has something to do with process improvement and the introduction of IT systems, but if you go deeper into the topic of digitization, you realize that this actually shakes the entire corporate structure and business processes at its core, and you actually end up with a completely different company” (h1). Thus, the potential for disruptive change was evident (and also the reason the firms joined the research project). At the same time, the benefits of digital innovations were often not immediately visible. “With digitization and digital technologies, you have to be careful at what point you really get the benefits” (f4). This opacity led to innovations being written off prematurely or considered a failure because certain KPIs were not quickly met. Instead of adapting to these particular challenges, however, companies fell back on their existing innovation processes. In some cases, even establishing the digital innovation projects was difficult because “the benefits versus the costs of these projects are not necessarily easy to quantify” (f3). Rather, companies had a strong focus on financial KPIs, in which projects had to

be justified from a short-term financial standpoint. The complexity of the projects together with the short-term focus led project members to choose the known paths of traditional development processes and methods. They were aware of this conflict and emphasized the necessity to extend their skills regarding fast and agile innovation and development processes: “We could sometimes be a little more innovative and faster. We might be a little slow sometimes” (a3) and “We notice...that we sometimes have very, very good ideas but are too slow in implementing them... We have a solution that has not been available anywhere else on the market. That means we would be the market leader. [The solution] even had the potential to become a huge success, but we then took too long to develop, distribute, and market it until others overtook us (g1). This seemingly impossible choice between reaching disruptive digitization goals with existing skills and processes and a focus on short-term goals led to the focus on incremental modifications.

This conflict was further perpetuated by restrictive data management procedures that prevented project members from deviating from the existing *modus operandi*. For example, at the beginning, the consortium emphasized selecting uniform data formats to enable data exchange and further data processing between the different organizations. While the choice of appropriate data formats was only a matter of discussion, the data exchange was at risk from problems with the physical transfer and storage of data, as well as other factors. For example, MiningCor reverted to outdated technologies, such as storing data on magnetic tapes, out of security concerns. Its data management procedures did not allow the manufacturing data to be stored in a cloud. Magnetic tapes, however, allowed data storage but not simultaneous data analysis. MiningCor also noted that the geographic location was “still a big discussion at the moment. Where does the server have to be? Does it have to be on our site...or can it also be at the headquarters...? Can plants in other countries also access it or should we introduce local servers?” (g1). Next, data exchange was hampered by administrative issues preventing the sharing of data, even though that was desired by the project members: “Many companies are afraid of sharing data, which could...represent a risk for them in terms of vulnerability... Of course, the press sometimes plays against this, because somehow a Facebook case or something else comes up, where...the entire management on the customer side, but also on our side, isn’t sure, because the topic is new for everyone and no one really has the holy grail of knowledge, and accordingly everyone wants to act securely in a new area. And that is...always difficult with digitization, where you don’t know what the impact will be once I have shared the data” (e1).

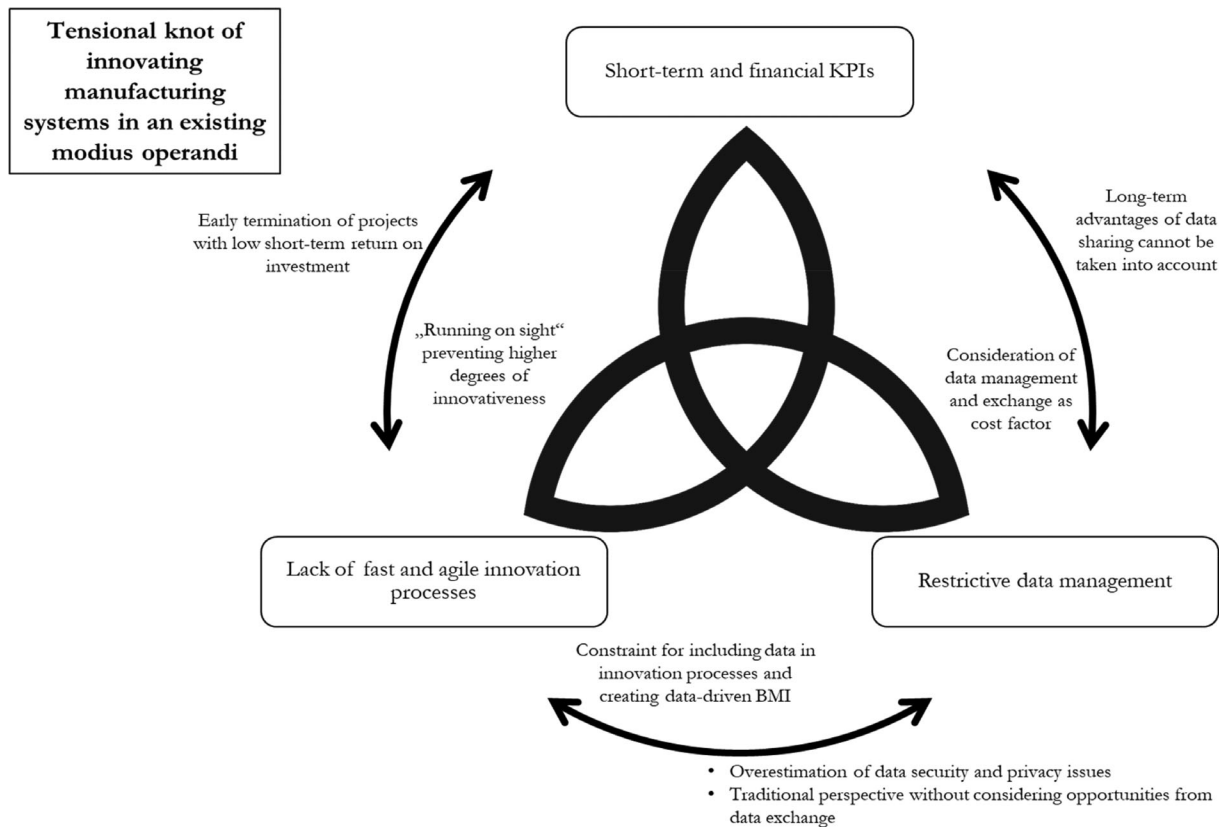


FIGURE 3 Tensional knot of innovating manufacturing systems in an existing modus operandi.

Figure 3 illustrates the distinct challenges and their inter-related effects behind this tensional knot. Taken together, the focus on financial, short-term KPIs led companies to view data management and exchange primarily as a cost factor and confirmed the attention to restrictive data management. In turn, the companies never experienced the longer-term benefits of data sharing, which in turn reinforced the focus on short-term KPIs. At the same time, project members tended to terminate innovation projects early if they did not achieve a short-term return on investment, which was confirmed by the use of traditional, rigid development structures. These rigid processes prevented higher levels of innovation. At the same time, they overemphasized data security and privacy issues without considering the possibilities of networked data, reinforcing restrictive data management. As project members had no agency to change these well-established procedures, they downgraded their ambitious innovation goals and focused on short-term goals that seemed doable.

4.2.3 | Tensional knot of integrating internal and external stakeholders

The third tensional knot encompasses tensions originating from the interdisciplinary nature of digital innovation

projects, their isolated execution, and open versus closed innovation in internal and external partnerships. This intertwined set of challenges demonstrates the dynamic nature of how digitizing the manufacturing system requires collaboration with additional stakeholders to achieve more ambitious goals. When confronted with the need to involve stakeholders in an innovation project, manufacturers were unwilling to make concessions, but instead sought control over their business relationships in order to manage their individual digital projects as they saw fit. This desire for control prevented interdisciplinary collaboration, as other departments or external partners of the companies were involved in certain activities, but did not become equal partners in the projects. At the same time, project members did not engage in joint value creation and ideas for collaborative business models with external partners for fear of losing entrepreneurial autonomy or self-determination. Thus, they perceived a simultaneous need for collaboration and control, so that individually implementing collaborations competed with their desire for control.

This tension of interdisciplinarity arose when the digital innovation projects required greater integration of internal IT experts and external partners, especially in the areas of data management and analytics, which led to

conflicting discussions among the manufacturing system engineers, the IT specialists, and external experts. For example, DataCor had to provide IT experts because the individual user companies did not have them in-house. These experts, in turn, lacked the domain-relevant knowledge from the manufacturing use-cases, which was required for data integration. During the first months of the collaborative research project, most of the user companies employed additional external IT specialists, especially in the field of data science. These external partners provided important external resources and capabilities and showed the relevance of involving enabler companies, arranging the collaborative project as business ecosystems. In some cases, “this was the first project..., where we worked together with external partners” (b1), and in others, “there were fewer external partners before” (b2), but in all user companies “it is rather an unavoidable step” (a2). The establishment of new partnerships was not obvious, because “you have to speak the same language first” (g1), and with an incumbent firm and a new partner, “there’s just worlds in between. We are designed for continuity...and the start-up could be off the market tomorrow” (g1). Equally, the inclusion of an existing external partner in digital innovation projects was difficult (e.g., MaterialsCor, QualCor), because the partner may “rest on his laurels. It is then very, very hard to make him move and to say: ‘We would like to have something new...’ Some matters are already so big and slow that it is really tough to get anything through” (b3). At the same time, some external stakeholders changed their role (e.g., from supplier to development partner). This role change also led to difficulties: “This [role change] is already indicated in the word “partner,” which means that you are on the same level and working together... In the case of the supplier, it was more of an order... Now...there was the question of data sovereignty. We provide data, the partner processes the data, and who owns the data now? We both put work into the data” (b1).

Integrating different departments was often difficult. At MiningCor, the R&D department managed its contributions to the research project, “although now purely by description, it would fit more into our service department. At that time, the service department approached us...because the algorithms are too complex. So, we got the project” (a1). The required cooperation with other internal stakeholders also resulted in discussions about the fair distribution of resources. Especially, when a department needed to draw on resources from other departments (c2), “this [would] take persuasion” (a1). This interdisciplinary cooperation was especially important during the interpretation of analyzed data. “The problem is that sometimes you blindly trust the data. If

[the worker] does this incorrectly or not properly, we have completely wrong data...You can’t approach it gullibly, because you can draw the wrong conclusions very quickly” (b3). Often, the IT department was assigned to help with certain tasks, but the IT experts only worked on digitization projects under previously defined conditions. As this formal involvement of other departments was always associated with additional effort and also often with internal transfer costs, the project members tried to avoid involving others or simply did not inform other departments in the company, such as a central department for BMIs, as this would complicate things unnecessarily (g1). Often, project coordinators would have benefited from changing to a more boundary-spanning role, in which their main task is to foster collaboration and knowledge exchange between internal and external partners, but they usually remained in their role as a traditional R&D engineer. They were also not always happy about the impact of data on the project and the integration of other disciplines, because “new things are not always perceived positively” (b2) and “it is difficult for them to let go [of] old structures and start something completely new” (b1). Thus, the R&D project members often did not trust the data-driven approach to their manufacturing systems, which was an essential part of digitizing them.

This tension could have been addressed by learning from other initiatives, but the digitization projects were usually executed in isolation from each other, and “each sub-sector or [activity] that is about to be started has been considered separately” (b2). However, it became clear that integration across digital innovation initiatives was important. Interviewees called for an inventory of current and possible future digitization activities (b2) and for a consideration of the entire value chain in production. “We have a component which goes through different production steps, and I collect the data for the component. Then I could actually get a very good understanding of what comes out at the end of the production to what I put in at the beginning... That would be a huge step if we could do that.” (b1). Several experts missed a “group-wide exchange on digitization projects” (b3) and a corporate coordination of these activities (g1). Not exchanging across the entire value chain in production also led to compartmentalized thinking and inhibited disruptive solutions that took a more holistic approach to the entire manufacturing system. Instead, projects only optimized smaller parts of the manufacturing system without considering upstream and downstream consequences.

Project members were aware that the collaboration with external stakeholders was important in digital innovation projects and often intense to compensate for a lack of required skills, knowledge, or data. Therefore, they

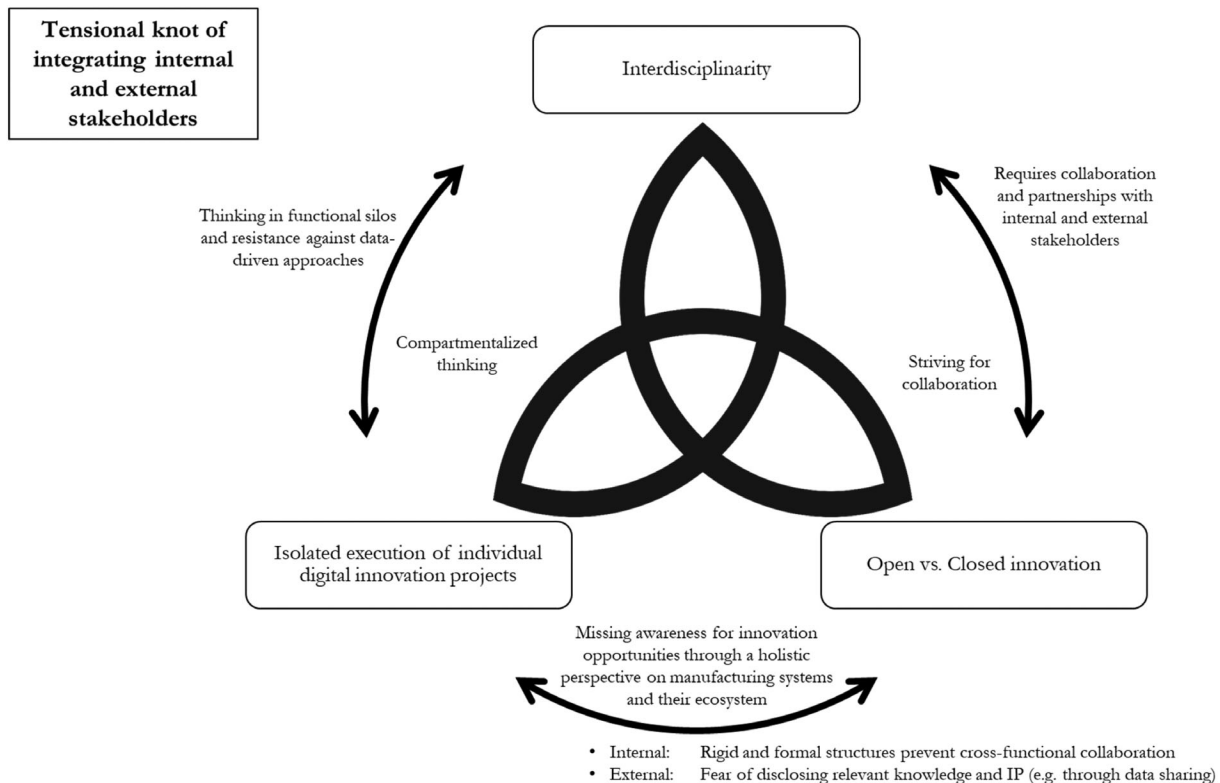


FIGURE 4 Tensional knot of integrating internal and external stakeholders.

initially had some drive to open up their innovation projects to these collaborations and perceived them as positive. “It’s positive because of course you get more creative” (f5) and especially new partners “are not so in our box, but a little more open-minded. They often come up with fresher ideas and are more motivated than an [existing] supplier” (c1). Most interviewees were also aware of different working methods in other sectors (d1) and their partners’ expectations. “Small companies are much faster. They expect us to respond much faster” (f1). However, at the same time, interviewees had a strong urge to keep their manufacturing systems close and away from more open innovation initiatives. While they wanted to benefit from improved or new data-driven products and services, they did not want to reciprocate. An informant at MiningCor shared an incident of a customer who never wanted “to open his system for third parties, even if he trusts MiningCor. It quickly became clear that the customer had disconnected his entire network from the internet. That means the entire network is offline. Many customers do this. If I think of a nuclear network, for example, there will probably be mechanisms in place to ensure that there is no chance of accessing the internet from anywhere. That way, nothing can get in from the outside or out from the inside.” (a1). Thus, while there was an individual push for opening up innovation of their manufacturing systems, both the

manufacturers and some of their customers feared external intrusion. The collaborations required for more disruptive change failed because companies imposed strict conditions on their partners, which they could not meet. “Various questions arise, such as where the partner manufactures the product and what environmental certificates are available, what quality management standards are in place, whether our legal conditions can be fulfilled, and much more” (d2). In addition to such administrative barriers, companies expected their partners to follow their established habits and contribute fully functional solutions, because something else “contradicts the classical approach of our development, whether software or hardware” (c2). This also applied to data sharing, as it is “necessary for the cooperation to share this data, but then you don’t like to give it away. So the current understanding is still that this is our data” (f3).

Figure 4 illustrates the distinct challenges and their interrelated effects leading to the third tensional knot. Taken together, the need for and, to a certain degree, lack of interdisciplinarity led to thinking in functional silos, fighting for resources, and resisting a more data-driven approach. Consequently, projects were executed in an isolated manner, which further resulted in compartmentalized thinking, failure to consider the complexities of the entire manufacturing system, and lack of more ambitious opportunities. This effect also fueled the tension

between open and closed innovation, as the siloed execution did not provide enough value to collaborate across the broader ecosystem and open up innovation activities. Instead, project members perceived confirmation of their fear to externally disclose relevant knowledge (e.g., through data exchange) and minimized the need for cross-functional collaboration. The tension between open and closed innovation also persisted in both the desire to control collaborations and the complexity of engaging in cross-functional and cross-organizational exchanges. Overall, project members prioritized their individual, incremental innovation projects, which optimized only a small part of the manufacturing system because the integration of internal and external stakeholders was less complex.

5 | DISCUSSION AND IMPLICATIONS

We set out to investigate how digital innovation managers experience interrelated tensions in their digital innovation projects. We had the unique opportunity to study this issue in a longitudinal collaborative project (Digmasys), where the initial ambitious BMI goals were continuously downgraded to more incremental process improvements. While continuous improvement is clearly important (especially in a manufacturing context), the project members failed to realize their disruptive innovation ambitions, such as developing data-driven digital manufacturing services based on a pool of shared data. Goal downgrading occurred because of the multiple, interrelated, and dynamic tensional knots.

5.1 | Implications for theory

Previous research indicates that using digitization for BMI enforces systematic changes in the drivers of operational efficiency, control modalities, and inter-organizational knowledge (Lanzolla et al., 2020). Our findings reveal the combined effect of these multiple forces, as the knots present specific interrelationships among tensions, rather than isolating them. These knots reflect how digital innovation managers juxtapose multiple, interrelated tensions: they must amalgamate their physical and digital assets to develop new business models, while their manufacturing systems need to work efficiently. They also need to innovate data-driven approaches, even if they do not trust autonomous decision making and incorporate their need for human control, thereby reducing the potential effectiveness of digitization. Their ambition is transformative change

through isolated digital innovation projects that must adhere to an existing business model and are to be carried out using established innovation processes and practices as known *modus operandi*. They need to collaborate with internal and external stakeholders, but they think in functional silos, do not want to share resources, and strive for control. Companies need to recognize that an ambitious digitization of their manufacturing system also requires a different way of organizing innovation activities (e.g. Rindfleisch et al., 2020). They need to have a better overview of these complexities and therefore engage differently in terms of structures, processes, and practices. For example, they could deviate from their existing *modus operandi* for these types of projects and allow project members to develop more appropriate innovation practices.

Our analysis also shows how digital innovation managers become entrapped in the entanglements of these tensions. This entrapment leads them to justify the downgrading of their initially ambitious goals and to redirect their innovation efforts toward incremental improvements that only are small steps toward digital transformation of manufacturing systems. In these established firms, conducting digital innovation projects as evolutionary, complementary activities is rather difficult. The intractability of the interrelated, multiple tensions within the tensional knots highlights the increased complexity of digital innovation management (Schad & Bansal, 2018), especially for established manufacturers. Furthermore, these tensional knots do not occur in isolation, further contributing to their intertwined complexity. For example, the restrictive data management prevalent in the knot of innovating within an existing *modus operandi* interacts with the fear of disclosing relevant knowledge and intellectual property, which is common in the knot of integrating internal and external stakeholders. Showing how these multiple tensions together form a “wicked” network of issues helps to understand how the different challenges coexist, reinforce, and amplify each other. In this context, we contribute to the emerging literature on the co-occurrence of paradoxes (Cunha & Putnam, 2019; Jarzabkowski et al., 2013; Sheep et al., 2017).

Digital innovation projects depend on individual innovation managers, who are embedded in organizational routines and processes and need to collaborate with external stakeholders. Thus, our findings on tensional knots in digitizing manufacturing systems further contribute empirical evidence to the understanding that these paradoxes and tensions need to be assessed across different levels of analysis (Nambisan et al., 2019; Smith & Beretta, 2021). This calls for a systemic view, where interdependent elements cannot be changed in

isolation, and where the interconnectedness of multiple issues is acknowledged and managed. Research on grand challenges that proposes robust actions of participatory architecture, multivocal inscriptions, and distributed experimentation could provide an interesting perspective for future research on this issue (Ferraro et al., 2015). For example, experimentation with diverse actors affects the potential for novelty to emerge. A better understanding of these complexities would then help to develop coping strategies to balance the interrelated tensions inherent in digitization efforts in established firms. For innovation management research and practice, this implies that the different dimensions of innovation should not be considered in isolation, as tensions occur across all dimensions and can only be addressed in a cross-dimensional manner (Sawhney et al., 2006).

Each distinct challenge within the knots is likely to be individually solvable, but due to their co-occurring entanglement, they are not easily separated (Sheep et al., 2017).

We followed a novel ontological approach (Hahn & Knight, 2021) to show empirically that such a conceptualization of paradoxes combines inherent and socially constructed elements. Latency comprises the unspecified probability that organizational actors experience the paradox in a given situation, which can also include different sets of interwoven paradoxes. Saliency refers to the contextual enactment of specific perceived paradoxes that are co-created through socio-discursive and socio-material factors. If these salient enactments continue to happen, the paradox persists (Hahn & Knight, 2021). In particular, the salient, distinct challenges result from the situated enactment of the tensional knots. These distinct challenges co-comprise socio-discursive factors, such as emphasizing the focus on short-term KPIs, and socio-material factors, such as the durable and optimized physical manufacturing infrastructure. The entanglement of the tensional knots and the interrelated, dynamic nature of the multiple tensions that co-occur within the knots represent inherent potentialities. We therefore contribute to paradox theory by showing how latency and saliency manifest in our context of digitizing manufacturing systems. We believe that similar effects are at work in other contexts of BMI, and suggest that further research on (failed) BMI projects could benefit from adopting this perspective.

We also expect the tensional knots to represent rather persistent entanglements, as indicated by the repeated enactment of interrelated, multiple tensions. The digital innovation managers were not always aware of these configurations; therefore, their central coping mechanism was to downgrade their goals. Rather than addressing complexity through a more transformative change in

their situations, they acted to reduce complexity to a manageable level, experiencing what Berti and Simpson (2021) call a “pragmatic paradox”: lacking the agency to change their situations more fundamentally, and suffering from the unacknowledged situatedness of the tensional knots, they lowered their ambitions.

5.2 | Implications for practice

Navigating the coexistence of these interrelated, multiple tensions requires a stronger and more comprehensive change in organizations than simply adding a few isolated digitization projects. Our analysis showed that the lack of awareness of tensional knots and their intractable interrelationship of multiple tensions is the main reason why digital innovation projects fail to achieve their initial ambitions of delivering new business models, but instead result in incremental adaptations. Therefore, managers should, first of all, focus more on defining, prioritizing, and adhering to digital innovation problems rather than designing short-term solutions too quickly. Firms need to ensure sufficient agency for their digital innovation projects and carefully consider how, when, and in what cultural and structural embedding they want to pursue more radical BMIs (Brenk et al., 2019).

In consequence, leaders need to adopt new forms of organization so that digital innovation projects can become a catalyst for transformative digital change (Lanzolla et al., 2020). For example, addressing the tensional knot of integrating internal and external stakeholders often requires a hybrid orchestration mode that combines dominant and consensus-seeking leadership during these projects to facilitate interactions between different employees with different backgrounds and diverse external stakeholders (Reypens et al., 2021). Thus, the integration of internal and external stakeholders has implications not only at the individual and project levels, but also at the organizational and inter-organizational levels, as it affects the firm's ability to relate to key partners (Aversa et al., 2021).

Dealing with these tensional knots is by no means trivial for practitioners. While the individual challenges were salient to them, the managers in our case companies did not always perceive the interwoven and dynamic configuration of the knots in the digital innovation projects. They lacked awareness of the paradoxes that created the multiple tensions. Building on paradox theory, our analysis suggests that practitioners could benefit from becoming aware of the underlying paradoxes. Managers need to adopt a paradox mindset and acknowledge the dynamic and conflicting forces (Lauritzen & Karafyllia, 2019). Accepting the interrelated coexistence

of multiple tensions caused by a paradox can drive new thinking. Developing a paradox (both/and) mindset would help managers drive more disruptive change (BMI), as they can shift their conceptual frameworks to better understand the complexity and interdependent dynamics of perceived tensions.

Leaders can develop more legitimate coping mechanisms that create new synergies. Specific training or external facilitation, for example, can support the development of such a mindset to better navigate the tensional knots and provide episodes of reflection in which managers can recommit to the original, more ambitious goals. For example, Smith and Beretta (2021) show how employees cope with the paradox of separation and integration, which indirectly changes the organizational model for implementing digital transformation. Since goal downsizing appears to be a coping mechanism to deal with salient tensions in digital manufacturing projects, managers need to integrate mechanisms to avoid this into their digital innovation practices. However, our study could not provide evidence on the effectiveness of coping mechanisms in this regard. This is a promising area for future research, investigating the design and deployment of specific training and awareness programs on digital manufacturing paradoxes (and, related, paradoxes of digital BMI).

Our discussion of the tensional knots demonstrated the high level of complexity that projects to digitize manufacturing systems entail. Implementing these projects requires clear priorities for amalgamating the physical and digital assets of their manufacturing systems, a changed set of digital innovation capabilities, and interdisciplinary integration of internal and external stakeholders. Remarkably, one way to deal with these complexities could be the expanded use of digital technologies. For example, the expanded use of digital twins for simulation, forecasting, and prediction could help prepare for changes in the physical manufacturing infrastructure and serve as a communication instrument among internal and external stakeholders (Fukawa & Rindfleisch, 2023). This would allow for more experimentation with the technical implementation of such changes, but also provide a platform for communication with involved internal and external stakeholders and facilitate prototyping.

6 | LIMITATIONS AND FUTURE RESEARCH

As with most qualitative studies, a major limitation of our research is the generalizability of our findings. Although we focused on established manufacturers

engaged in collaborative digitization projects, the companies operate in different industries. Despite our intention to uncover findings and implications that are applicable to other contexts, some of our findings may be specific to the respective companies, their manufacturing backgrounds, and their cultural contexts. In addition, the maturity or degree of digitization of a company's manufacturing system and the extent of collaboration in a business ecosystem were not central to our research. Future research could apply more large-scale, quantitative methods to examine the role of digitization maturity in industrial incumbents. Our article aims to better understand the paradoxical tensions faced by manufacturers. In line with paradox theory, it contributes to managers' awareness of these paradoxical forces. Overall, prior research suggests that embracing a paradoxical mindset leads to better performance as it stimulates new thinking and innovation (Lauritzen & Karafyllia, 2019). Therefore, future research using an intervention methodology could more systematically test how a shift to paradoxical thinking would affect individual, project, and organizational performance.

Furthermore, our findings have implications for the discourse of strategic openness (Alexy et al., 2018). The three tension nodes address different levels of openness. The digitization of manufacturing systems requires higher levels of collaboration with internal and external stakeholders, while at the same time demanding control over the manufacturing system. Future research could explore how agile development processes enable new types of experimentation, not only for technical development, but also for testing different strategies for data sharing, open hardware interfaces, or ecosystem integration. Further research could expand the drivers and governance modes for collaboration in a digital business ecosystem, and focus on strategies to overcome the tensions we identified. Our findings also provide an opportunity to complement the existing literature on ecosystems in the context of Industry 4.0 (e.g., Benitez et al., 2020). Adopting a paradox perspective could provide a promising theoretical lens for studying, for example, the positioning strategies of incumbents in emerging industrial ecosystems.

We recognize that manufacturing is complex and rigid. Incumbent manufacturers have long-lived and costly technical infrastructures and highly optimized processes that are barriers not only to digital innovation but also to their core competency. As we show, forcing digital innovation into this manufacturing environment is a non-trivial task. Likewise, digital solutions are intangible and immaterial in nature (Aversa et al., 2021), which triggers different cognitive frames in different individuals. Therefore, further research could improve our

understanding of what cognitive frames exist for digital manufacturing and innovation, and how different educational backgrounds affect these frames. This would support the design of frame alignment strategies for digital innovation projects.

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