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Cascading Digital Options and the Evolution of Digital Infrastructures: The Case of IIoT

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Completed Research Paper

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Abstract

Digital infrastructures provide a space where possibilities for innovation continuously emerge. They are not stable entities but are evolving. Their boundaries are subject to constant negotiation among multiple organizational actors as well as changing connections of digital technologies, operations, and users. In this paper, we explore the evolution of an Industrial Internet of Things (IIoT) infrastructure in a leading manufacturing company. We find that the IIoT infrastructure provided actionable spaces upon which organizational actors discovered opportunities for improving process performance which, in turn, led to investment decisions. We explain this process through the lens of digital options theory and highlight how IIoT infrastructure provides the material foundation for the identification of digital options, how the realization of digital options leads to the emergence of more digital options, and how these "cascading" digital options are implicated in the evolution of IIoT infrastructure. We discuss theoretical and practical implications.

Keywords: Digital infrastructure, digital option, internet of things, industrial internet of things

Introduction

Digital infrastructures, such as social media networks, e-health infrastructures, or digitalized manufacturing systems, provide a space where possibilities for innovation continuously emerge (Hanseth and Modol 2021). Digital infrastructures cannot be defined in terms of fixed functionalities and boundaries (Tilson et al. 2010a) because they are inherently incomplete, underspecified, and open for further development (Tilson et al. 2010b). Thus, research around the evolution of digital infrastructures has provided insights into how and why they grow and develop (e.g., Hanseth and Modol 2021; Henfridsson and Bygstad 2013). Digital infrastructures grow into more complex forms over time as boundaries are renegotiated, components are added, and new domains of use are discovered (Hanseth and Modol 2021). Digital infrastructures are characterized by generativity as new services are being developed and/or more services are being offered (Henfridsson and Bygstad 2013).

Previous literature has highlighted how digital infrastructures neither result from centralized design decisions nor pure bottom-up organic development (Hanseth and Lyytinen 2010). Instead, they evolve through the interplay of bottom-up organic growth and top-down influences, such as architectural decisions (Hanseth and Modol 2021). While previous research has pointed to various dynamics through which digital infrastructures emerge and evolve at larger scales (Henfridsson and Bygstad 2013; Koutsikouri et al. 2018), one important question is how organizational actors discover opportunities to develop and evolve the digital infrastructure into increasingly complex forms. This question becomes increasingly important as companies, especially in the manufacturing sector, implement an extensible infrastructure of Industrial Internet of Things (IIoT) technologies and seek to generate value through these systems (Zysman and Kenney 2018). IIoT-based systems are open and evolving digital infrastructures that connect physical objects and digital technologies to provide services and facilities for a company (Henfridsson and Bygstad 2013; Sisinni et al. 2018). Functions and control mechanisms in IIoT emerge as both physical and digital elements are added to a growing infrastructure (Seidel and Berente 2020).

IIoT-based systems, hereafter referred to as IIoT infrastructures, are characterized by high complexity and heterogeneity. They integrate data collected from different devices with multiple interfaces from various manufacturing processes and through multiple steps (Sisinni et al. 2018). Developing an IIoT infrastructure involves numerous stakeholders with diverse backgrounds from various parts of the organization, including managers, workers, and developers (Jackson et al. 2006). Taken together, the growth of an IIoT infrastructure is a complex socio-technical process involving multiple organizational actors and digital technologies. It changes both organizational practices and functionalities of digital technologies. But what is the process underlying IIoT emergence and evolution as organizational actors interact with the material aspects of IIoT infrastructure and decide when and how the infrastructure should be extended by, for instance, adding new peripheral hardware (e.g., sensors), information processing capacity (e.g., more powerful CPUs), or more advanced algorithms? While previous literature has unpacked the dynamics that explain how digital infrastructures evolve, little is known about how actors drive the discovery and realization of emerging possibilities proffered by digital infrastructures, especially IIoT infrastructures. To further explore how organizational actors drive and influence the evolution of digital infrastructures, we thus ask:

> *How do organizational actors discover and realize emergent possibilities in digital infrastructures, such as IIoT infrastructures, and thus contribute to their evolution*?

To answer this question, we conducted a case study with a manufacturing company that has implemented an IIoT infrastructure for various application scenarios. To make sense of our data and understand how organizational actors interact with the material aspects of IIoT infrastructure in the course of their evolution, we draw from the literature on "digital options" (Sandberg et al. 2014). A digital option represents a specific investment opportunity in IT that supports competitive actions. Digital options are rooted in an organization's capabilities, including technical capabilities, and environmental opportunities. They are thus a suitable theoretical lens to study how emergent capabilities of digital infrastructures are identified and realized. Sensitized by this perspective, we used an adapted grounded theory approach and identified key theoretical concepts and mechanisms that provide a lexicon to theorize about the evolution of IIoT infrastructure.

We proceed as follows. The next section briefly outlines the theoretical background in terms of research on digital infrastructures and the IIoT as a primary example to study digital infrastructures and their emergence in organizations. We also provide a brief overview of digital options as our theoretical lens. Next, we describe our research method. We then describe the findings from our analysis. We discuss these findings and develop a theoretical model of the option-based evolution of IIoT infrastructures before we conclude with a summary and outlook.

Theoretical Background

Digital Infrastructures

Digital infrastructures are socio-technical networks of physical objects and digital technologies that operate on behalf of an organization's goals. They represent arrangements of technologies, users, systems, and processes (Tilson et al. 2010a). Examples of digital infrastructures range from the Internet to social media networks or e-health infrastructures, among many others (see Koutsikouri et al. 2018; Osmundsen and Bygstad 2022). Regardless of the context and purpose, digital infrastructures share a set of distinct features (e.g., Bygstad and Øvrelid 2020; Hanseth and Modol 2021; Osmundsen and Bygstad 2022; Tilson et al. 2010a). First, they are layered and interconnected (Yoo et al. 2010) by given standards and gateways with which new products or services need to align. Second, they are recursive, allowing users to add, change, and remove services on the grounds of existing components. Third, they are scalable; developing new services can happen at low cost and with little effort. Fourth, digital infrastructures are flexible as they are based on malleable code that can be adjusted in response to business needs.

A key point made in the literature on digital infrastructures is that they are continuously evolving and changing. Because they are highly generative, they cannot be defined in terms of fixed functions and boundaries (Tilson et al. 2010a); they are constantly in the making (Langley and Tsoukas 2016). The success of digital infrastructures depends on how adaptable they are (Koutsikouri et al. 2018); they grow and develop into more complex forms over time (Tilson et al. 2010b). At the same time, digital infrastructures as IT artifacts require a certain level of stability for new features to be developed and novel actors to join (Tilson et al. 2010a). This gives rise to digital infrastructure's paradox of change, characterized by the two opposing logics of stability and flexibility. As a result, the boundaries of digital infrastructures are constantly shifting and renegotiated as digital infrastructures grow. Along these lines, research has been concerned with digital infrastructure evolution, studying how a digital infrastructure expands as an "installed base through gradual growth of users and functionality" (Osmundsen and Bygstad 2022, p. 6). Broadly speaking, these works are interested in how a digital infrastructure evolves as heterogenous organizational actors—for instance, managers or organizations—align and adapt a digital infrastructure in response to demands from internal and external environments (Henfridsson and Bygstad 2013). Such processes entail developing novel products and services and socio-technical relations among those who organize around a digital infrastructure (e.g., Bygstad and Øvrelid 2020).

In general, previous literature has found that digital infrastructure evolution is incremental and can take unpredictable turns when possibilities emerge that were not pre-specified by management (Osmundsen and Bygstad 2022). In this stream of research, some works highlight mechanisms that drive digital infrastructure evolution. For example, Henfridsson and Bygstad (2013) suggest that digital infrastructures can evolve in different ways, depending on whether organizations engage in innovation, adoption, or scaling. Others point to growth tactics through which organizations can enable the evolution of digital infrastructures, such as adding new services or providing interfaces that facilitate the connection between products and services (Koutsikouri et al. 2018). The evolution of digital infrastructures has also been linked to tensions (Montealegre et al. 2019) and it has been repeatedly found that digital infrastructures are characterized by a paradox of control (Tilson et al. 2010a): On the one hand, they are dependent on some form of centralized control to ensure connectivity and reliability. On the other, they need to allow for autonomy so that new artifacts, processes, and actors can be enrolled (Hanseth and Modol 2021; Tilson et al. 2010a).

Whereas the existing body of knowledge has focused on the dynamics that explain how digital infrastructures evolve, we know little about the decisions and strategic considerations that drive the recognition and realization of emerging possibilities in the form of new products and services. For example, there is a general tendency in existing research to emphasize the organic growth of digital infrastructures enabled by bottom-up dynamics (Bygstad and Øvrelid 2020). Managerial considerations and rational control, however, have often been neglected (Koutsikouri et al. 2018). Only recently, research has sought to draw a more nuanced picture of digital infrastructure evolution by integrating organic, bottom-up dynamics and strategic decision-making (Zimmer and Niemimaa 2020). Osmundsen and Bygstad (2021), for instance, explain digital infrastructure evolution through an interplay of top-down and bottom-up dynamics that is enabled by cycles of sense-giving (e.g., as managers seek to realize strategic goals) and sense-making (e.g., as users at operational levels perceive emerging possibilities).

Taken together, digital infrastructures are subject to continuous change and evolution as organizational actors perceive new opportunities for adding or refining services. Most existing research has studied how digital infrastructures evolve as services and products are added or refined. Recent research has attempted to unpack why emerging possibilities for new services and products are recognized and realized. The interplay between organic growth dynamics *and* organizational actors' rational and strategic decisions requires more attention.

Industrial Internet of Things (IIoT)

The Internet of Things (IoT) describes “a system of interconnections between digital technologies and physical objects that enable such (traditionally mundane) objects to exhibit computing properties and interact with one another with or without human intervention” (Baiyere et al. 2020, p. 557). The physical object could refer to any type of object (e.g., light bulb, refrigerator) that may be enhanced through its combination with digital technologies, such as sensors, actuators, data storage, processors, software, or wireless connectivity. An IoT technology stack usually includes three layers: the device, the connectivity, and the cloud layer (Porter and Heppelmann 2014). The combination of sensors, actuators, data storage, processors, software, and wireless connectivity enhances everyday objects to exhibit digital capabilities and may result in cyber-physical systems, where one cannot distinguish the digital and physical components any longer (Lasi et al. 2014).

The concept of IoT has received much attention among practitioners and in the computer engineering (e.g., Kortuem et al. 2010; Laya et al. 2014) and innovation management disciplines (e.g., Kiel et al. 2017; Müller et al. 2018). In particular, the *Industrial* IoT (IIoT—note the additional “I”), often referred to as Industry 4.0 or smart manufacturing—the specific application of IoT technologies in manufacturing processes—has been widely discussed in terms of its opportunities for organizations and society (Zysman and Kenney 2018). Companies can benefit from implementing IIoT solutions through performance improvements (Büchi et al. 2020). The implementation of IIoT-based systems triggers changes in the business model of manufacturing companies, especially with respect to key activities and resources, as well as value proposition, creation, and capture (Metallo et al. 2018; Müller et al. 2018). Recent studies have illustrated the business implications associated with the rise of IIoT solutions (Arnold et al. 2016).

In recent years, information systems researchers have increasingly engaged with issues surrounding IoT and IIoT, for instance, through a stakeholder analysis of IIoT ecosystems (Petrik and Herzwurm 2020), by identifying business model archetypes (Endres et al. 2019), and by developing design principles for IIoT-based systems (Hermann et al. 2016). Researchers have developed taxonomies to describe the IIoT platforms’ architectural features (Arnold et al. 2021) and business-to-thing interaction patterns (Oberländer et al. 2018). Nevertheless, critical issues at the intersection of business and technical aspects of IoT have received little attention (Baiyere et al. 2020).

IIoT represents a primary example of a digital infrastructure. As it connects various devices, such as sensors and processing units, to enable operations on behalf of organizations, IIoT-based systems implement core features of digital infrastructures: (1) they operate on the grounds of some standards according to which services and objects are connected with the IIoT-based system; (2) they enable services and products to build on existing components recursively; (3) they allow for scalable solutions by means of new services and products; and (4) they are based on editable software which provides the system with flexibility. We aim to contribute to research on digital infrastructures by exploring the development and emergence of complex IIoT-based systems (which we also refer to as IIoT infrastructures). To this end, we analyze how organizational actors discover and realize the opportunities provided by these systems, how this process is grounded in the systems’ material properties, and how it is related to the investments organizations make.

Theory of Digital Options

Digital options theory (Sambamurthy et al. 2003; Sandberg et al. 2014) provides a suitable lens to study how organizational actors engage with IIoT infrastructure, identify possibilities, and translate these possibilities into growth of the digital infrastructure. Digital options are “a set of IT-enabled capabilities in the form of digitized enterprise work processes and knowledge systems” (Sambamurthy et al. 2003, p. 247) and address specific information requirements of an organization. Previous research has used the theory of digital options to understand the evolution of one IT system (Sandberg et al. 2014) or digital platforms (Rolland et al. 2018). We build on these earlier findings and theoretical contributions to understand the emergence of IIoT infrastructures—increasingly distributed, decentralized, emergent, and perhaps intelligent systems.

The lifecycle of digital options includes three steps: (1) an available option, i.e. a possible IT investment, within a variety of investment opportunities whose potential still needs to be recognized; (2) an actionable option, i.e. an IT investment that has been deemed desirable and feasible after in-depth examination; and (3) a realized option, i.e. an IT investment that has been made (Sandberg et al. 2014). The realization of a digital option to address an existing information requirement in an organization may improve process performance or increase a system's technical and informational offerings (Rolland et al. 2018; Sandberg et al. 2014). The realized digital option may also give rise to newly available options waiting to be recognized (Sandberg et al. 2014). At the same time, a realized digital option may also lead to digital debt, if a realized IT investment leads to technical or informational restrictions or obligations for the future evolution of an IT system (Rolland et al. 2018). Especially for managing digital platforms, a tension between digital options and digital debt can arise for new IT investments in the long term. This tension may be resolved iteratively by eliminating digital debt to develop options or leveraging digital options to resolve debt (Rolland et al. 2018).

Earlier research has identified three categories of information requirements that may be addressed by realizing a digital option: connectivity, uncertainty, and equivocality (Sandberg et al. 2014). In addressing these information requirements, digital options cannot only be components of digital infrastructure but also constitute complementary resources, such as applications, skills, and processes (Bharadwaj 2000; Sandberg et al. 2014).

Research Method

We employ an exploratory single case study approach to study the implementation of IIoT infrastructures and build theory about their emergence and evolution. We chose to study the emergence of IIoT infrastructure in a single case setting, because it allowed us to gain in-depth knowledge about the associated decisions and underlying processes (Yin 2018). The research setting in the large manufacturing company we studied represents a typical case of manufacturing companies in Western Europe, which are transforming their traditional production lines into assemblages of sensors, data storage and processing units, and connected production machinery (Sisinni et al. 2018). Consequently, our case study allows us to gain insights into the evolution of IIoT infrastructure that can be generalized to other manufacturing companies.

Our data collection and analysis draw on the grounded theory method (Strauss and Corbin 1998) as we aimed to derive a theoretical understanding of IIoT infrastructure emergence and evolution grounded in empirical data (Urquhart et al. 2010). Our approach was iterative and characterized by an intensive interplay between analyzing and collecting data (Strauss and Corbin 1998). While we formulated a tentative research question as well as preliminary theoretical hunches for our project early on, we also allowed for the emergence of other important research themes (Charmaz 2014; Seidel and Urquhart 2013). In the following, we outline our data collection and data analysis.

Research Setting

In this case study, we explore the introduction of an IIoT infrastructure at a large stock-listed manufacturing company with a headquarters in Western Europe. It operates in 120 countries and employs more than 25,000 employees worldwide. The company is a market leader in its industry branch and strongly focuses on innovation and early IT adoption. The company's competitive advantage is based on the development and production of high-quality and innovative products.

The case company had been experimenting with implementing predominantly small-scale IIoT solutions for some time. To this end, smaller production machinery was equipped with sensors, data was collected about a production step or process and its parameters, and employees analyzed the data to identify possibilities for improvement within the production process. These first initiatives to implement an IIoT infrastructure took place de-centrally across different plants of the company.

In 2019, the company decided to opt for a large-scale initiative that bundles and scales IIoT across different plants. Consequently, the case organization chose to implement a large cloud solution that could process all information collected by the sensors of the production machinery across plants. Subsequently, employees were encouraged to form teams to develop and implement IIoT use cases. Within these initiatives, new sensors were implemented in the machinery and connected to the cloud; here, the acquired data were analyzed in order to improve production processes and outcomes. These IIoT use cases constituted small, specific extensions of the IIoT infrastructure to address specific problems and questions that production lines faced. These steps, supported by top-level management, were taken to ensure the company's long-term competitiveness by adopting and gaining experience with innovative production technology and developing ways to further increase production quality.

Data Collection and Analysis

In order to gain a comprehensive understanding of the evolution of the IIoT infrastructure, we interviewed thirteen stakeholders between January and May 2021. Each interview lasted between 45 and 55 minutes and took place online using videoconferencing tools. The respondents were situated across the case company's four plants operating in Western Europe. These four plants were the focus of the efforts to implement the IIoT infrastructure. The interviews enabled us to gain an overview of the implemented IIoT infrastructure at the case organization and explore investment decisions taken by organizational actors during the development of the IIoT infrastructure. We also analyzed additional data sources, such as descriptions of IIoT use cases.

The interviews followed a semi-structured approach. They were based on a pre-specified interview protocol but also allowed for flexible adjustments based on the interviewees' responses. We interviewed a variety of employees who had initiated or promoted an "IoT use case"—a specific extension of the IIoT infrastructure—and reported on their experiences in creating and implementing these use cases. We selected interview respondents with the help of the responsible IT manager, who disclosed key stakeholders for IIoT initiatives and the IIoT infrastructure at the firm; subsequently, we engaged in snowball sampling. Table 1 provides an overview of the interview respondents. The interviews were conducted by two or three authors, who met after each interview to reflect on them and write memos.

Period of data collection	Respondent	Role of respondent
January 2021	Respondent 1	Engineer, developer, project manager
	Respondent 2	Product owner IIoT, IT process consultant
	Respondent 3	Head IT
	Respondent 4	Trainee, project manager
	Respondent 5	Project manager
March 2021	Respondent 6	Project manager
	Respondent 7	Project manager, product owner machine connectivity
	Respondent 8	Engineer
	Respondent 9	Engineer
	Respondent 10	Project manager
April 2021	Respondent 11	Developer
	Respondent 12	Head prototyping, coach technology management
May 2021	Respondent 13	Developer

Table 1. Interviews and Respondents

The interviews were complemented by additional data sources, such as diagrams of the architecture of the IIoT infrastructure and use case descriptions. Additionally, we accessed and studied the project management repository of the IIoT infrastructure. These additional data sources enabled a validation of the timeline for different use cases and allowed for the triangulation of our findings. Table 2 provides an overview of the additional data sources and the insights generated from these data sources.

Additional data source	Insights
Diagrams of the IIoT infrastructure	- Understanding of overall architecture of the IIoT infrastructure - Identification of individual components of the IIoT infrastructure - Changes to the architecture of the IIoT infrastructure over time
Use case descriptions	- Insights into requirements and focus of use cases - Description of use case components - Identification of key stakeholders - Validation of interdependencies between use cases
Project management repository	- Construction of timeline of use case implementation

Table 2. Additional Data Sources and Their Insights

For the data analysis, all interviews were transcribed and coded through the lens of digital options theory. Before starting our data analysis, we also considered alternative theoretical lenses (e.g., assemblage theory). However, the theory of digital options fit best with our goal to understand how actors discover and realize emergent possibilities in digital infrastructures. Digital options theory enables tracing the lifecycle of IT investments, such as IIoT infrastructures, in a structured and granular manner. By considering different levels of maturity of digital options—available, actionable, and realized options—the theory of digital options allowed us to trace the process underlying the evolution of the IIoT infrastructure in the case organization, such as by attending to actors' decisions to realize or discard certain IIoT use cases and features. When deciding on a theoretical lens, we first coded five interviews before we considered the additional data sources using the lens of digital options. Once all authors had agreed on the suitability of the chosen theoretical lens, we continued coding the interviews.

The coding was conducted by the first author, who discussed the codes critically with the other two authors. The coding of the interviews took place within multiple, iterative rounds. The initial round of coding helped us identify preliminary theoretical hunches that we recorded in memos. These initial theoretical hunches were then validated and further explored in later interviews (Glaser and Strauss 1967). Some preliminary theoretical hunches were discarded, as new contrary evidence emerged during the interviews. Other initial theoretical hunches were refined as additional, corroborating insights were revealed during the interviews. We also ensured that additional data sources were necessary or helpful to validate the theoretical hunches and concepts gained from the interviews.

Case Analysis

In this case study, we explore the evolution of an IIoT infrastructure. The central component of this infrastructure is a cloud-based IoT platform, which stores data generated by the production machinery and which is used for data processing and analysis. It also enables integration with other third-party systems, connects to web apps to visualize data, and has a database for long-term storage. Data analysis occurs both centrally on the IoT platform and de-centrally on so-called edge devices, if real-time data analysis with low latency is required. The edge devices are small computing units located close to the production machinery. They not only enable real-time data analysis but also perform data transformation to facilitate communication between the IoT platform and the OPC-UA server. OPC-UA is the open standard for connecting machines' sensors in the production lines. As a socio-technical system, the users also form part of the IIoT infrastructure.

The IIoT infrastructure evolved over time, especially through developing and realizing IIoT use cases. To this end, IIoT use cases are specific applications of the IIoT infrastructure in manufacturing. IIoT use cases were predominantly designed to solve a particular problem within the production process. One use case, for example, was designed to prevent the deterioration of the quality of products on a specific production machine for soldering metal. Other use cases were more generic in nature and focused, for instance, on calculating key performance indicators for all machines within a given plant. Table 3 illustrates the nature of an IIoT use case at the case company by means of a vignette. Use cases are implemented by identifying and fulfilling different information requirements.

The case company started to implement the first IIoT use cases in the period from 2017 to 2019. IT management promoted the development and implementation of use cases with the goal of increasing product and production quality, reducing production costs, and expanding production flexibility. This effort was supported by top management. Developing the IIoT infrastructure became a strategic priority in 2019. It involved the restructuring of the IT department and the creation of a centralized IT department. Subsequently, a comprehensive IIoT infrastructure was designed and implemented.

The soldering use case was initiated due to a quality drift during a specific step of the production process, where two parts were soldered together. Respondent 1, an engineer by training, was responsible for the development of the use case. He implemented the use case himself by developing the software code to collect and analyze the data. The reasons for the quality drift were hard to identify because the produced items could not be easily tested without destroying them. Therefore, this was a promising and interesting setting for one of the first IoT use cases. At the time of the interview in spring 2020, the use case was still being refined and extended to consider additional possibilities to improve production quality. Essentially, the use case is centered around automating the collection and analysis of data from various sensors in order to gain in-depth insights into the soldering process. Before the quality drift was discovered, no sensor data was collected and analyzed at the respective production machine. While sensors were already available, the data collection and analysis were only possible on one specific computer within the manufacturing plant. Accordingly, new processes for data collection and analysis were designed and realized by respondent 1. Moreover, the engineer had to acquire an in-depth understanding of the possibilities of the collected data and their relationship to the production step. Today, more than 1400 different sensor data points are collected for each item produced, and the quality of the product could be improved based on the analysis of the temperature curves. The use case was among the first ones to be implemented at the case company. Its realization proved challenging in many respects. One challenge was, for instance, that no labels for the produced items existed. Accordingly, it was necessary to develop a labeling method when the use cases started, so that sensor data could be matched with the individual items. Moreover, data was collected but had to be manually transferred from one computer to another in order to analyze the collected data. This also involved complex processes of data transformation. Once this digital option of automatic data collection had been realized, it could also open up new available and actionable digital options, since the process of data collection could be—with some customization and adjustments to technical requirements—be applied to other production machines. But challenges were not only of technical nature; they also included social challenges, such as convincing other employees that the use case provides value and getting them onboard. Despite these challenges, respondent 1 reported that the use case gained momentum once key stakeholders could be convinced and the top management supported the use case.
Table 3. Vignette: Soldering Use Case

In the following, we present our case analysis, where we explore how the IIoT infrastructure at our case company evolved over time. To illustrate our findings, we offer translated key excerpts from the conducted interviews. We first examine the conditions that enabled IIoT infrastructure evolution. The IIoT infrastructure evolved through the investment in specific standards and services as well as applications of the IIoT infrastructure, which fulfill information requirements. Theoretically, these constitute digital options. In the next step, we, therefore, present findings on the nature and dynamics of digital options of IIoT infrastructure. Finally, we explore the role of key organizational actors in discovering and realizing digital options.

Conditions for IIoT Infrastructure Evolution

One crucial step was the adoption of a large cloud-based IoT platform 2020, which then formed the foundation of the IIoT infrastructure. When comparing different possible solutions for an IoT platform and deciding upon a cloud solution, essential criteria were the **openness of the IIoT infrastructure** and prospective future opportunities for the evolution of the infrastructure. As the following interview excerpt illustrates, IT management felt that a proprietary system could not offer a sustainable solution, which could keep up with future demands:

> *Then we made a decision: Okay, we want a platform. How open should it be? Because we would be faster if we had a predefined one with the overall equipment efficiency, for example, precalculated there and so on. There are well-known manufacturers […] that offer you this! After much deliberation, we decided against it. We said we would use a more open platform […] because we*

> *don't know what the business will need in three years. We don't know what information we want to continue to use. And we don't want to be in the tight corset that a proprietary system is providing us with now. That was the point. That's how we came to this. (Respondent 3)*

Other landmark decisions regarding the features of the IIoT infrastructure relied on similar considerations. Several respondents emphasized the focus on promoting and realizing use cases that offer scalability for the IIoT infrastructure in the future. While the use cases are usually first implemented and tested on one production machine, respondents suggested that those use cases that could later be applied to other production machines were prioritized. This is illustrated by the following interview excerpt from the product owner of the IIoT infrastructure:

> *We actually try to prioritize all cases based on scalability. If we now say that this [use case] really only works for one system, it is much less interesting for us to implement this case. For the majority of the cases I'm thinking of now, we're looking to be able to apply them—at least with slight modifications—to many production machines and even in different plants. (Respondent 2)*

Interview partners also expressed their perception of a **functional threshold** within the IIoT infrastructure. Thus, several digital options had to be realized, that is, information requirements had to be identified, examined, and filled, until the foundation for an easier expansion of the infrastructure as well as numerous, profitable new use cases had been formed. One respondent expresses this perception in the following:

> *I assume that over time and when this platform is used more intensively, also in various plants, it will become a success naturally because you then have a data basis, and you know that this option exists. And then, people will try to implement new processes since the whole foundational structure and the basics, so that you can access the data, have been established. Of course, if you want to display the sensor data somehow and don't yet have a basis for collecting and transporting the data, then that's a much bigger point that you need as a unique selling point in order to amortize it than if everything already exists. (Respondent 11)*

Characteristics of Digital Options Influencing IIoT Infrastructure Evolution

Our analysis highlights that the IIoT infrastructure evolves through the identification, examination, and realization of digital options. Key stakeholders invested in specific standards and services as well as applications to expand the IIoT infrastructure and fulfill existing information requirements. We could observe the investment process of digital options from their first identification as available digital options to their verification as actionable options and their realization. At the same time, we identified several new characteristics of digital options that influenced the IIoT infrastructure evolution.

First, our analysis suggests that digital options emerge in a cascade where the realization of standards, services, or applications laid the groundwork for implementing subsequent digital options, which, in turn, espoused additional, novel digital options. We conceptualize this as the **evolution of digital options in cascades**. The following interview excerpt illustrates this:

> *And this web application has now been used over and over again for, I believe, at least four use cases. So we use the same architecture, where we connect the IoT platform to an infrastructure service, which in turn is connected to the web hook and the web application, where we analyze data [...]. That means that the use case has actually enabled other use cases. (Respondent 2)*

Similarly, the implementation of the OPC-UA interface and the creation of the cloud-based IoT platform led one department to realize the potential use of spare sensors acquired earlier:

> *I think they bought very small sensors a year and a half ago that could now be connected with OPC-UA. [...] Then the request was: OK, we want to use your cloud-based IoT platform to bundle these sensor values to have them available centrally and to visualize them. (Respondent 2)*

Our analysis further illustrates the **varying levels of generality** of the IIoT infrastructure and digital options. The following interview excerpt shows the high level of generality of the implemented cloud-based IoT platform across the different plants:

> *The system worked in Plant X, or it could be scaled very well in Plant X. It is now also used for other plants, although there must be a slight adaptation because they had to accommodate other data types. But in principle, the solution used in the IoT pipeline is identical everywhere. (Respondent 11)*

The key stakeholders of the IIoT infrastructure were well aware that use cases had different levels of generality. Some possible IIoT use cases and their available options solved very specific problems and/or technical requirements and therefore provided features only applicable to one or two production machines. Such use cases could not be generalized and applied to other production machines and were thus terminated. In contrast, other use cases included generic digital options and could be scaled across the different plants of the case company. The level of generality had implications for the digital options arising from implementing one use case. Thus, the implementation of one generic digital option can give rise to several available digital options, while other available digital options may not lead to new digital options. Some digital options realized for the soldering use case described in Table 3 are characterized by a high level of generality. The following excerpt refers to methods that were developed to trace each produced part; it illustrates a large number of available digital options after its implementation:

> *In principle, this is simply also applicable to any product. So, everything that somehow passes through quality control. The idea behind this is to detect the source of the error during production. So, I could imagine that this will actually mature beyond this use case. (Respondent 9)*

In the soldering case, the high level of generality was assessed based on an estimate of its potential to lead to available options in the future. Additionally, other respondents pointed to the rapid growth of the IoT infrastructure, due to the high generality of an implemented use case. The following respondent emphasizes this with regards to a use case that calculated the overall equipment efficiency, an essential indicator in the manufacturing process:

> *And I think we now have a total of 100 machines connected to the system, so connected machines can [...] generate quality data; all machines transmit the data on the overall equipment efficiency, and of course, they also use the same platform. (Respondent 12)*

In contrast, one use case monitoring the condition of tools turned out to consist of digital options with a low level of generality. Thus, the implemented IIoT solution would have needed to be adjusted individually for a small number of products produced on only one machine. Consequently, it was disregarded after some testing; one respondent explains:

> *That was very favorable for us, but it then turned out that we could not pursue this use case any further, because we manufactured 2000 different products on the machine, I think. And they had, let's say, very different properties, which made the analysis way too time-consuming. So, the added value was simply not there for this plant. (Respondent 1)*

As mentioned earlier, digital option theory identifies three possible types of digital options: an available option, an actionable option, and a realized option. Our analysis reveals a fourth type: a **latent digital option**. While some available digital options may be disregarded at a certain point in time, they may be realized later once the necessary resources are available or the required skills could be acquired. This is exemplified in the following use case, where a learning algorithm was first disregarded in favor of a hard-coded program. But then, as the project manager pointed out, the learning algorithm was explored again:

> *And for us, the first thing that was important at the beginning was: Is it at all possible to achieve the 97 percent accuracy we envision? And of course, we wanted the supplier to prove that before we invested 100,000 euros. And the problem with the learning algorithm is that you can only make this statement after you have put in, say, 80 or 90 percent of the work. That means taking pictures, training labels, and so on. It's extensive effort [..]. So simply by using a hard-coded program, we could make this statement faster [and see] whether it works or not. And maybe also to add: A project team is currently working on this topic and trying to build a learning algorithm. (Interview 9)*

The analysis also demonstrates the existence of **feedback mechanisms** for digital options, where the realization of one digital option has implications for other earlier realized digital options:

> *And now, after we have provided the whole pipeline, the entire basic functionality, there are more and more things like that, where then one use case has an impact on the other so that we can use information from one use case to improve the other. (Respondent 11)*

Thereby we can differentiate between two feedback mechanisms. On the one hand, a recently realized digital option may lead to changes/improvements in a digital option realized earlier. This is illustrated by the following respondent, who outlines the relationship between the use case focused on calculating overall equipment efficiency and the soldering use case:

> *Yes, so we started with overall equipment efficiency data, as a first use case. That was the actual key element of our initial hook. Then we just tried the other use case, until we came to the soldering use case at some point. This then passed the prototype status and was developed further. The lessons learned from the soldering use case then flowed back into the data acquisition for overall equipment efficiency data. (Respondent 13)*

On the other hand, the realization of a digital option may not only give rise to new digital options but also increase the available digital options linked to another digital option that was already realized through acquired skills/knowledge:

> *The experience we had gained there, especially with the PLC Broker interface, has taught us a lot about how to implement other things. These were not classic IIoT use cases, but the knowledge we had acquired when working with these data exchange formats or something like that then flowed into use cases that had quality data transfer as a goal. (Respondent 13)*

Organizational Actors Impacting the Evolution of IIoT Infrastructure

Our analysis also emphasizes the importance of particular actors in the organization for the emergence and evolution of the IIoT infrastructure. These actors predominantly were not the users of the infrastructure. First, the developer team functioned as a **gatekeeper.** They gathered information about use cases and then selected the most promising ones. Developers described how they prioritize use cases under consideration of limited available development resources and may give the final approval to implement a use case.

> *So the bundling, the collecting, really refers to several use cases. Precisely because we have relatively limited resources, i.e., development resources. We are only two people at the moment, after one left the team. Accordingly, we have to prioritize this properly to see whether we have to approach certain developments that we are implementing now or later in a more generic way. So that this doesn't become a very, very specific use case for just one individual production line, if necessary, but that this also becomes more generic and globally usable. (Respondent 11)*

At the same time, this gatekeeping proved beneficial for dealing with limited resources for system maintenance and service. The developer team also monitored the IIoT infrastructure in order to keep the system administration and troubleshooting at a manageable level:

> *But as a team, we are also responsible for ensuring that it [the IIoT infrastructure] runs stable over the long term. In addition to a use case or feature that we implement, we always need a lot of time afterward so that we can also implement additional features. So we always strive to ensure that the maintenance effort we have in the team does not increase. Because otherwise, at some point, all we do is system administration and troubleshooting when something doesn't work. And this kind of basic requirement given in this team, we let it flow into the project and then also say openly and honestly: We can deliver that. But the consequence is that we can't do anything else. That means we try to find a solution with our colleagues that we think is the best for the company, i.e., not the 100% approach, because, at some point, the costs increase exponentially, but somewhere we find a healthy middle ground. (Respondent 13)*

It also became noticeable that some employees play an essential role in driving the IIoT use cases forward. Without their effort to promote an innovative idea in order to extend the existing IIoT infrastructure, some use cases would not have been successfully implemented. Based on existing literature, we classify them as **champions** for the IIoT infrastructure, that is, actors who promote the investment in a digital option or the realization of a use case vigorously:

> *I am now known internally as a data expert for this project. Before that, I would say, no one dealt with it, and I could only take what I was told and still had to find out a lot myself. (Respondent 6)*

This role is also explicitly confirmed by one respondent, who was not only essential for the success of the use case but had an impact on the future strategy of a whole business unit. Asked in the interview whether he initiated and promoted the project, he answered:

> *Yes, even more. Even more now. So there are different huge areas, so there is a complete manufacturing unit. And, based on these findings, the entire strategy, how this unit would like to develop, was based on this use case. (Respondent 1)*

Additionally, he also outlined the resistance he faced when first starting out and identifying as well as realizing the use case:

> *So I think one of the biggest hurdles is always with a new technology like this is that you have to be able to convince people that you can see something based on the data. (Respondent 1)*

Table 2 summarizes the key concepts we identified through our analysis.

Concept	**Definition**	**Level/ perspective**
Openness of IIoT infrastructure	IIoT infrastructure is non-proprietary, flexible, and scalable to allow for extension and adaption in the future.	IoT infrastructure
Functional threshold	Several digital options have to be realized before a functional threshold is reached that offers the opportunity to fully exploit the potential of an IIoT infrastructure.	IoT infrastructure
Cascading digital options	The realization of one digital option offers up new available options (i.e., new opportunities to extend/improve an IIoT infrastructure) that did not exist before.	Digital option
Generality of digital option	Digital options address requirements at different levels of generality to allow for the emergence of numerous other digital options. One example of a generic digital option is the cloud-based IoT platform.	Digital option
Latent digital option	A digital option that has been disregarded at first but may become an actionable digital option later.	Digital option
Feedback mechanism of digital options	The realization of a digital option may also prompt changes in another digital option or extend the available digital options linked to another realized digital option.	Digital option
Developer team as gatekeeper	The realization of digital options depends upon the approval or prioritization of the IT development team, who acts as a gatekeeper.	Organization
Use case leaders as innovation champions	The identification of available digital options and their realization is promoted by actors within the organization. As these may need to overcome resistance within the organization, they act as innovation champions.	Organization

Table 4. Conceptual Definitions

To summarize, our case analysis highlights how an IIoT infrastructure evolves by means of digital options. To this end, we presented key findings related to (1) the IIoT infrastructure (openness, functional thresholds); (2) the nature (nesting, latency, level of generality) and dynamics (cascading effects, feedback mechanism) of digital options; and (3) the role of key organizational actors to discover and realize digital options. Next, we use these concepts to move towards a theoretical model of IIoT evolution as a substantive case of digital infrastructure evolution.

Discussion

Our study highlights how an IIoT infrastructure evolves through the discovery and realization of digital options. These digital options, in turn, arise in response to specific information requirements identified in the organization (Sambamurthy et al. 2003; Sandberg et al. 2014). Taken together, this view yields several implications that explain how and why digital infrastructures grow into more complex forms over time (Tilson et al. 2010a). To this end, we present six conjectures that we derive from our findings.

First, we find that organizational actors identify and realize digital options in the case company's IIoT infrastructure in a step-by-step approach. Organizational actors recognize available options by discovering how novel combinations of sensors, actuators, and information processing capabilities, located in the cloud-based IoT platform as well as edge devices, can help satisfy information demands. These identified available digital options are examined with respect to their feasibility and desirability. If evaluated positively, they become actionable options. Organizational actors may then realize these digital options:

> ***Conjecture 1:*** *Digital options in IIoT infrastructures are realized through investments into specific configurations of sensors, actuators, and novel information processing capabilities (services).*

If realized, digital options lead to an extension of an IIoT infrastructure. One key insight is that in an IIoT infrastructure, digital options can accumulate and thus lead to cascading digital options and growth. Individual IIoT use cases at our case company are linked together as the functionality and required digital infrastructure developed for one use case offers novel digital options for other use cases. Realized digital options in terms of implemented configurations of sensors, actuators, and information processing capacity provide the foundation of combinatorial innovation (Yoo et al. 2012). However, the key is, that these innovations necessarily require investments to be realized. We suggest:

> ***Conjecture 2:*** *The discovery and realization of digital options through investments evolves in cascades where realized digital options drive subsequent digital options.*

Cascades of digital options are strongly linked to the overall orientation towards openness that was favored by the key stakeholders at the case company when designing and implementing the IIoT infrastructure. Thus, for the IoT platform, IT management preferred an open cloud solution over a proprietary system in order to enable high flexibility and a wide range of digital options arising in the future. The IT department's software developers also internalized the principle of openness, as they favored the implementation of digital options with a high level of generality to keep the overall infrastructure open for future developments and generate opportunities for numerous new actionable digital options. We suggest:

> ***Conjecture 3****: The emergence of new digital options on the grounds of a realized digital option presupposes the general orientation of the digital infrastructure towards openness as well as the prioritized realization of digital options with a high level of generality.*

The openness of platforms, such as the cloud solution, has been emphasized in the literature on digital platforms (Tiwana et al. 2010). Our case study demonstrates that this openness needs to extend beyond the platform (here: the cloud) itself and constitute a more general orientation towards openness in the organization to allow for the successful evolution of the IIoT infrastructure.

We now turn to the dynamics underlying the evolution of IIoT infrastructures. An IIoT infrastructure evolves through an interplay of bottom-up and top-down dynamics. At the case organization, employees drove initial initiatives in a bottom-up fashion. Subsequently, the associated small-scale efforts in promoting and developing use cases revealed the need for a wide-scale IIoT infrastructure. In response, IT management decided to implement a cloud-based IoT platform. This top-down decision of IT management was a significant antecedent for the evolution of the IIoT infrastructure. It set the stage for the emergence of numerous smaller available digital options. Working in teams, employees developed and realized these digital options through the development and implementation of specific IIoT use cases across the different plants of the case organization. Accordingly, we find:

> ***Conjecture 4****: The realization of digital options in IIoT infrastructures is based on a recursive combination of bottom-up and top-down dynamics.*

Existing literature has emphasized the role of bottom-up, employee-driven efforts for digital innovation (Opland et al. 2020; Reibenspiess et al. 2022). Similarly, the importance of a digital business strategy oriented towards enabling digital innovation and digital infrastructure evolution, a top-down approach, has been emphasized in the past (Bharadwaj et al. 2013). Yet, our case study identifies how bottom-up and top-down approaches interlock for the successful evolution of a digital infrastructure. IT managers must be willing to allow and encourage employees to create and develop IIoT use cases independently. But at the same time, IIoT infrastructures are part of a broader change process inside the organization, and IT managers must pave the way for its success by ensuring an appropriate strategic direction through top-down decision-making. While Osmundsen and Bygstad (2021) explain this interplay of bottom-up and top-down dynamics in the evolution of digital infrastructure through sense-making and sense-giving, we offer another explanation through the theoretical lens of digital options. Additionally, we identify a significant role of employee-driven efforts, not only for digital innovation but also for digital infrastructure development.

The strategic considerations crucial for the successful evolution of IIoT infrastructures are also substantiated by the existence of a functional threshold for digital options. The full potential of an IIoT infrastructure can only be reached after a functional threshold is overcome and numerous digital options have been realized. Moreover, our case suggests that flexibility in the evolution of the IIoT infrastructure is another critical aspect associated with strategic considerations regarding IIoT infrastructures. The potential of some digital options is not evident when they first arise but becomes only apparent after other digital options have been realized (a phenomenon we labeled as latent digital options). Similarly, the potential of available digital options may change through feedback mechanisms when other seemingly unrelated options are realized. We suggest:

> ***Conjecture 5:*** *The realization of digital options needs to be considered by stakeholders within a long-term perspective and by allowing for fluidity in the evolution of IIoT infrastructures.*

This conjecture adds a novel perspective to the existing literature on digital options, which has so far considered only three types of digital options—available, actionable, and realized—with a linear investment decision process (Sandberg et al. 2014) We illustrate that digital options may not be realized by following a linear process. Instead, the evolution of an IIoT infrastructure is characterized by feedback mechanisms between new and realized digital options. The realization of a digital option may, therefore, also alter the potential investment possibility for seemingly unrelated components of an IIoT infrastructure and change the trajectory of IIoT infrastructure evolution.

Analyzing how the IIoT infrastructure evolved in the case organization, we identified actors to assume several roles in promoting the realization of digital options. In filtering out and prioritizing digital options with a high level of generality and the potential to offer numerous possibilities for the future development of the IIoT infrastructure, software developers in the IT department acted as gatekeepers for the evolution of the IIoT infrastructure. These gatekeepers collect information on available digital options and filter out the most promising options to be realized by the organization (de Brentani and Reid 2012). At the same time, employees identified promising available options and promoted their realization. By promoting these digital options and overcoming resistance among other employees, these champions (Beath 1991; Drechsler et al. 2021) were essential for the success of the evolution of the IIoT infrastructure. Thus, we find:

> ***Conjecture 6****: The identification and realization of digital options in IIoT infrastructures are tied to actors who serve as gatekeepers and champions.*

This observation not only extends to our understanding of the evolution of digital infrastructure but also adds a novel perspective to knowledge on the realization of digital options. While previous literature has mainly focused on understanding the lifecycle of digital options (Sandberg et al. 2014) or the interplay of digital options and digital debt (Rolland et al. 2018), our case study underscores the relevance of understanding dynamics at the level of actors for the evolution of an IIoT infrastructure. It illustrates the interaction between actors taking up different roles in the investment in a company's digital infrastructure.

To summarize, our study suggests three main contributions to information systems research. First, we contribute to the literature on digital infrastructure by studying the strategic considerations and investment decisions of organizational actors tied to digital infrastructure evolution. Prior literature has predominantly provided insights into the mechanisms underlying digital infrastructure evolution and has foregrounded the organic growth of infrastructure (Bygstad and Øvrelid 2020). Only recently, the discourse has turned to studying the dynamics of decision-making contributing to digital infrastructure evolution (e.g., Osmundsen and Bygstad 2022; Zimmer and Niemimaa 2020). We extend this stream of research by explaining how bottom-up and top-down dynamics interact as an IIoT infrastructure grows into more complex forms. Additionally, we show that actors take up the roles of gatekeepers and champions in enabling digital infrastructure evolution.

Second, we extend the theory of digital options. In our case study, we identified a number of new theoretical concepts that advance our understanding of the dynamics of investment in digital infrastructure and possibly information technology in general. We identify that the discovery and realization of digital options evolve in cascades and are characterized by feedback mechanisms and a functional threshold. By identifying these concepts, we challenge the assumption of a linear process of digital option realization, implicitly underlying digital option theory so far. Moreover, we identify the level of generality of digital options and the latent digital options as two new concepts, essential for a comprehensive understanding of explaining investment decisions in digital infrastructure through the theoretical lens of digital options.

Finally, we contribute to the information systems discourse on IIoT. We explain the evolution of an IIoT infrastructure from a socio-technical perspective. In doing so, we complement existing research that has mainly focused attention on technical issues. We contribute by exploring how organizational actors discover and realize the opportunities provided by an IIoT infrastructure, how this process is grounded in the systems' material properties, and how it relates to the organizations' investment decisions.

Additionally, our study offers managerial implications for companies that leverage—or consider leveraging—IIoT. To this end, we illustrate important conditions for IIoT infrastructure evolution, such as openness of the infrastructure and functional threshold. We also point to the specific characteristic of digital options influencing IIoT infrastructure evolution, such as cascading digital options and feedback mechanisms. These findings can help companies decide when and how to further develop their IIoT-based systems. Additionally, our identification of the significant role of specific organizational actors in impacting the evolution of IIoT infrastructure can raise awareness in companies and encourage them to create fitting organizational conditions for innovation champions and gatekeepers to impact IIoT infrastructure evolution.

Conclusion

IIoT -based systems are digital infrastructures that allow organizations to implement more flexible and less error-prone manufacturing processes. One fundamental assumption is that IIoT infrastructures are open and extensible and enable organizations to account for changes in their environment. Our study highlights how the emergence and evolution of IIoT infrastructures follow a cascading growth pattern grounded in the continuous discovery and realization of digital options in terms of novel configurations of sensors, actuators, and information processing capabilities in response to changing information requirements.

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