administrative sciences

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Prototyping for Digital Innovation: Investigating the Impact of Digital Technology on Prototyping Elements

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Abstract: Prototyping is an important part of any development activity since it supports communication and knowledge creation among the members of the developing organization. Although prototyping is well established in the development of physical products, less is known about its use and effect on digital service innovation and development. Since digital technologies today are embedded in almost every level of an organization, from its processes to its offerings, it can be argued that it is crucial for an organization to be able to handle not only digital aspects of prototyping, but also physical and digital aspects simultaneously. This study addresses this need by exploring the impact of digital technology on prototyping, answering the research question "How does digital technology affect the different elements of prototyping?" By taking a comprehensive view on prototypes, implications for development are analyzed and developed based on the complex nature and ontology of digital technology. The result encompasses a set of nine different propositions for digital prototyping which contributes to both academia and the work of practitioners.

Keywords: digital transformation; digital technology; prototyping; prototype; agency; semiotic binding; ontology

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Citation: Wenngren, Johan, and Aya Rizk. 2024. Prototyping for Digital Innovation: Investigating the Impact of Digital Technology on Prototyping Elements. *Administrative Sciences* 14: 142. https://doi.org/10.3390/admsci14070142

Received: 24 April 2024
Revised: 2 June 2024
Accepted: 3 July 2024
Published: 5 July 2024

1. Introduction

Digital technologies are transforming organizations and societies. In recent years, especially with a pandemic catapulting its accelerated diffusion, these technologies changed how we work, collaborate, and socialize (United Nations 2021). The myriad of digital technologies is therefore changing how organizations develop and innovate, with increasing pressure to use digital technology to compete and survive in the global marketplace (Mandal 2020; Marion and Fixson 2021). As more products and services are embedded with such technologies, we turn to the digital innovation discipline to understand the complex outcomes and processes that take advantage of these technologies (Nambisan et al. 2020).

Digital innovation can be described as "the creation of (and consequent change in) market offerings, business processes, or models that result from the use of digital technology" (Nambisan et al. 2017, p. 224). Such a view encompasses both the discovery of new opportunities and the development of products and services as part of the digital innovation process (Fichman et al. 2014). And while it may be argued that a change in form does not necessarily mean a change in type, scholars have repeatedly pointed out the unique nature of digital technology and how the ontology of the digital is fundamentally changing the dynamics of digital innovation (Baskerville et al. 2020; Kallinikos et al. 2013; Lyytinen et al. 2020). They also have profound effects on innovation management and the various stages of the innovation process. The early stages, especially, are susceptible to uncertainty about both the user and the future solution (Parida et al. 2017). One such stage that we focus on is prototyping.

Prototyping, as a fundamental approach to development and innovation, has a positive influence on the fulfillment of the organization's goals and objectives (Thomke 2003), the efficiency of the team (Exner et al. 2015), and the lead time of development (Kleinsmann and ten Bhömer 2020). Yet, developing concepts and prototypes for new digital solutions is different from doing that for traditional (non-digital) ones since digital technology brings additional dimensions and new aspects to be taken into account (Ramsgaard Thomsen and Tamke 2016). Recently, scholars began tackling the role of prototyping in developing digital solutions to address this gap in the literature, focusing primarily on physical products, and the practice dominated by pervasive digitalization (Kleinsmann and ten Bhömer 2020). Consequently, while prototyping is widely used in mature areas, like the development of non-digital goods and services (Passera et al. 2012; Razek et al. 2018b), it is still under-explored for digital solutions (Blomkvist 2014; Blomkvist and Holmlid 2010; Winby and Mohrman 2018) and their contexts (Camburn et al. 2017).

To this end, the purpose of this paper is to explore the impact of digital technology on prototyping in order to fill the identified research gap and answer the research question "How does digital technology affect the different elements of prototyping?" We answer this research question by employing a qualitative case study research design. Our empirical analysis reveals various implications that digital technology has on the representation, communication, and motivation, among the actors involved in prototyping. On the conceptual level, this paper advances our understanding of prototyping for digital innovation by unraveling the key characteristics of digital technology and fundamental elements of prototyping. When integrated, various propositions are developed on the impact of such technologies on prototyping.

The paper is organized as follows. Section 2 reviews related work on prototyping for digital and hybrid solutions, as well as digital prototyping. Section 3 lays the conceptual foundations for the analysis with emphasis on two main dimensions: (a) characteristics of digital technology, and (b) prototyping elements. Section 4 presents the research method and analytical framework derived from the above dimensions. A case analysis that illustrates our empirical findings is presented in Section 5. Section 6 then discusses the findings towards our set of propositions and the study's implications for research and practice. Conclusions, limitations, and future research are provided in Section 7.

2. Related Work

Identifying business opportunities has been shown to be one of the most important abilities for entrepreneurs and companies to become successful in the long-term (Nicholas et al. 2013). Digital technology has a layered architecture that blurs the conventional boundaries of constituting elements, compared to traditional products and services (Yoo et al. 2010). This leads to an organizational need for being better equipped at identifying opportunities that could arise during the development of digital technology, specifically across these elements (Yoo et al. 2010). Opportunities may be recognized instantaneously but are foremost a development process of their own where ideas and needs are consciously transformed into opportunities (Ardichvili et al. 2003). Whether this is a systematic process or happens by accident, it includes factors that link social components to technical processes, such as recognizing socio-technical patterns or exploiting casual acquaintances (Ardichvili et al. 2003).

Traditionally, what used to be differentiated as either goods or services (Vargo and Lusch 2004) are today often a mix, consisting of different types of material and nonmaterial components combined in an offering or a solution (Annarelli et al. 2016; Faulkner and Runde 2019). Fundamental approaches for developing and designing solutions from open-ended problem statements (i.e., innovation) have a strong connection to aspects such as creativity, tacit knowledge, and interaction (Brown and Katz 2011) and even if such approaches take on different expressions depending on the context (i.e., non-digital or digital offers) they have common features and structures. Communicating using analogies or developing by means of pre-types are structures that are evidential for most design contexts and can be brought together in the activity of prototyping, or simply put, to create prototypes (Schrage 1996).

Prototyping for product development is traditionally and innately more focused on physical requirements and principles of how to achieve a specific solution (Cross 1997), i.e., sketches, functional prototypes, proof-of-concepts, demonstrations, mock-ups, etc. Service prototyping is, in contrast, more focused on achieving a specific value or apprehending the user experience (Blomkvist and Holmlid 2010), i.e., "experience prototyping", service blueprints, service journeys, bodystorming, service walkthroughs, etc. Prototyping for digital innovation would therefore inherit all the above-mentioned classes of techniques as well as carving out its own unique needs. Yet, it is not fully known what these needs are or their implications for prototyping.

Recent studies have examined how emerging digital technologies such as virtual and augmented reality can be used to improve the service development process (Bae and Leem 2014; Boletsis 2018; Razek et al. 2018a), support the adoption of new digital co-creation practices (Kostis and Ritala 2020), and support experiential learning (Santos et al. 2013). Other studies have focused more on a mixed approach where being able to quickly move between digital and more traditional prototyping technologies in a lab environment has been shown to be promising for the ability to reach a more comprehensive understanding of specific service situations (Meiren and Burger 2010; Rontti et al. 2012). Nevertheless, setting up such environments is cumbersome and mostly focuses on high fidelity and high resolution of service prototypes (Razek et al. 2018b). Also, an important implication of prototyping in a virtual environment is that the development team must pay attention to the fact that the validity of the result depends upon the accuracy of the digital reality that is created, i.e., the reality in the lab is still artificial (Meiren and Burger 2010).

While such empirical studies contribute to the discourse of digital prototyping and their implications for digital innovation, empirical accounts of how the specific characteristics of digital technology affect the various aspects of prototyping beyond the lab environment are still limited. This study targets this gap in the literature and in the following section, we describe the theoretical foundations of digital technology's characteristics and prototyping; the two dimensions informing our analytical framework.

3. Conceptual Background

3.1. Digital Technology

Digital innovation may refer to the use of digital technology in the process of innovation, or to the outcome of innovation (i.e., a product/service, process, etc.) that are digitally ingrained. Kallinikos et al. (2013) define digital objects as editable, interactive, reprogrammable, and distributable. Such objects are embedded with capabilities such as communication and memory (Yoo et al. 2010). Digital objects can also be defined in terms of their material and nonmaterial properties, and the subsequent hybrids when their components possess both properties (Faulkner and Runde 2019). Together, these properties make digital solutions distinct from earlier generations of IT-driven ones as they have been observed to be open-ended or incomplete upon their release (Monteiro and Parmiggiani 2019). To better understand digital solutions in the context of digital innovation, we take a step back and examine the characteristics of digital technology. Nambisan et al. (2020) define three characteristics that contribute to (and challenge) our assumptions of digital innovation in general and prototyping specifically.

First, they argue that digital technology has an *agential core* due to its highly mutable and recombinable components, as well as the flux of emerging affordances, which change the role of technology in social contexts, leading to new forms of joint socio-technical agency (Tilson et al. 2010). This type of autonomy and agency may be obvious in new forms of knowledge production systems relying on technologies such as AI and automation (van den Broek et al. 2021), but they are also observed in studies of other digital technologies (e.g., see Freude et al. 2020 on agency in VR environments). Joint sociotechnical agency impacts both the scope and range of the role of technology in extant theories that remain unaccounted for (Nambisan et al. 2020).

Second, digital technology paves the way for a layered modular architecture, where there is separation between physical devices, networks, services, and content layers (Yoo et al. 2010). This separation leads to novel semiotic bindings between the various content or data representations and their contextualized meanings for the target actors who use them. Monteiro and Parmiggiani (2019) refer to this separation quality as the liquefaction of material digital objects, and accordingly suggest that it fundamentally changes the perceptions of surrounding phenomena—a key notion in prototyping. Such semiotic bindings, unlike their physical counterparts, are only "socially approximate" (p. 6), which leads to actors in different contexts finding different ways of binding the data/content to their social context in different and intermediate ways (Hukal and Henfridsson 2017).

Third, objects are increasingly first created as digital objects and then physically manifested, whereby the pervasiveness of digital technology is leading to a new "digital default". This is known as the ontological reversal of digital technology (Baskerville et al. 2020). Ontological reversal challenges the common assumption in classical technology and innovation theory that digital representations reflect physical objects and relationships that exist in reality (Baskerville et al. 2020). On the contrary, it is often that "physical objects are the outcome of 'printing' digital objects onto physical bearers" (p. 21), such as in the cases of 3D printing or printing a booked flight ticket. Ontological reversal also challenges what we know about physical prototypes and prototyping activities, as we detail in the following section. Together, these three characteristics are assumed to change the nature, processes, and outcomes of digital innovation as well as how we conceptualize and theorize digital prototyping (Lyytinen et al. 2020; Nambisan et al. 2020).

3.2. Prototyping and Prototypes

Prototyping is the process that includes design activities "characterized as a goal oriented constrained, decision-making exploration, and learning activity" (Gero 1990, p. 28). A large portion of the literature suggests that the process of creating prototypes is equally important as the prototype itself, especially for innovative design (Cross 1997; Dorst 2011; Camburn et al. 2017). For innovative design, prototyping can explain how the team makes sense of new knowledge and create new solutions out of open-ended problems (Klein et al. 2006a, 2006b). This activity typically has explorative or validating purposes (Cross 1997), or similarly divergent or convergent abilities (Kleinsmann and ten Bhömer 2020), meaning that it can be used to both understand the problem and its context, but also to create possible solutions, i.e., problem setting versus problem solving. In the context of digital innovation, this dichotomy also relates to accounting for untapped opportunities in asynchronous development (i.e., when digital traces are collected but the variables are yet to be known) as opposed to developing solutions synchronously with known variables and relevant data (Rizk et al. 2020). If the team can investigate a phenomenon that they have decided upon (known variables) but at the same time can be open and make room for new perceptions of the same phenomenon (unknown variables) they are more likely to find a fitting solution (Jensen et al. 2017).

As for prototypes, Maher et al. (2011) illustrate that three fundamental elements of a design situation are (a) a representation of (parts of) a problem, solution, or both; (b) the communication between actors that affects the representation; and (c) the motivation for why actors engage with, communicate around, and affect the representation.

Prototypes are typically physical visualizations but may also be abstract concepts such as narratives. They are embodiments or **representations** that development teams create for specific purposes, i.e., to evaluate the look or feel, communicate, test, etc. (Exner et al. 2015). It can be argued that an important feature of a prototype is the balance between the resource that the team spends and the knowledge they gain, implying that the purposes must be aligned with the effort (Passera et al. 2012). Hence, the creation of primitive forms of envisioned ideas may be a natural activity for designers but should be aligned with other design principles, e.g., setting up goals or learning (Leifer and Steinert 2011).

A prototype also emphasizes the context, since the prototype itself can have many different purposes depending on how it is used (Aversa et al. 2018). As context gives us a reference of how to interpret the prototype, so does also the starting point of the process, since "the information needed to understand the problem depends upon one's idea for solving it" (Rittel and Webber 1973, p. 161). This mindset has eventually improved our way of looking at how to define problems and how to solve them, as a sequential process from problem to solution, to a co-existence of problem and solution in an iterative process (Dorst 2019). On the other hand, every team member has their own interpretation of the prototype, adding to its contextual diversity (Brereton and McGarry 2000). Eventually, interaction with users or other actors triggers new insights and the representation changes accordingly. To make sense of a prototype, Ruecker (2015) emphasizes the importance of a defined purpose of the prototype, e.g., research, production, or provocation. The use of systematic processes is therefore a necessity to balance our efforts and help us come to conclusions (Jacoby and Rodriguez 2007), and likewise selecting a suitable method by being able to reflect upon what is to be learnt from the prototype (Real et al. 2021).

In addition to this systematic process, teams that utilize prototyping develop a "language" within the team which enhances **communication** and makes it possible to align expectations, beliefs and perspectives (Brereton and McGarry 2000; Schrage 1996). The representation that the prototype makes out enables the team members to not only communicate with each other, but also to interact with the prototype itself. At first, the interaction is only indirect, through verbal communication between team members and the mental representation that they share, but later it also occurs through direct physical interaction.

Another way of explaining the communication or interaction in the team and around the prototype is through the creation of frames (Dorst 2011). Frames are created by team members to draw attention to specific parts of the problem–solution space (Dorst 2011). Accordingly, assumptions play an essential role in the creation of a frame which is then shaped by reasoning in the team until it is agreed upon (or discarded). For products, functions and physical characteristics are typical subjects to be tested, but for services it may be easier to look for values, or the experience that the service provisions (Blomkvist and Holmlid 2010; Kleinsmann and ten Bhömer 2020). To develop new knowledge, and subsequent innovation, it is important for the team to both frame a situation but also to do this in several sets or iterations, i.e., to reframe, although studies show that this progression is not always the case (Wenngren et al. 2016). Often frames are poorly understood, challenged, or questioned, which could lead to inaccurate frames that persist too long, or the opposite, where the team misses out on important opportunities by testing a frame too early, i.e., a goal orientation.

As mentioned previously, the prototyping process assumes a specific purpose, in the form of problem setting or problem solving, set by the design team. However, the choice to engage with the prototype and the team is bounded by the stakeholders' **motivation** to do so. In a prototyping situation the chosen variables are often connected to the social properties of the situation that are to be improved and may be difficult to come across by other methods (Houde and Hill 1997), and, hence, the experience of using the prototype play an important role in user-centered development (Buchenau and Suri 2000). In this interplay with different stakeholders, the prototype becomes an important boundary object between different social worlds (Star and Griesemer 1989). Boundary objects "are non-human actors that enable groups without shared knowledge or goals to work together towards an end, enabled by differences and similarities in actors' understanding of the object" (Thompson 2016, p. 2). The use of boundary objects in digital innovation enables stakeholders' views to be integrated and stabilized into the outcome of digital innovation (cf. Rizk 2020) serving their motivation to engage.

4. Research Method

To answer the abovementioned research question, a qualitative explorative case study research approach is adopted. Empirical studies investigating digital prototyping are limited, and the phenomenon itself is one of a contemporary nature, which motivates the qualitative and explorative orientation. In addition, the boundaries between the prototyping activities, the prototype itself, the digital technology, and the context are not easy to separate in practice, which are ideal conditions for case study research (Yin 2018). The following sections detail the case context, data collection, and analysis.

4.1. Case Context

This study uses empirical data collected within the frame of a smart city project called OrganiCity, which is a concluded EUR 7.2 million project funded by the European Commission's Research and Innovation framework program. The scope of the project was to build an Experimentation-as-a-Service (EaaS) platform where third-party teams innovate using Internet of Things (IoT), urban data, and digital co-creation tools in three European cities: London, Santander, and Aarhus. The project provided the platform and cascaded funds to teams that are interested in prototyping in one of these cities. The funding was cascaded in two rounds of open calls. A total of 37 teams (made up of 2–7 members each) have been funded by the project with up to EUR 60,000 each. The teams executed their experiments over a period of up to 6 months: the first round was from October 2016 to April 2017, and the second round was from October 2017 to April 2018.

4.2. Data Collection

The primary data collected for this study come from semi-structured in-depth interviews conducted with the team leads one month before finalizing their respective experiment. Interviews are used to collect rich data about a phenomenon in its natural context (Kvale 2008). Semi-structured interviews are guided by a set of questions that are designed beforehand in order to address relevant information, in addition to open-ended questions to account for unexpected information (Hove and Anda 2005). A total of 24 teams agreed to be interviewed: 13 from the first round and 11 from the second. The selection of the respondents was based on purposeful sampling (Patton 2005), where the respondents were knowledgeable about both the technology and prototyping process, which makes it suitable to study the target phenomenon and unit of analysis (Coyne 1997). Accordingly, initially, the interviews were scheduled with the team lead, and they invited other team member(s) who were needed to provide details about the areas that the team lead was not familiar with. Respondents from all three cities are represented in the sample.

All interviews were conducted online through Skype or Google Hangouts, and were voice recorded and later transcribed. An interview protocol containing open-ended questions was used, addressing different themes around the processes, activities, and tools and technologies used throughout their 6-month experimentation period. Follow-up questions were asked when needed to clarify and/or expand on a certain technology or activity. Interviews lasted between 45 and 115 min. All interviews were conducted in English, transcribed, and sent to the team leads to confirm accuracy.

In addition to the interviews, we collected secondary data from the teams to better understand their prototypes. The secondary data sources include their initial proposals, planning documents and progress reports, and public communications such as blogs. The secondary data was particularly important because they used these sources to document their co-creation journeys with their respective end-users in almost real-time, which is relevant to prototyping. In addition, some teams chose to share other materials such as their developed prototypes or user engagement workshop materials.

4.3. Data Analysis

The interview transcripts were analyzed iteratively following an abductive reasoning approach (Svensson 2011). This means using the existing literature to inform our operationalization of the chosen concepts but generating theoretical propositions inductively that illustrate the relationship between these concepts. To answer the research question, our end goal is to develop relational propositions that elaborate the effects of digital technology on prototyping. Leshem and Trafford (2007) emphasize the importance of the interpretation of concepts, but also the analysis of the relationship between them. By performing these steps, researchers can demonstrate a "*unity within appropriate theories, direction to research design and accompanying fieldwork, and a coherence between empirical observations and conceptual conclusions*" (Leshem and Trafford 2007, p. 101). To achieve this purpose, we conducted our analysis as follows.

First, the three characteristics of digital technology were used to guide the first round of analysis, i.e., every excerpt relevant to one of the three characteristics was highlighted for further analysis. Second, each of these excerpts was coded with open codes, with the aim to identify emerging concepts under each characteristic. The guiding question in this analysis was how that specific characteristic (e.g., the described agential core of the technology) impacts the prototype and the activities shaping it. These concepts were further examined, compared, and discussed between both co-authors to find inductive patterns between them and the overarching characteristics. The so-called intermediary concepts from the analysis can be seen in Appendix A. At this stage, patterns pertaining to the prototype's representation, communication, and motivation emerged, and accordingly the excerpts were reorganized to be classified along these three clusters, leading to a 3 × 3 analytical framework used to refine the analysis, explained as follows.

4.4. Concept Operationalization

The existing literature suggests that prototyping is a means to develop knowledge by design. In this paper, we use the following operationalizations in our analytical framework that merges the characteristics of digital technology and elements of prototyping. Prototyping is the activity, focused by a **motivation** (purpose), which lets the development team, based on its own previous experience, **communicate** with other actors in a specific realm (context) using a (set of) **representation** of the envisioned design. Central to the activity is the creation of representational frames, which the team can later test in a real-world setting (reframing), and consequently develop knowledge. It is important to note that these elements, such as communication, mainly concern the prototyping activity and its corresponding design setting, rather than the final solution the team is aiming to achieve. By investigating the characteristics of digital technology and elements of prototyping, we formally define and operationalize each of these dimensions in Table 1.

Table 1. The analytical framework of this study.

Characteristics of Digital Technology	Description
Agential core	Forms of (joint) socio-technical agency in the social context of prototyping that manifest as a result of digital technology.
Semiotic binding	Different actors finding new and novel ways of contextual sensemaking and value realization, afforded by digital technology.
Ontological reversal	Objects are first created in the digital realm then, if needed, they are physically replicated.
Elements of Prototyping	**Description**
Representation	Representation includes all elements that relate to the actors' common understanding of the problem and solution.
Communication	Communication concerns aspects of interaction between actors, and/or the representation, which ultimately affects and changes the representation or the actors' own mental model.
Motivation	Motivation concerns aspects of the actors' willingness/ability to communicate and influence representation and/or change their own mental model.

5. Analysis

This analysis is organized by the analytical framework: three sections covering characteristics of digital technology, under which subsections describe how these characteristics affect the elements of prototyping.

5.1. Agential Core

Our empirical analysis suggests that digital technology exhibits new configurations of joint social and technical agency that affect the three elements of prototyping: representation, communication, and motivation. The following subsections detail examples of these observations.

5.1.1. Agency and Representation

One of the key elements fueling the redefined notion of agency in digital technology is data. Our interviewees pointed out different ways in which actions informing representation choices were data-driven. For example, one team describes how their digital service is driven by a classification algorithm where, depending on its predicted class, different information gets extracted from users' tweets to show in their stream-of-events content.

> *"We encapsulate the tweet and classify it into 4 different categories: Soccer, basketball, news or general/other sports event. Depending on these categories an action is taken. For example, if it's news-related, we extract location and content. If it's about soccer, we extract more information; the two teams, time of the event, weather conditions, traffic, location, score, and time of the tweet" (Respondent 4)*

Further, another team shows how it is the machine learning algorithms that are the "agents" creating more accurate estimates for their prototypes when faced with noisy data:

> *"So the data is actually very noisy, and we have to use machine learning algorithms to try to cluster the data to work out where you really are in that data. So we have the algorithms that analyse the data to try to make it cleaner and work out start and end points, as well as different routes" (Respondent 8)*

In both examples, the design team mainly designs the frame of the digital prototype, but activities such as the design of the content and inferencing are delegated to a data-driven agent that is part of the prototype and eventual service. With data powering algorithms, we observe a special type of agency, "data-driven agency". This notion describes how the teams design their prototypes in ways that make them unfinished representations until the data starts being generated and fills in such representational frames of the prototypes.

5.1.2. Agency and Communication

A key opportunity that follows from such data-driven agency and affects communication is the ability of the experimenting teams to communicate specific values related to their prototypes, such as allowing users to take control of their own data. Indeed, these values differed based on the type of stakeholder involved in the prototyping phase, as well as the type of data. But the common values observed relate to owning one's data, transparency, and openness. As one team puts it when asked about the aim of their experiment/prototype:

> *". . .to find ways for people who own this data—citizens—for themselves to find ways to represent that data. So it's about showing it to others, but also for finding ways to show it to themselves or the process for visualising is also insightful for themselves" (Respondent 9)*

However, there is also an act of balance that needs to be maintained in giving control to the users with data-driven agency in place. Especially with user-generated subjective data, teams need to maintain the integrity of their services (e.g., by ensuring the data is actually accurate); thus, some form of moderation is needed. This act of balance between openness and integrity is elaborated by the following respondent:

> *"Yes, it's probably embracing our tagline, which is curating to some extent, but in a delicate way, because we're very aware that we want to keep it open and as transparent as possible and we're not tweaking them, apart from making sure that they're in the right location" (Respondent 14)*

5.1.3. Agency and Motivation

The new agential configurations also affect the motivation behind the prototypes developed by our respondents, mainly through making data, information, and knowledge about the city more accessible to its residents. The characteristics of digital technology make it malleable and deliverable to end-users in a simple, cost-effective, and customizable manner.

> *"So we work in the space of quantifying air quality in cities and we have built a series of mobile sensors that have been basically deployed at reasonable cost and can capture high quality data . . . So, the main value proposition that we offer at least for municipalities customers is that we can enable them to see what is happening in the city with very little effort. That's the main thing that we do" (Respondent 7)*

In addition to motivating the solution representation, this malleability also motivates its deployment environment to suit different levels of technological literacy, again bringing new forms of agency to users that earlier had no agency with regard to data-driven solutions. As one team elaborates:

> *"We thought they will be accessible to designers as well as programmers, coders, and data scientists. It was a bit of a barrier to engagement for people who had a medium level of tech literacy, like us. That's why we chose motion.ai. We can deploy it to SMS or Facebook Messenger" (Respondent 3)*

5.2. Semiotic Binding

Our analysis also reveals that semiotic binding of digital technology affects all three elements of prototyping in eight different ways.

5.2.1. Semiotic Binding and Representation

In the empirical data, the need to understand different perspectives is apparent. The different companies and organizations in this study were all part of a program where interactions with stakeholders and other actors involved were encouraged by the program officials. This procedure was unfamiliar to many of the developers and that they struggled with co-creating solutions. Despite the instructions to "co-create", there was a strong indication by the respondents that the different organizations realized the importance of understanding the value proposition to users by accepting that both problem and solution *co-evolved* during the process. When entering the program, the developing organizations all had a clear idea of what they wanted to do. As time passed by, several of the companies started running workshops with stakeholders where they departed from a vision of a solution, and at the same time encouraged input on both the problem they were solving and the solution they were developing. One respondent explains how co-evolution can be achieved:

> *"So, it was all collected in real-time and after the walk itself, when we get back into the workshop space we did show them all the perceptual data that's collected at each location, so, what we did was, we showed them the perceptual data that they had collected in each location and also showing them another screen, where we showed them the air quality data that was collected by this small air quality sensor that we carry with us for the walk. So, then we did this mini session where we look at real-time air quality data collected and compare it to the other sessions." (Respondent 15)*

Another aspect of the semiotic binding related to representation is that the developers realized that they needed to *start from users' reality*, since users had a different mental model than the developers. Those that started with presenting a final solution to users had difficulties communicating its value and instead needed to step back and try to understand the users' mental model for understanding the solution, i.e., intermediaries that users knew about before, specifying bounded tasks when interacting, or educating the users. Keeping both the users' understanding of the representation and their own representation in mind created challenges for the development team. One respondent talks about the importance of having a process that kept it together:

> *"Yes it was part of the learning journey I guess. For that reason it was really important for us to be quite transparent with [user group], but have a design process that held it all together and felt really safe and bounded; knowing what we could do and what we couldn't do. We had clear briefs, knew what was possible, and we refined that as we went along." (Respondent 3)*

5.2.2. Semiotic Binding and Communication

Semiotic binding and communication intersect between the value the digital technology brings and how actors interact with the prototype (the representation). In this study several of the companies collected data from different sources such as sensors, external databases, users, etc., with the purpose of creating a synergetic effect from the interaction with the digital technology. Some examples of digital services in this study are applications that let the user understand the environment, finding less stressful urban areas, or managing carpools. The developers argued that if the right type of data is compiled, translated, and presented, *value is realized if users act*. Although, the interviews show that there can be a difference between recommended action and user action. The developers argued that it is important to know if users act, how they interpret the recommendation, and also that this type of communication needs to be bi-directional, i.e., that users interact via the digital technology. The developers also realized that the digital interface may affect and formalize communication, which could hamper communication from users:

> *"Yes, well, the interactive display was not something we were planning to do. . . .but at the same time we noticed in the workshops in London and Aarhus that people wanted to give their own opinion on particular matters. So we always envisioned it to be something where the citizen owns a particular display and communicate his or her point of view on this display. But we noticed throughout these workshops that people wanted to respond immediately in a quick and volatile way." (Respondent 9)*

The *need for interaction* is also evident in another intermediary concept in this cluster. Even if some of the applications originally were not intended to be based on user involvement, the majority of companies saw it as important or critical for their solutions at the end of the projects. Those companies that based most of their data collection on user involvement naturally had the strongest user-centric mindset, i.e., the users' experience, tendencies to interact, user value, etc. Other companies still saw the need for interaction with the users, but not as clearly or urgently as the first group. In these cases, users were seen as important to improve some function of the application, for example, improving analytics or being able to collect feedback on GUIs, etc. Lastly, even if user involvement was not a main part of some companies' applications, they were aware that users valued their data. As an example, companies thought of transparency and how to present "where and how" data where used in their services:

> *"I think the idea that we want to get across is that, first of all we want them to feel like the things that they have done that's actually an output, there's actually a result to look at and not just collecting data without knowing what's going to happen to it. So, we wanted to make it transparent, for them to know what type of data were being collected, what are they seeing." (Respondent 15)*

5.2.3. Semiotic Binding and Motivation

Centering on motivation aspects and semiotic binding, four intermediary concepts were located among the interviews. Firstly, the companies and their developers were or became aware that the experimentation they conducted required caution in terms of change. Since social factors often infer a degree of complexity, this can be interpreted as developers needing to understand which factors created value and why; simply put, they wanted to *understand the change* in the representation for every step they did in their process. Some developers also pointed to the importance of using elementary material methods to establish confidence among the actors involved:

> *"So we got to that simple generation stage, we used paper wireframes, we used storyboards, roleplaying, we tested things out really quickly and cheaply. It affected all the [user group] confidence—and our own confidence actually." (Respondent 3)*

Connected to this desire to understand value, companies also saw the need to understand how different contexts changed the users' perception of the value the prototype created. The developers reasoned that just because they understood one context does not mean it will be the same if the prototype was located elsewhere. This difference in *localization* may come from differences in the physical context (weather, altitude, sunlight, etc.) but also in the user (culture, norm, occupancy, etc.). One of the respondents argued that their prototype may solve different problems depending on the context:

> *". . . so that's why we went to look for different angles in which we can, there are definitely different problems that are solved by commuting together and we really needed to know which angle to play in [city]." (Respondent 6)*

Another aspect that can be connected to the same type of phenomenon is that the companies in this study ended up in situations with many different stakeholders to relate to, i.e., the digital technology may be intended for one group of end-users but often has a *network of actors* that are affected or that it affects. This may be a natural aspect for a digital service but also adds to the complexity in how the developers frame the scope of their ideas:

> *"So what we discussed yesterday with [organisation] that if you design new services around overcrowded homes you could also look at other aspects around wellbeing that might give you more return in terms of your service investment. So they really explored in terms of positive or negative correlation and they thought this is really useful and they wanted to see more detailed information around the reasons and drivers." (Respondent 3)*

An aspect of digital technology which seems to largely affect motivation is the *privacy of actors*:

> *"Obviously, it's difficult for people to want to share all their location data, it's a very private thing. So a couple of weeks ago we've also added an annotation map, where they can anonymously just put different markers on the map and say this is a problematic area. They can also connect that with GPS locations as well, if they want to login." (Respondent 8)*

Privacy affects the motivation of the user and other actors because the digital technology reveals too much information which feels unsafe and unwanted from an individual perspective. The developers have to tackle this issue from many angles in this study, which involves a balance between the privacy of the individual user and the functionality of the service.

5.3. Ontological Reversal

In our analysis, we found seven dimensions of ontological reversal related to prototyping digital solutions.

5.3.1. Ontological Reversal and Representation

Constructing digital representations when prototyping digital innovations seem like an expected practice and our analysis revealed three intermediary concepts related to OR and representation. To begin with, developers often turn to representing physical objects, events, or phenomena digitally in the form of a *digital twin,* either as a precursor to another value-added digital solution or as a standalone one. It is often assets of interest to their target users that are represented as such; for example, plotting all empty buildings in a city, or creating a digital twin for a city with a focus on specific aspects of its typology. An issue connected to the digital twin is the question of validity or compliance between the two realms. One respondent refers to the accuracy of the representation dependent on the level of network coverage:

> *"The accuracy that you see is about 50 to 100 m. But sometimes if you lose certain connection it goes to a cell tower so then it can become 200 m." (Respondent 8)*

While this dimension seems to be a static representation of objects, it is often associated with a *temporality* that plays a major role in digital solutions. For some teams, this temporal dimension is crucial to delivering value in their prototype. For instance, providing a map of available parking spots in a city requires that their availability be temporally accurate. However, in other cases, real-time representation poses other risks such as privacy risks if people's locations are revealed in the process. In such cases, if the phenomenon of interest permits, an added delay or temporal masking may be embedded in the representation to preserve individuals' privacy:

> *"Hosting sensors on vehicles that contain people, for data protection reasons you cannot output a public pin on a map. For geographical privacy, you know so we cannot say there is a delivery here at this time. We can't do this live because then we violate our agreement with [delivery company] and it would violate the privacy of their drivers. So what we can do is we can show some historical data as these points." (Respondent 1)*

The third intermediary concept can be described as *data layering* and occurred when experimenters mixed or aggregated different types of representations, or data/information, into one, which, in turn, made new types of digital representations emerge:

> *"So I thought why don't we make a tool that can make a use of this information? We can find patterns, location. . .then we can get something out of it...we get information from sensors, from people, and other sources, then you mix everything together. That's what we do." (Respondent 4)*

5.3.2. Ontological Reversal and Communication

Ontological reversal and communication mean that there is a communication route to the digital representation. Establishing ways for external actors to communicate with a digital prototype or concept is important in order to get input from them, but a factor for such communication is also that the digital prototype will probably not include the development team's entire representation in early phases. Many of the companies were faced with a challenge in their *digital interaction with end-users* because it was difficult to establish these communication routes, i.e., how to communicate and where to meet, but also because of the "innovation" itself, i.e., the actors did not know what it was or how to use it. A common experience among the cases in this study was that the developers had to identify and establish routes, facilitate them, and develop them further. Some tried to understand this by collecting data via the prototype itself:

> *". . . we have a number of data plots to understand user engagement and also data-side of analysis. But that is not really structured at the moment. We are also not sure if that is really useful to keep some insight but as a concept we want to keep that one." (Respondent 3)*

Others established communication iteratively by moving back and forth between the digital prototype and the real world:

> *"Freely written tweets were very challenging to analyze. So we started with a very strict structure, but people can't follow a rigid structure, they are not robots. So we had to be flexible. It was a compromise. Our community manager is really good at reading tweets from readers online. The current structure came as a suggestion after the first workshop, when we realized it was too rigid. Another workshop was held to follow up on structure." (Respondent 4)*

Moving back and forth between the two dimensions connects to a second intermediary concept of calibration between the digital prototype and real world elements, interpreted as being either *technical calibration* or *socio-technical calibration*. The developers were adapting their prototypes to specific social and technical contexts, which can be interpreted as the developers needing a known reference set to test their ontological reversal concept with, but also as the companies being sure that they initiated communication with users showing them the right vision or goal, i.e., that they showed users the right type of representation. Being able to succeed in creating this "connection" between the real world and the digital one was, in some cases, the main business idea:

> *"We are clear that we want to develop, 'Sensing as a Service'. The device and the hardware is an excuse to collect data and we have to build this of course and deploy them and there is alot of work in that but eventually data is the currency, so what we will eventually be offering customers is a clean API and data point where we take care of all the calibration, deployment, management of the devices, hardware and things, and then you get something on the other end."* (Respondent 7)

5.3.3. Ontological Reversal and Motivation

Two intermediary concepts were found in the ontological reversal dimension affecting the motivation, or the drive, to communicate with the representation. On the users' end, *trustworthiness* in the new prototypes seemed to be a challenge the teams faced. This trustworthiness was connected to sensing and analyzing real-world data in an accurate way. For example, the developers were worried that if the digital representation did not reflect true aspects of the real world, users would have less trust in the solution:

> *"The parameters that we get from this experiment, precision scaling, is not enough. We also need to co-locate the sensors to compare reading levels with reference monitors to find out accuracy. That is called accuracy scaling and what we need to do with our sensors to get them to estimate actual reference value of each is understand the difference in the way they react."* (Respondent 1)

Another intermediary concept found among the cases was both seen as a challenge and an opportunity, interpreted as a *prototype scale*. Some companies saw a possibility in increasing the scale of the prototype and incorporating larger geographical areas or different user groups, to enhance functionality, trustworthiness, granularity, etc. Others, on the other hand, saw an issue with reaching out too much because that created motivational issues among the end-users:

> *"I think a big barrier was working with the partners and the way we expected them to be resourceful in terms of getting their user group engaged. That was an unexpected constraint where we expected them to be able to go, 'Yes, we'll send out everything to-,' their users. We expected them to advise us in how they wanted us to engage."* (Respondent 14)

6. Discussion

In this section we discuss our findings by elaborating how each of the three elements of prototyping is impacted by digital technologies, summarized at the end of each subsection by a set of propositions.

6.1. Representation in Digital Prototyping

The properties of digital technology extend to prototypes in a way that challenges our assumptions about prototypes as stable or fixed objects. Our analysis suggests that digital technology's agential core entails that a digital prototype is rather dynamic and emergent, properties that extend from digital objects in general being recombinable and open-ended (Monteiro and Parmiggiani 2019). This emergence opens opportunities for design practices that take advantage of such agency. A digital representation of physical objects, phenomena, or events (i.e., digital twins) makes the recombination of these elements both easy and more feasible, reinforcing the malleability of digital technology (Yoo et al. 2010, 2012). Data layering is one of the ways in which such malleability manifests. Another key effect is the data-driven agency that can be observed more commonly in digital solutions, where teams design the frame for representations while the data generated through the interaction dictates the actual prototype. A common example is recommendation-based systems that rely on actual purchases to recommend products and/or services, leading to a different representation for each and every user.

On the other hand, this emergent nature of digital prototypes also poses several challenges. First, it comes with uncertainty as to whether the representation and behavior of the prototype are replicable in different (digital) contexts (Brereton and McGarry 2000; Dorst 2011). Replicability affects, for example, the robustness and reliability of tests and experiments and the team must therefore be aware of what it is that actually creates value (for a user) in the specific context. Second, it creates a continuously evolving problem and solution spaces. Unlike traditional prototypes with fewer versions, digital prototypes can have more frequent and cheaper revisions, for instance, revisions with minor feedback or features. It is, accordingly, of utmost importance for the team to assess and evaluate which feedback to incorporate and which to ignore.

Proposition 1A. *Digital technology's agential core yields feasible frames and recombinations of representational components in prototypes, but also brings sociotechnical complexity which challenges traditional (engineering) ways of thinking about problems and solutions.*

A key stakeholder in this process of an evolving problem and solution space is the end-user. Our analysis suggests that the teams that embraced this evolving representation based on the end-users' contextual experience were better equipped to address the changes induced by digital technology's semiotic binding. In the project's terms, these were the teams deemed to have achieved successful co-creation and co-evolution efforts with their stakeholders. It also brings forward the importance of starting from the users' reality and contextual experience, as in experience prototyping (Buchenau and Suri 2000). This reality could translate to accounting for new types of requirements when designing digital prototypes, such as specific data structures. In addition, the advantages of malleability and access to recombination increase the expectations from digital prototypes and open new possibilities for value creation, such as incorporating a temporal dimension (of the user's data) to digital solutions, since real-time or near real-time solutions are expected in certain contexts. Capturing subjective experiences and being open to unknown variables will be more challenging in digital prototyping (cf. Jensen et al. 2017). Nevertheless, these two specific dimensions of digital technology's agential core extends our assumptions about the impact of this agency on the knowledge production processes enabled by these technologies (van den Broek et al. 2021).

Proposition 1B. *Digital technology's semiotic binding redraws the attention to the co-creation and co-evolution of prototypes' representations, especially with regard to the users' social, technical, and temporal realities.*

The learning and knowledge exchange during digital prototyping also implies that a fluid, two-way translation between the physical and the digital realms may be necessary. Capturing functions and values in the physical realm to translate them to the digital one, and vice versa, are crucial aspects of digital prototypes. The two-way translation is not consistent for both directions especially for social aspects. As described in the case, it is important for the team to test assumptions from specific frames, and allow reframing, i.e., to have a result that is connected to reality (Dorst 2011). Although this translation may not always be straightforward, teams must understand the references for interpretation in both realms to make a connection. This entails that teams need the literacy of both digital and physical representations alike, in order to manage the knowledge exchange process among themselves, but also with the users (Brereton and McGarry 2000). Systematic methodologies that facilitate this process and document its impact on the prototype's representation need to take into account these two realms and their particular differences.

Proposition 1C. *Digital technology enhances certain aspects of reality based on, e.g., sensors and data layering, which create multiple and new references for developers to manage during prototyping.*

6.2. Communication in Digital Prototyping

An important action in prototyping is to sustain and support communication between the different actors involved since communication changes and develops the representation into its desired state, and results both in new knowledge and a new offer (Maher et al. 2011). Although, the agential core of digital technology challenges this explanation. When users' become a co-creator and when their input becomes part of the representation and value realization itself, things must change in the way the internal team allows communication. Firstly, this means that the prototype can be seen as both a boundary object and an actor with varying degrees of agency (Thompson 2016). Communication is bidirectional between two parties, or more, and our analysis shows the importance of both directions when developing digital prototypes. Secondly, users feel ownership and want to be able to affect the representation and see their own contribution. It is important to acknowledge that users have different purposes for why they give input, compared to the internal development team. They want to see how their data is used and who is using it, which, in turn, needs some level of transparency of usage and openness from the internal development team.

Proposition 2A. *Digital prototypes change the way we communicate because the prototype itself can be seen as an actor in its development. When the user becomes a co-creator, the prototype needs to be able to convey how the user's input is used and within what limits.*

Just as the potential agency of digital technology may influence design considerations in the prototype, it also influences the process of collaboration and knowledge sharing during prototyping. As argued above, digital prototypes (and services) necessitate communication with the user on a different level compared to traditional offers. Users are co-creators in the technology's development, they produce content to the representation, and they are recipients of the value created. The most important aspect for prototyping is that it should be founded upon shared understanding and effective communication (Wenngren et al. 2016). Insufficient interaction will lead to abstract or individual representations which eventually will lead to misunderstanding and inefficient prototyping. Having the same representation, but having different perspectives, is crucial for the prototype as a boundary object and for the possibilities of digital innovation (Rizk 2020; Star and Griesemer 1989). Hence, different perspectives must be elaborated through shared connected representations and there must be a way to support bi-directional communication in every level of prototyping, since the value is produced when the user acts upon the representation.

Proposition 2B. *Digital technology extends the meaning of interaction between actors and digital prototyping should support two-way communication.*

The ontological reversal of the digital idea innately calls for communication via the digital representation. Relying only on the (unfinished) digital representation might create misunderstanding since there are fewer possibilities to understand different individual representations, i.e., the digital representation does not communicate all the aspects of what the team wants to represent or the team does not understand the user's context enough, etc. In this study, developers became aware of this and handled it by considering alternative interaction options, i.e., workshops, educating the user, feedback forms, etc. To not miss out on any perspectives, it is proposed that developers consider communication via all four areas, synchronous, asynchronous, digitally, and physically. Focusing only on the digital communication path, another aspect of the ontological reversal is that abstract individual sensemaking models can be more difficult to communicate to others. This may not trigger new ideas of other team members. Accordingly, there is a need to be able to sometimes use simpler means to communicate in a prototyping session than those intended (Exner et al. 2015), for example, being able to make a simple sketch in an otherwise advanced simulation in a VR-tool. These prototypes created in the virtual space must be aligned with how the team creates frames. Reflecting on such digital defaults is crucial in the teams' communication of assumptions (Schrage 1996) and frame creation. Missing out on part of this process may lead to staleness where the team does not create new knowledge (Wenngren et al. 2016) or make too quick decisions (Leifer and Steinert 2011). Therefore, how and where that prototyping session takes place has implications for the process, i.e., the use of a co-located team in the same physical environment interacting with the same digital technology, or a separated team only connected through digital technology. Hybrid environments of these two bring other challenges, as we are witnessing in the post-pandemic workplace.

Proposition 2C. *Developers of digital prototypes need a secondary communication path to the user for both parties to communicate their individual representations.*

6.3. Motivation in Digital Prototyping

The characteristics of digital technology create opportunities in prototyping by narrowing knowledge gaps, which brings in different social actors (i.e., people) with diverse knowledge backgrounds. Such unprecedented heterogeneity, in addition to the technology's agential characteristics, leads to social and cognitive processes that may have a new meaning in this type of "teamwork". There may be a need to go through roles, purposes, goals, etc., more carefully to embrace this heterogeneity while ensuring appropriate accountability among participating actors. In this study, the role of the developer became more of a facilitator during the prototyping sessions, implying that traditional roles may change when the context changes, also known as re-contextualisation (Thompson 2016). This may not be problematic in cases where there are defined tasks and clear validation purposes. However, it becomes problematic for how the joint socio-technical agency enabled by digital technology may play out when the objective is explorative or seeking divergence for innovation, or when algorithmic design becomes more pervasive. Since teamwork is a highly social activity, it is important to sustain culture and social settings while at the same time promoting and encouraging more diverse roles to join in (Cross 1997). The agential characteristic may, however, problematize the concept of motivation in this context. Since it is essential for the prototype that social actors express their opinions and assumptions, as well as build on each other's ideas and trigger each other, the motivation to communicate may vary depending on the modality of the respective actor, such as an AI, an (human) employee, or an user.

Proposition 3A. *Digital prototypes are promoted by heterogeneous actors' collaboration but need support in the form of facilitation and overall goals and objectives.*

Prototypes develop knowledge by testing assumptions or hypotheses. Traditionally, the outcome of a prototype must be observable, i.e., there is evidence that the assumption is right or wrong. For digital prototypes, the change in the nature and timing of value realization due to the semiotic binding leads to the need for new value capturing mechanisms that are compatible with different dimensions of the digital prototyping (i.e., those that are physical, digital, live, synchronous, etc.) in a seamless manner (Rizk et al. 2020). In this study, information was often recorded in live sessions, but it may be more difficult to capture such information in other cases without deliberately mediating and accounting for it. While most relevant to the prototype user, it is the developing organization that needs to devise such a mechanism if they want to capture it (Houde and Hill 1997). A comparison to boundary objects (Thompson 2016) involves the "inscription" of needs and values in the prototype itself or the activity.

Proposition 3B. *Digital prototyping turns the focus from fulfilling needs and requirements to value realization when testing, and developers must therefore turn the focus to a value-capturing mechanism during prototyping.*

The digital prototype's compliance with the real world is essential for actors' trust and motivation. Factors such as technical determinism, the physical and social environment, context, malicious behavior, noise and errors, etc., play a vital roles in compliance. In this study, three areas were identified as being important for digital prototyping. Firstly, policies and agreements managing rights and responsibilities are problematic, for example, when collecting data or collaborating with another organization. Secondly, finding a balance between the privacy of the individual and the openness of data is difficult. Thirdly, the calibration of sensors and collected data is a resource-intensive activity. In the cases we analyzed, different kinds of calibration were observed. Calibration in the traditional sense relates to using new sensors or using sensors in new environments they were not designed for.

Proposition 3C. *Prototyping is a step along the way, and while the digital realm attracts high precision and compliance, digital prototyping benefits from a gradual build-up of accuracy and resolution.*

7. Conclusions

With the growing pressure to innovate and the pervasive use of digital technologies, organizations are faced with changing practices in relation to their prototyping and development. This study set off to answer the research question: *How does digital technology affect the different elements of prototyping?* Through our analysis, we conclude that the characteristics of digital technology have a profound impact on prototyping. Our nine propositions detail how the "digital first" practice of digitalization, the increasing of agency, and the semiotic binding that digitalization allows impact the three core aspects of prototyping: representation, communication, and motivation. Our analysis provides a foundational overview for the study of digital prototyping, but does not dive deep into all nine relationships. Instead, this study shows, by theorizing previous research and comparing it to empirical findings, emergent aspects that need to be considered when creating digital prototypes. Our propositions focus on how digital prototypes should be developed to create favorable conditions for success. The propositions help us see a difference compared to a traditional procedure as well as an understanding of the increased degree of complexity and abstraction compared to pure products or services. Our aim by doing this is firstly a theoretical contribution to evolve theoretical knowledge so that research can build on and expand this understanding. These propositions can be later used as analytical instruments in other cases in different contexts, as well as being tested using quantitative research designs.

Secondly, the contribution of this study also has practical implications with regard to managing the development of digital solutions, especially in the early stages of prototyping. Digital prototyping is shown to have dynamic and emergent properties and its development should therefore focus on socially situated and data-driven framing. It also brings forward the importance of starting from the users' reality and contextual experience. Based on the nine propositions, we also provide recommendations for practices, as shown in Table 2. The recommendations contribute to the ongoing discourse on holistic digital transformation in three ways. First, it supports practitioners with an understanding of objectives when conducting digital prototyping activities. Secondly, it provides practitioners with a concrete analytical tool to empirically investigate cases, either holistically or more in-depth by utilizing the included set of guiding statements. Third, it may be used to analyze and explain phenomena related to prototyping activities in relation to emerging technologies.

Table 2. Propositions based on practical recommendations.

	Representation	Communication	Motivation
Agential core	Design for agency	Allow ownership	Facilitate heterogeneity
Semiotic binding	Co-evolve with users	Aim for interaction	Test for value
Ontological reversal	Find the reference for interpretation	Handle virtual ideas	Balance accuracy and resolution

The study also has some limitations. The nature of the study context and the diversity of the interviewed teams may account for some variations in the propositions. Further, the context of the respondents indicates that it is most likely that these propositions are most applicable for entrepreneurs, intrapreneurs, start-ups, etc., that are aiming to develop new digital services without the limitations of a large organizational structure. A continuation to test these propositions is necessary to verify their cross-contextual validity. As mentioned previously, it also tackles nine different relationships simultaneously, creating a compromise between the study's depth and breadth. Our future research aims to execute an in-depth investigation of these relationships through both quantitative and qualitative studies by, for example, testing the impact of innovation structures in large organizations.

Author Contributions: Conceptualization, J.W. and A.R.; methodology J.W. and A.R.; software, J.W. and A.R.; validation, J.W. and A.R.; formal analysis, J.W. and A.R.; investigation J.W. and A.R.; resources, J.W. and A.R.; data curation, J.W. and A.R.; writing—original draft preparation, J.W. and A.R.; writing—review and editing, J.W.; visualization, J.W. All authors have read and agreed to the published version of the manuscript.

Funding: The empirical data used in this paper was collected during the project "OrganiCity" funded by the European Commission's Horizon 2020 programme under grant number 645198.

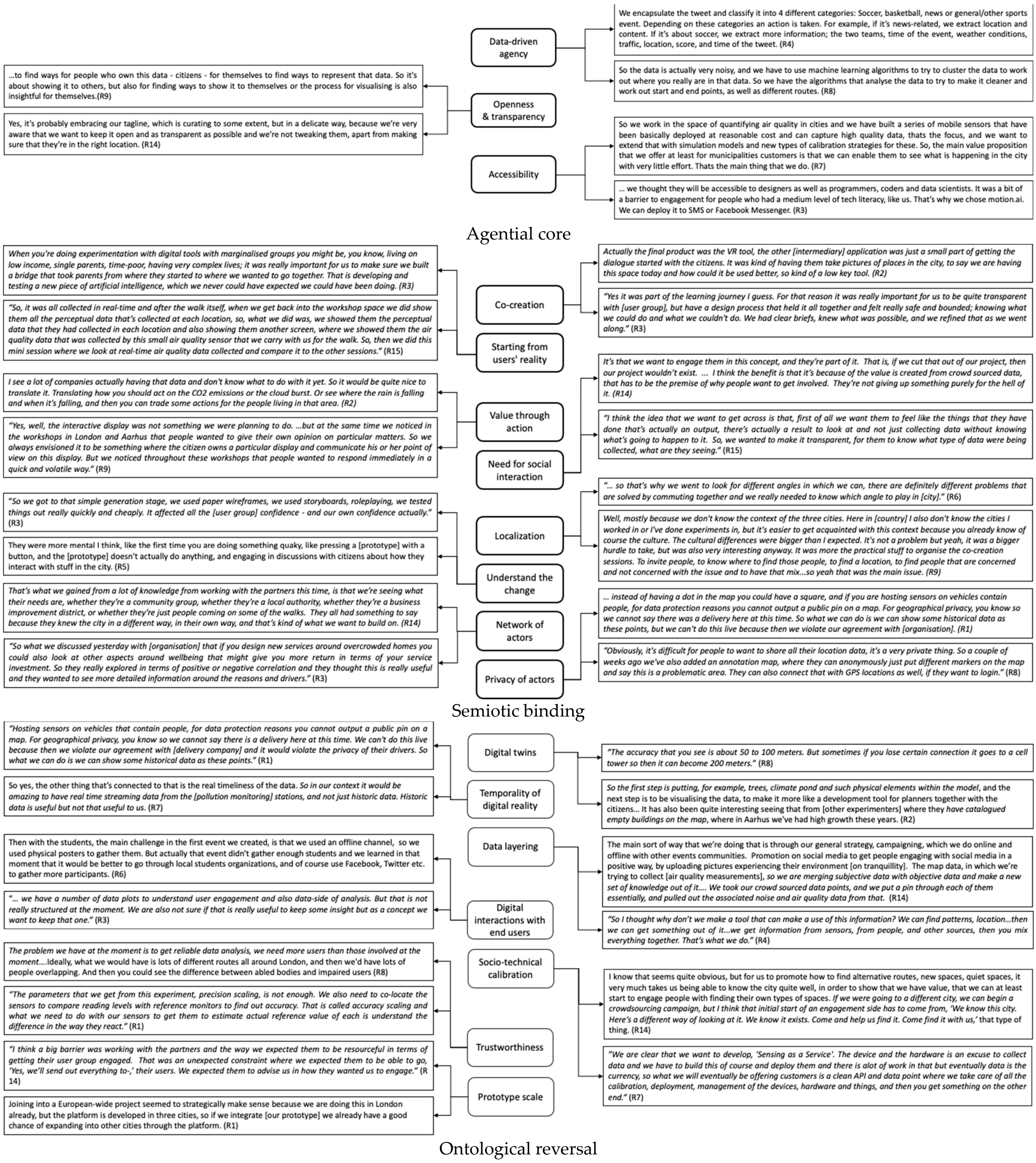
Institutional Review Board Statement: Not applicable. An ethical review was not required when the research study was conducted. The research project although followed ethical research practices.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: There are no publicly archived datasets available.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A. Intermediary Concepts from Analysis



References

Annarelli, Alessandro, Cinzia Battistella, and Fabio Nonino. 2016. Product service system: A conceptual framework from a systematic review. *Journal of Cleaner Production* 139: 1011–32. [CrossRef]

Ardichvili, Alexander, Richard Cardozo, and Sourav Ray. 2003. A theory of entrepreneurial opportunity identification and development. *Journal of Business Venturing* 18: 105–23. [CrossRef]

Aversa, Paolo, Laure Cabantous, and Stefan Haefliger. 2018. When decision support systems fail: Insights for strategic information systems from Formula 1. *The Journal of Strategic Information Systems* 27: 221–36. [CrossRef]

Bae, Dae Jung, and Choon Seong Leem. 2014. A visual interactive method for service prototyping. *Managing Service Quality* 24: 339–62. [CrossRef]

Baskerville, Richard L., Michael D. Myers, and Youngjin Yoo. 2020. Digital first: The ontological reversal and new challenges for IS research. *MIS Quarterly* 44: 509–23. [CrossRef]

Blomkvist, Johan. 2014. Representing Future Situations of Service: Prototyping in Service Design. PhD thesis, Linköping University Electronic Press, Linköping, Sweden.

Blomkvist, Johan, and Stefan Holmlid. 2010. Service prototyping according to service design practitioners. Paper presented at Conference Proceedings, ServDes. 2010, Exchanging Knowledge, Linköping, Sweden, December 1–3; Linköping, Sweden: Linköping University Electronic Press, pp. 1–11.

Boletsis, Costas. 2018. Virtual Reality for Prototyping Service Journeys. *Multimodal Technologies and Interaction* 2: 14. [CrossRef]

Brereton, Margot, and Ben McGarry. 2000. An observational study of how objects support engineering design thinking and communication: Implications for the design of tangible media. Paper presented at SIGCHI Conference on Human Factors in Computing Systems, The Hague, The Netherlands, April 1–6; pp. 217–24.

Brown, Tim, and Barry Katz. 2011. Change by design. *Journal of Product Innovation Management* 28: 381–83. [CrossRef]

Buchenau, Marion, and Jane Fulton Suri. 2000. Experience prototyping. Paper presented at 3rd Conference on Designing Interactive Systems: Processes, Practices, Methods, and Techniques, New York, NY, USA, August 17–19; pp. 424–33.

Camburn, Bradley, Vimal Viswanathan, Julie Linsey, David Anderson, Daniel Jensen, Richard Crawford, Kevin Otto, and Kristin Wood. 2017. Design prototyping methods: State of the art in strategies, techniques, and guidelines. *Design Science* 3: e13. [CrossRef]

Coyne, Imelda T. 1997. Sampling in qualitative research. Purposeful and theoretical sampling; merging or clear boundaries? *Journal of Advanced Nursing* 26: 623–30. [CrossRef]

Cross, Nigel. 1997. Descriptive models of creative design: Application to an example. *Design Studies* 18: 427–40. [CrossRef]

Dorst, Kees. 2011. The core of 'design thinking'and its application. *Design Studies* 32: 521–32. [CrossRef]

Dorst, Kees. 2019. Co-evolution and emergence in design. *Design Studies* 65: 60–77. [CrossRef]

Exner, Konrad, Kai Lindow, Rainer Stark, Jussi Ängeslevä, Benjamin Bähr, and Emilia Nagy. 2015. A transdisciplinary perspective on prototyping. Paper presented at 2015 IEEE International Conference on Engineering, Technology and Innovation/International Technology Management Conference (ICE/ITMC), Belfast, UK, June 22–24; New York: IEEE, pp. 1–8.

Faulkner, Philip, and Jochen Runde. 2019. Theorizing the Digital Object. *MIS Quarterly* 43: 1279. [CrossRef]

Fichman, Robert G., Brian L. Dos Santos, and Zhiqiang Zheng. 2014. Digital innovation as a fundamental and powerful concept in the information systems curriculum. *MIS Quarterly* 38: 329–354, A1–A15. [CrossRef]

Freude, Henrik, Caroline Reßing, Marius Müller, Bjoern Niehaves, and Michael Knop. 2020. Agency and body ownership in immersive virtual reality environments: A laboratory study. Paper presented at 53rd Hawaii International Conference on System Sciences, Maui, HI, USA, January 7–10.

Gero, John S. 1990. Design prototypes: A knowledge representation schema for design. *AI Magazine* 11: 26.

Houde, Stephanie, and Charles Hill. 1997. What do prototypes prototype? In *Handbook of Human-Computer Interaction*. Amsterdam: Elsevier, pp. 367–81.

Hove, Siw Elisabeth, and Bente Anda. 2005. Experiences from conducting semi-structured interviews in empirical software engineering research. Paper presented at 11th IEEE International Software Metrics Symposium (METRICS'05), Como, Italy, September 19–22. 10p.

Hukal, Philipp, and Ola Henfridsson. 2017. Digital innovation—A definition and integrated perspective. In *The Routledge Companion to Management Information Systems*. London: Routledge, pp. 360–69.

Jacoby, Ryan, and Diego Rodriguez. 2007. Innovation, growth, and getting to where you want to go. *Design Management Review* 18: 10. [CrossRef]

Jensen, Matilde B., Christer W. Elverum, and Martin Steinert. 2017. Eliciting unknown unknowns with prototypes: Introducing prototrials and prototrial-driven cultures. *Design Studies* 49: 1–31. [CrossRef]

Kallinikos, Jannis, Aleksi Aaltonen, and Attila Marton. 2013. The Ambivalent Ontology of Digital Artifacts. *MIS Quarterly* 37: 357–70. [CrossRef]

Klein, Gary, Brian Moon, and Robert R. Hoffman. 2006a. Making sense of sensemaking 1: Alternative perspectives. *IEEE Intelligent Systems* 21: 70–73. [CrossRef]

Klein, Gary, Brian Moon, and Robert R. Hoffman. 2006b. Making sense of sensemaking 2: A macrocognitive model. *IEEE Intelligent Systems* 21: 88–92. [CrossRef]

Kleinsmann, Maaike, and Martijn ten Bhömer. 2020. The (new) roles of prototypes during the co-development of digital product service systems. *International Journal of Design* 14: 65–79.

Kostis, Angelos, and Paavo Ritala. 2020. Digital Artifacts in Industrial Co-creation: How to Use VR Technology to Bridge the Provider-Customer Boundary. *California Management Review* 62: 125–47. [CrossRef]

Kvale, Steinar. 2008. *Doing Interviews*. Thousand Oaks: SAGE Publications, Ltd.

Leifer, Larry J., and Martin Steinert. 2011. Dancing with ambiguity: Causality behavior, design thinking, and triple-loop-learning. *Information Knowledge Systems Management* 10: 151–73. [CrossRef]

Leshem, Shosh, and Vernon Trafford. 2007. Overlooking the conceptual framework. *Innovations in Education and Teaching International* 44: 93–105. [CrossRef]

Lyytinen, Kalle, Satish Nambisan, and Youngjin Yoo. 2020. A transdisciplinary research agenda for digital innovation: Key themes and directions for future research. In *Handbook of Digital Innovation*. Cheltenham: Edward Elgar Publishing, pp. 279–86.

Maher, Mary Lou, Mercedes Paulini, and Paul Murty. 2011. Scaling up: From individual design to collaborative design to collective design. In *Design Computing and Cognition'10*. Dordrecht: Springer, pp. 581–99.

Mandal, Pratap Chandra. 2020. How can we generate innovative ideas for new product development? *International Journal of Quality and Innovation* 5: 17–32. [CrossRef]

Marion, Tucker J., and Sebastian K. Fixson. 2021. The Transformation of the Innovation Process: How Digital Tools are Changing Work, Collaboration, and Organizations in New Product Development. *Journal of Product Innovation Management* 38: 192–215. [CrossRef]

Meiren, Thomas, and Thomas Burger. 2010. Testing of service concepts. *The Service Industries Journal* 30: 621–32. [CrossRef]

Monteiro, Eric, and Elena Parmiggiani. 2019. Synthetic knowing: The politics of the internet of things. *MIS Quarterly* 43: 167–84. [CrossRef]

Nambisan, Satish, Kalle Lyytinen, Ann Majchrzak, and Michael Song. 2017. Digital Innovation Management: Reinventing Innovation Management Research in a Digital World. *MIS Quarterly* 41: 223–38. [CrossRef]

Nambisan, Satish, Kalle Lyytinen, and Youngjin Yoo. 2020. Digital innovation: Towards a transdisciplinary perspective. In *Handbook of Digital Innovation*. Cheltenham: Edward Elgar Publishing, pp. 2–13.

Nicholas, John, Ann Ledwith, and John Bessant. 2013. Reframing the search space for radical innovation. *Research-Technology Management* 56: 27–35. [CrossRef]

Parida, Vinit, Pankaj C. Patel, Johan Frishammar, and Joakim Wincent. 2017. Managing the front-end phase of process innovation under conditions of high uncertainty. *Quality & Quantity* 51: 1983–2000. [CrossRef]

Passera, Stefania, Henna Kärkkäinen, and Reetta Maila. 2012. When, how, why prototyping? A practical framework for service development. Paper presented at ISPIM Conference Proceedings, Barcelona, Spain, June 17–20; p. 1.

Patton, Michael Quinn. 2005. Qualitative research. *Encyclopedia of Statistics in Behavioral Science*. Wiley Online Library. Available online: https://onlinelibrary.wiley.com/doi/book/10.1002/0470013192 (accessed on 2 June 2024).

Ramsgaard Thomsen, Mette, and Martin Tamke. 2016. Prototyping Practice: Merging Digital and Physical Enquiries. In *Rethink!* Edited by Christoph Gengnagel, Emilia Nagy and Rainer Stark Prototyping. Berlin and Heidelberg: Springer International Publishing, pp. 49–62.

Razek, Abdul Rahman Abdel, Christian Van Husen, Marc Pallot, and Simon Richir. 2018a. A comparative study on conventional versus immersive service prototyping (VR, AR, MR). Paper presented at Virtual Reality International Conference-Laval Virtual, Laval, France, April 4–6; pp. 1–10.

Razek, Abdul Rahman Abdel, Christian Van Husen, Marc Pallot, and Simon Richir. 2018b. A proposed research framework and model for service prototyping. Paper presented at 2018 IEEE International Conference on Engineering, Technology and Innovation (ICE/ITMC), Stuttgart, Germany, June 17–20; New York: IEEE, pp. 1–8.

Real, Ricardo, Chris Snider, Mark Goudswaard, and Ben Hicks. 2021. Dimensions of knowledge in prototyping: A review and characterisation of prototyping methods and their contributions to design knowledge. *Proceedings of the Design Society* 1: 1303–12. [CrossRef]

Rittel, Horst W. J., and Melvin M. Webber. 1973. Dilemmas in a general theory of planning. *Policy Sciences* 4: 155–69. [CrossRef]

Rizk, Aya. 2020. Data-Driven Innovation: An Exploration of Outcomes and Processes within Federated Networks. Ph.D. thesis, Luleå University of Technology, Luleå, Sweden.

Rizk, Aya, Anna Ståhlbröst, and Ahmed Elragal. 2020. Data-driven innovation processes within federated networks. *European Journal of Innovation Management* 25: 498–526. [CrossRef]

Rontti, Simo, Satu Miettinen, Essi Kuure, and Antti Lindström. 2012. A laboratory concept for service prototyping: Service Innovation Corner (SINCO). In *ServDes. 2012 Conference Proceedings: Co-Creating Services; The 3rd Service Design and Service Innovation Conference; 8–10 February; Espoo, Finland*. Linköping: Linköping University Electronic Press.

Ruecker, Stan. 2015. A brief taxonomy of prototypes for the digital humanities. *Scholarly and Research Communication* 6: 1–11.

Santos, Marc Ericson C., Angie Chen, Takafumi Taketomi, Goshiro Yamamoto, Jun Miyazaki, and Hirokazu Kato. 2013. Augmented reality learning experiences: Survey of prototype design and evaluation. *IEEE Transactions on Learning Technologies* 7: 38–56. [CrossRef]

Schrage, Michael. 1996. Cultures of Prototyping: Bringing Design to Software. *Terry Winograd*. [CrossRef]

Star, Susan Leigh, and James R. Griesemer. 1989. Institutional ecology, translations' and boundary objects: Amateurs and professionals in Berkeley's Museum of Vertebrate Zoology, 1907–39. *Social Studies of Science* 19: 387–420. [CrossRef]

Svensson, Peter. 2011. Teorins roll i kvalitativ forskning. In *Handbok i Kvalitativa Metoder*. Stockholm: Liber.

Thomke, Stefan H. 2003. *Experimentation Matters: Unlocking the Potential of New Technologies for Innovation*. Boston: Harvard Business Press.

Thompson, Ed. 2016. An Actor-Network Theory of Boundary Objects: Construction and Disappearance. Paper presented at British Academy of Management Conference 2016, Newcastle, UK, Septemeber 6–8.

Tilson, David, Kalle Lyytinen, and Carsten Sørensen. 2010. Research commentary—Digital infrastructures: The missing IS research agenda. *Information Systems Research* 21: 748–59. [CrossRef]

United Nations. 2021. Available online: https://www.un.org/en/un75/impact-digital-technologies (accessed on 23 April 2024).

van den Broek, Elmira, Anastasia Sergeeva, and Marleen Huysman. 2021. When the machine meets the expert: An ethnography of developing AI for hiring. *MIS Quarterly* 45: 1557. [CrossRef]

Vargo, Stephen L., and Robert F. Lusch. 2004. Evolving to a new dominant logic for marketing. *Journal of Marketing* 68: 1–17. [CrossRef]

Wenngren, Johan, Åsa Ericson, and Vinit Parida. 2016. Improving Team Activities in the Concept Development Stages: Addressing Radical Development and Open-Ended Problems. *Journal of Promotion Management* 22: 496–510. [CrossRef]

Winby, Stu, and Susan Albers Mohrman. 2018. Digital sociotechnical system design. *The Journal of Applied Behavioral Science* 54: 399–423. [CrossRef]

Yin, Robert K. 2018. *Case Study Research and Applications: Design and Methods*. Thousand Oaks: SAGE Publications.

Yoo, Youngjin, Ola Henfridsson, and Kalle Lyytinen. 2010. Research commentary—The new organizing logic of digital innovation: An agenda for information systems research. *Information Systems Research* 21: 724–35. [CrossRef]

Yoo, Youngjin, Richard J. Boland, Jr., Kalle Lyytinen, and Ann Majchrzak. 2012. Organizing for innovation in the digitized world. *Organization Science* 23: 1398–408. [CrossRef]