Design Thinking in Digital Innovation Projects—Exploring the Effects of Intangibility

Leonard Przybilla, Kai Klinker, Michael Lang, Maximilian Schreieck, Manuel Wiesche, and Helmut Krcmar

***Abstract*—The locus of innovation has shifted from mechanical advances to digital solutions. By emphasizing the importance of user needs, Design Thinking is apt to develop human-centered innovation, including digital solutions. Using two representative examples from 21 Design Thinking projects spanning the gamut of mechatronic to fully digital solutions, we report on critical incidents as opportunities and challenges of applying Design Thinking in a digital context. In the case of mechatronic solutions, we identified opportunities related to improved collaboration and higher quality prototyping as well as in innovative business models, which in turn created challenges in managing stakeholders. In the fully digital context, we observed opportunities in improved needfinding and the ability to offer individualized products. Conversely, we uncover difficulties in imagining digital features, estimating their feasibility, and correctly setting the fidelity of prototypes. Based on these observations, we discuss the intangibility of digital artifacts as enabler and inhibitor of Design Thinking in a digital context.**

***Index Terms*—Creativity, design engineering, design tools, innovation management, project management, research and development management, technological innovation.**

I. Introduction

INNOVATION, that is, changing the status quo and developing new or improved products, services, or processes, is the lifeblood of competitive advantage and thus a key consideration for organizations [1]. In recent times, the locus of innovation has shifted from mechanical advances to digital features [2]–[4]—either as standalone products or as part of hardware- and software-based, mechatronic, solutions. Digital innovation, that is, innovation enabled by software products and services, has specific traits. Unlike physical goods, software is intangible as it integrates knowledge and thought as its main constituents [5].

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Leonard Przybilla, Kai Klinker, Maximilian Schreieck, and Helmut Krcmar are with the Technical University of Munich, 85748 Garching, Germany (e-mail: leonard.przybilla@tum.de; kai.klinker@tum.de; maximilian.schreieck@tum.de; helmut.krcmar@tum.de).

Michael Lang is with the msg nexinsure ag, 85737 Ismaning, Germany (e-mail: michael.lang@msg.group).

Manuel Wiesche is with the TU Dortmund University, 44227 Dortmund, Germany (e-mail: manuel.wiesche@tu-dortmund.de).

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Since the increasing shift to value creation in digital features forces "traditional" industries to change their strategy and embrace digital technologies [3], [4], many innovation projects, ranging from optimized internal processes to novel offerings designed to draw in new customers, may naturally lead to digital outcomes. As a consequence, the rapid introduction of digital technologies touches upon nearly every aspect of life [6], which puts it at the heart of several megatrends of our time [7].

Although the gold rush sentiment that digitalization can make anything faster, more efficient, or more user friendly implies infinite possibilities, digital innovation projects still face the issues commonly encountered in innovation. Given the high rate of new products failing in the market [8], [9] and given that innovation is inherently a risky and uncertain process [10], [11], the recent push to start innovation projects based on user needs, instead of technical feasibility, is not surprising. A focus on user needs and the requirement of an elaborate toolset for innovation made approaches such as Design Thinking widely popular [6], [12]. As a methodology for achieving human-centered innovation by addressing actual human needs [13], Design Thinking is applicable to the type of ill-defined or "wicked" problems [14] presented by innovation initiatives. Through its strong emphasis on repeated interaction with users [12], it can tease out what issues should be addressed within a broader problem area. By providing guidance throughout the course of the innovation process and by integrating specific tools, Design Thinking improves innovation outcomes by acting as a social technology [15].

Despite its recent growth in popularity, Design Thinking is not new, but builds on a rich foundation of theories and applications [12], [16]. Rooted in how designers work, Design Thinking encompasses a variety of different processes and tools [12] and is not bound to any specific application area [1], but is meant to address "wicked," that is, ill-defined and hard-to-grasp, problems in a variety of areas [12], [14]. While digital innovation provides new means to tackle wicked problems, making sure solutions address *actual* needs calls precisely for approaches such as Design Thinking [6]. At the same time, the development of digital solutions *is* a wicked problem requiring Design Thinking approaches [17]. Considering the shift of innovation to the digital realm [2]–[4] and given the general lack of research on Design Thinking in innovation [6], we raise the research question: "What are the opportunities and challenges of applying Design Thinking in digital contexts?" In this article, we help to fill this void by reporting on our experiences with opportunities and challenges of using Design Thinking in real-world projects set in a digital context.

The remainder of this article is structured as follows: first, we provide background information on Design Thinking and describe our methodological approach. Drawing on critical incidents in two projects representing mechatronic and fully digital projects, we illustrate the key opportunities and challenges of Design Thinking we observed in a digital context. We discuss our findings, especially those concerning the intangible nature of digital artifacts, before ending with concluding remarks.

II. Background on Design Thinking

While the term "Design Thinking" enjoys wide popularity in management [18], there is no commonly accepted definition [12]. Overall, Design Thinking can refer to a discipline, an approach to attain specific aims, or a mindset [12]. Considering the area of application, Design Thinking can either pertain to different, parallel, schools of thought concerned with *designerly thinking* or to separate streams of discussions in management [16]. In our projects, we utilize Design Thinking in the managerial tradition of transferring approaches usually adopted by designers to other domains [13], [16]. The key objective of the most widely referenced managerial application of Design Thinking is to accomplish human-centered innovation, while also maintaining technical feasibility and economic viability [12], [13]. Human-centricity means the needs and wishes of users are the guiding considerations in development [13].

While constituting a distinct practice for problem-solving, Design Thinking does not comprise a clearly defined set of ingredients, but constitutes a "'basket' of tools and processes" [18, p. 925]. Based on insights from industrial practice, Design Thinking exhibits the key traits *user focus, problem framing, visualization, experimentation*, and *diversity* [12]. *User focus* implies adopting an empathic approach, based on rich interaction with users [12]. *Problem framing* refers to practices for working with, for example, restating or further expanding, the problem instead of seeking a solution from the outset [12]. *Visualization* means concepts and results should be made tangible, and *experimentation* calls for teams to iteratively implement, test, and refine ideas [12]. *Diversity* implies that both the team and outside contacts to stakeholders should be varied [12]. A common theme of working in Design Thinking is to embrace abductive reasoning, that is, creating new solutions, in conjunction with the "traditional" inductive/deductive ways of working [12], [18].

Comparing state-of-the-art processes of Design Thinking, such as the ones used by Ideo and the Stanford Design School, yields a common set of core phases [18]. To understand user needs and to delineate the problem to be solved, all surveyed processes start out with an *exploratory phase*, which provides input for the second phase of *idea generation* [18]. The third and last phase aims at creating prototypes and testing them with users, in order to gather feedback for further development [18]. Each of these phases is supported by numerous tools such as ethnographic observation or brainstorming [18]. Notwithstanding a common set of activities, all of the surveyed processes use slightly different terms and structures. For example, Stanford

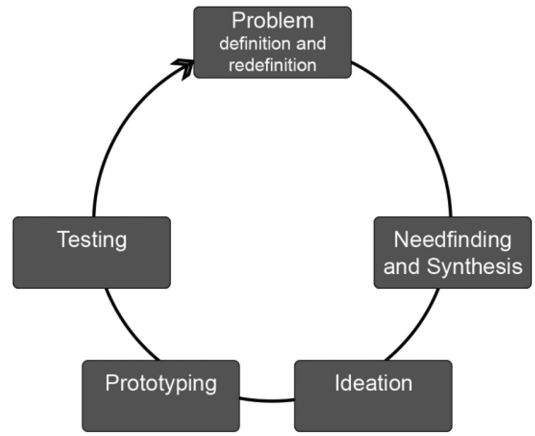

Fig. 1. Design thinking microcycle, based on [22].

Design School splits the third phase in "prototype" and "test," whereas Ideo uses the terms "experimentation and evolution" [18], [19].

In addition to a common structure, all of the processes surveyed emphasize iterating between these steps, harnessing diversity in teams, and involving users [18]. Since these key traits, which were uncovered by comparing process models of Design Thinking, closely align with the criteria found in organizational use [12], we will apply them as hypothetical defining criteria of a Design Thinking process in this article.

As one specific example of a Design Thinking process, we introduce the Design Thinking Micro-Cycle. This process originally developed in the ME310 Design Innovation course at Stanford, where it is called Stanford Design Innovation Process [20]–[22]. The iterative process, depicted in Fig. 1, which we used in all projects underlying this research, covers the steps *problem definition and redefinition, needfinding and synthesis, ideation, prototyping,* and *testing*.

Problem definition and redefinition initiates the cycle by putting forth a goal-oriented, yet solution-neutral, question [22]. *Needfinding and synthesis* harnesses a variety of tools for inquiry and analysis, such as interviews, observations, and frameworks, in order to unveil user needs and to derive precise insights [22]. These insights provide a starting point for *ideation* to generate ideas for potential solutions that address user needs, for example, through brainstorming [22]. *Prototyping* aims to make these ideas tangible by creating a first implementation [22]. Prototypes help to create shared understanding within the project team and to test assumptions, raise new questions, and thus to refine concepts [22]. Early in a project, prototypes should be of low fidelity to allow for testing core ideas [19], [22]. Over time, fidelity should increase to allow for more detailed representations and gathering feedback on details of concepts [22]. As the last step, *testing* calls for handing prototypes to potential users and other stakeholders to establish the validity of assumptions and whether solutions address actual user needs [22]. Testing results, in turn, help to reformulate the problem [22] and thus restart the cycle.

In iteratively applying this Design Thinking process, the relative focus on each step may shift: Early iterations emphasize needfinding and gathering detailed stakeholder information to broaden the problem space, whereas later iterations focus on idea generation and testing to establish a final concept [20]. By actively involving stakeholders and testing prototypes to iteratively refine the problem definition, this process exhibits the defining traits of Design Thinking processes described in literature [12], [18].

III. Method

To investigate how a digital context affects Design Thinking projects, we drew on the Critical Incident Technique (CIT), a well-established qualitative research method meant to be flexibly adapted to the context [23], [24]. Since the CIT was first introduced in organizational and industrial psychology, with the goal to make observations of behavior usable for practical purposes such as job assessment [23], it has been applied in diverse areas [24]. Critical incidents are defined as events that constitute extreme behavior or make a significant contribution [23], [24]. We thus deem the CIT to fit well with our intention of providing an explorative account of how a digital context affects Design Thinking projects.

As outlined in the seminal account by Flanagan [23], a CIT study comprises five steps:

1) General Aims.
2) Plans and Specifications.
3) Collecting the Data.
4) Analyzing the Data.
5) Interpreting and Reporting.

In the following, we describe how we instantiated each of the five steps.

The first phase *General Aims* sets out to clarify the scope of the research project [23], [25]. Following our aim to investigate Design Thinking in the digital context, we defined the scope as the opportunities and challenges a digital context evokes in conducting Design Thinking projects.

Based on the *General Aims*, *Plans and Specifications* cover the detailed design of the study such as who is to be observed and how data is gathered [23], [25]. We included 21 Design Thinking projects of three types: research projects as well as long and short classroom projects. All projects incorporated Design Thinking using the previously introduced Design Thinking Micro-Cycle. As detailed in Table I, the projects covered a variety of subjects from a regulated health care context to emergent possibilities in B2C mobility services, and lasted between five months and four years. This variety helped us to establish a comprehensive view of Design Thinking in the digital context. While several projects comprise hardware-based aspects, each project worked on software-based or -supported artifacts, which positions them in a digital context. Depending on the project type, at least two of the six authors either took part as team members or acted as coaches. Our experience with Design Thinking and active involvement enabled us to act as knowledgeable experts called for in CIT [23] and to report critical incidents from the unique vantage point of researchers directly involved in the projects.

Research projects encompass interdisciplinary teams from both research institutions and industry. Researchers, such as the participating authors of this article, typically led the projects, developed and evaluated concepts. Industry partners provided relevant domain knowledge, engaged in testing, or helped with implementation. While Design Thinking was only introduced to Projects 1 and 2 while they were already underway, all research projects harnessed the Design Thinking Micro-Cycle. Each project especially used tools for needfinding, such as ethnographic observations, in combination with iterative prototyping.

Long Industry Class Projects comprise graduate student projects on topics given by industry partners. Student teams, which typically encompassed diverse disciplines such as information systems, informatics, business, design, or mechanical engineering, worked on these real-world challenges for nine months as part of a two-semester course. Several of the authors, who had been trained on conducting and teaching Design Thinking projects based on a detailed curriculum derived from Stanford university's ME310 course, see [26], provided methodical input in a weekly two-hour lecture as well as coaching to individual projects in a weekly one-hour session. Students learned basic principles of Design Thinking as well as how and when to use tools, such as interviewing, observation, user journeys, or rapid prototyping. While putting special emphasis on detailed needfinding and exploration of the problem space in the beginning, the projects covered multiple iterations of the Design Thinking cycle. The teams usually collaborated with international partner teams and interacted frequently with external entities such as industry partners and users for testing.

Short Industry Class Projects also comprise student projects on topics given by industry partners. Compared to the Long Industry Class Projects, the projects had a shorter duration of five months with several student teams working on the same challenge in parallel. The methodical input was more condensed and teams ran through fewer iterations.

In *Collecting the Data*, we retrospectively self-reported observations of critical incidents [23], which is apt to collect recent or noteworthy incidents [23], [25]. To resolve inconsistencies in the critical incidents reported, we also used the project documentation summarized in Table II as a neutral instance. We integrated several approaches to identify and collect incidents for this article: we individually wrote down critical incidents across projects, held interactive group discussions, and exchanged documents such as category definitions and assignments as a critical incident log across projects. Iteratively drawing on emergent analysis results, we collected incidents that were 1) due to the digital context, for example, related to the digital nature of a prototype, and 2) inhibited or enhanced conducting Design Thinking by, for example, stalling ideation in the project.

Analyzing the Data as inductive, subjective reasoning [23], [25] aims at summarizing data in a practical format [23]. We coded all projects, based on where on a continuum stretching from fully digital to hardware-based the project outcome was. Within this general frame, we developed categories of challenges and opportunities in a digital context arising from the observed incidents, and validated them while also involving external expertise [23]. In the following, we report on five major categories of opportunities and four categories of challenges by detailing

TABLE I
OVERVIEW OF DESIGN THINKING PROJECTS IN THE DIGITAL CONTEXT

ID	Project Name	Type	Project Goal: How might we…
1	Improved Handover in Nursing	R	… improve handover between shifts in patient care?
2	Accurate Wound Documentation	R	… improve accuracy and efficiency of documenting chronic wounds in nursing settings?
3	Accurate Dispensing of Medication	R	… improve the accuracy of dispensing medication in hospitals?
4	Flexible Maintenance	R	…help maintenance workers deal with process variety?
5	Craftsmen Scheduling and Routing	R	… improve scheduling and routing of craftsmen within cities considering the traffic situation?
6	Nursing Service Scheduling and Routing	R	… improve scheduling and routing of nursing service employees within cities considering the traffic situation?
7	Energize	LICP	… design new offerings for residential customers considering the digitisation of the industry?
8	Foilizer	LICP	… use retrofit film solutions to advance the well-being in buildings considering different living conditions?
9	EuroAssist	LICP	… design innovative truck assistance services for drivers and freight forwarders?
10	LightCorp. 1	LICP	… design innovative exterior automotive lighting solutions in the context of fully automated driving?
11	ConsumeLit.	LICP	… design human-centred lighting to support elderly in X to extend living within their own home?
12	LightCorp. 2	LICP	… design individualizability using light for automotive mobility users considering a sustainable business model?
13	Automotive Inc.	LICP	… design the ultimate connected experience for future Automotive Inc. mobility users considering seamless, device-independent customer connectivity?
14	Capacity Development	LICP	… present consulting and information services for X citizens to prevent emigration and to support re-immigration into X considering Capacity Development's existing infrastructure?
15	Fleet Manager	SICP	… design a mobility service that builds on car data to create additional value for the car manufacturer's customers?
16	Gamification for Eco-friendly driving	SICP	… design a mobility service that builds on car data to create additional value for the car manufacturer's customers?
17	Parental Control for Young Drivers	SICP	… design a mobility service that builds on car data to create additional value for the car manufacturer's customers?
18	Secure Parking	SICP	… design a mobility service that builds on car data to create additional value for the car manufacturer's customers?
19	Crowd feedback service	SICP	… design the essential mobile service for smart urban transportation?
20	Location-dependent mobile advertising	SICP	… design the essential mobile service for smart urban transportation?
21	Matching service for transport and travel	SICP	… design the essential mobile service for smart urban transportation?
Legend: R: Research, LICP: Long Industry Class Project, SICP: Short Industry Class Project			

TABLE II
SUPPORTING DATA PER PROJECT TYPE

<table>
<tr><th>Research Project</th><th>Long Industry Class Project</th><th>Short Industry Class Project</th></tr>
<tr><td>- Scientific articles on outcomes
- Formal reports to project sponsors
- Working documents, e.g. results of experiments</td><td>- One-page summaries created ~ every 6 weeks
- Large presentations, ~ every 3 months
- Comprehensive reports, ~ every 3 months on
o Needfinding
o Prototypes
o Final Prototype</td><td>- Intermediate reports on
o Idea to answer challenge
o User Flow
o Final Prototype
- Final report on entire project including final prototype</td></tr>
</table>

a total of 43 major incidents, which each include a single or multiple events. Assessing the prevalence of each major category across all projects, we identified 63 occurrences, see Table III in the results section. The involvement of each author in different project types and in different roles allowed us to compare across project types, and thus to retest own observations [24]. We iteratively conducted interactive discussions in which at least two co-authors checked, discussed, and refined the categories and critical incidents. To improve reliability, we cross-checked observations [23], [24], also involving at least one author who had not been part of the project and thus in a “neutral” position. If there was no agreement among authors, we consulted project documentation as an additional, neutral instance to achieve consensus.

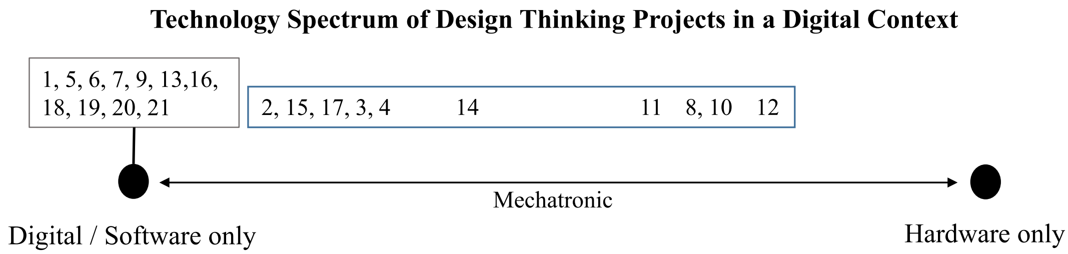

Fig. 2. Technology continuum of design thinking in a digital context.

In *Interpreting and Reporting* [23], we reflected on our use of the CIT and underlying themes of the resulting opportunities and challenges. Both intangibility as a key driver of observed critical incidents and potential limitations of our research approach are part of the discussion section.

IV. Results

To report on the effects of a digital context on conducting Design Thinking projects, we first describe the technology spectrum of projects—ranging from fully digital to hardware-based. Second, we report on opportunities and challenges observed in the opposing cases of fully digital and mechatronic projects. To conclude, we summarize our observations and assess their prevalence across project types.

While digital solutions become more and more important [2]–[4], innovation in hardware is not going away. We observed the outcomes of projects to lie on a continuum, which ranged from fully digital, software-based solutions at one end to hardware products at the other. Fig. 2 illustrates the relative position of the projects in our sample in the mechanical or digital space.

Hardware-only products constitute one extreme of the technology continuum. In these projects, a physical, hardware-based product made of tangible materials, such as metal, or flows of medium, such as electrical current, is the main outcome. Hardware-only projects are not part of the digital context this article focuses on.

Software-only or *fully digital* solutions, such as apps or technical backend solutions, are characterized as the outcome of pure knowledge work [5] and are thus intangible: that is, the underlying code is not physically perceivable. Naturally, all software has to run on hardware, which in these cases is, however, taken as a boundary condition and not elaborated as part of the outcome. While prototypes created throughout the project may include hardware elements, e.g., to explore the given boundary conditions or to hypothetically break assumptions, all projects attaining this position converged on a fully digital solution. In our sample, Projects 9 and 13 attained this position, for example. While Project 9 on roadside assistance dealt with services in the physical environment, these aspects did not form part of the final solution. Already from the outset, work in Project 13 on a "connected experience" was meant to run on a predefined hardware setup.

Many projects led to a mechatronic solution as a mix of hardware and software working together. The relative share of hardware and software determines the position on the continuum: At one end of the continuum, a software solution may be supported by specific hardware. At the other end, only minor digital features, such as a programmable digital timer, are part of the solution. Even though the software content may be small, by enabling the innovative function, it forms part of digital innovation. Between these extremes, innovative outcomes rely on a more even mix of hardware and software. For example, in Projects 8, 10, and 12, the key innovative outcome is embedded in software elements. This software is, however, tied to a hardware design specified in the project, which, if missing, would make implementing the solution impossible.

In the following, we elaborate on opportunities and challenges due to the digital context based on two projects at the opposing ends of the range we observed: Project 10 as a digitally enabled mechatronic project and Project 13 as a fully digital one. This choice enables us to summarize our key observations in critical incidents while considering the relative role of hardware in the project outcome. As applicable, we will draw on instances from other projects to explain the prevalence of the observed characteristics.

A. Digitally Enabled Innovation in a Mechatronic Solution (Project 10, LightCorp)

As a rich case of a mechatronic solution consisting of hardware and software, we chose Long Industry Class Project 10 to detail opportunities and challenges. LightCorp, a leading international innovator of lighting solutions, posed the project challenge "How might we design innovative exterior automotive lighting solutions in the context of fully automated driving?" Following LightCorp's focus on automotive OEMs, the challenge was set in a B2B context. As shown in Fig. 3, the project led to a mechatronic solution: Lights and their placement as hardware features were a key part, while software controlling these lights enabled innovative features.

In the setting of a Long Industry Class Project of nine months, a newly formed team, consisting of five graduate students with backgrounds in computer science, design, and management, collaborated with an international partner team of three students, who were located about three hours away by car. This distance enabled the two parts of the team to meet in person several times but still posed too much of a barrier to meet regularly. Interaction thus mainly took place via Skype and by exchanging documents. As neither the challenge nor the feature description referenced digital technology, the team embarked on broad needfinding, spearheaded by the exploration of the design space on lighting and fully automated driving. The first iterations of roughly built prototypes incorporated basic aspects of ideas, without any

Fig. 3. Final prototype in Project 10 (edited for anonymity).

consideration of implementation. As the level of detail increased, the digital control of lights to communicate with road users became salient. While the team first explicitly discussed digital features in prototyping, they subsequently also ideated on how to best address user needs via the digital control of lights.

Since work in Project 10 gained a focus on digital aspects only gradually, effects of the digital context stand out in comparison to work on hardware. We observed positive effects of the digital context on both the process of prototyping and the prototypes themselves. Moreover, the digital context allowed for the development of an innovative business model, which made addressing a larger number of human needs viable. However, we observed the management of stakeholders in the business model to be challenging.

1) Opportunity: Improved Collaboration in Prototyping and Testing: To implement light patterns for communication with road users in a mechatronic prototype, hardware modules provided light as a basic function, which was controlled by software to enable the innovative features. The local and the international collaboration team both had access to a hardware setup capable of showing the software features. This setting allowed us to observe the positive effects the ease of adjustments and the easy transfer of digital artifacts had on collaboration in prototyping and testing.

While changing digital aspects may not always be easier than adjusting hardware, already the local team in Project 10 benefitted from the relative ease of rapidly altering and updating software. The team very quickly created several variations of the software controls for testing, which they in turn adjusted based on testing results. Had the key feature been a hardware component, developing the same number of alternatives would likely have been prohibitively costly in terms of time and material. Thus, the digital context facilitated continued adherence to the key notion of Design Thinking to "fail quickly and cheaply" [19, p. 4].

The easy transfer of digital artifacts, moreover, played a very positive role in collaboration with the international team. Since digital artifacts are intangible, they can be moved and replicated electronically without hauling physical goods. The (marginal) cost of replicating and transferring a digital innovation is thus nearly zero [3]. In Project 10, this characteristic impacted profoundly, and compared to work on hardware components, improved collaboration. The international partner team, who were a three-hour drive away, had better testing conditions but were not as knowledgeable in software implementation. Since the main innovative feature used an Arduino program, bugfixes and new functions could be developed by the technical experts and shared as a file. If the team had needed to exchange physical items, leveraging these comparative advantages in testing would not have been feasible. This juxtaposition is exemplified by a critical incident in which the collaborating team called a local team member to fix issues with the hardware, which turned out to be a daunting task over the phone. The ability to easily share artifacts afforded high-quality testing while minimizing effort, which in turn enhanced the ability to iteratively learn about user needs.

In other projects: This effect may be more pronounced, the more a solution relies on software, that is, the further to the left on the technology continuum a project is situated. For example, Project 2, on wound documentation, involved only a minimal share of hardware. In such projects, fully software-based prototypes using standardized hardware can be nearly freely shared. We observed similar effects, for example, with a database prototype in Project 9 on roadside assistance and in Project 13 on a connected experience for mobility users.

2) Opportunity: High-Quality Prototypes With Low Effort: Project 10 also exemplifies the opportunity to harness high-quality predefined building blocks in digital innovation. As digital innovation is self-referential due to its reliance on existing digital technologies [27], there is an abundance of software packages, templates, and Application Programming Interfaces ready for use in prototyping features. There are marked differences compared to the use of prefabricated parts in mechanical prototypes: whereas mechanical parts need to be delivered first and may need major rework to function together as intended, digital building blocks are in many cases available for download and are meant to be integrated, which can lead to much faster results. In Project 10, the team identified a hardware and software extension to the open Arduino platform as promising. After the hardware had been delivered, the team swiftly created a working software prototype.

Compared to the mechanical part of the prototype, the software containing the innovative function attained a higher level of fidelity much more quickly. Notwithstanding the value of low-fidelity prototypes for testing [28], the higher fidelity of the digital artifact allowed for showing the intended feature in detail while still being easily adjustable. Combined with the ease of changes previously mentioned, this enabled the team to iterate very quickly in testing and prototyping by swiftly gathering and incorporating user feedback on the exact specifications of the light pattern contained in the solution.

In other projects: We made similar observations in Projects 12 and 13, for example. While Project 13 on a "connected experience" was inherently digital, Project 12 also resulted in a mechatronic solution. Project 12 had nearly perfected the software in user testing before work on sophisticated physical prototypes had even started, which illustrates the relative difference in fidelity between hardware and software.

Achieving higher fidelity within the same timeframe also changes the role of the final prototype. The value and the status of a final prototype as an artifact embodying the information gained through development [10], [29], [30] may vary between digital and hardware prototypes. A mechanical final prototype demonstrates core functionality and foreshadows what a production version may look like. Such prototypes are, however, frequently made using materials or processes that differ from those used in production. For example, a small quantity of prototypes may not allow for tooling such as diecasts. In comparison, digital final prototypes may afford more comprehensive reuse. By controlling the lights and thus showing the logic of the innovative feature, the software code was the most significant outcome of Project 10. The hardware elements of the prototype had the sole purpose of supporting the innovative software features, without detailed consideration of actual operational requirements or manufacturing. Relatively speaking, the software was much more mature and could be reused in further development by LightCorp.

In other projects: This observation also applies to several other projects. For example, Project 12 implemented the key function of improving well-being using context-sensitive light in the software of the mechatronic prototype. Compared to Project 10, the hardware, however, played a more prominent role: Hardware design was a key priority for the team, who, for example, developed different hardware types for children and adult users. In fully software-based prototypes, such as in Projects 9 or 13, the key software functionality may not be ready for use in a production version, but higher level aspects, such as the logic and user flow, may be directly carried over into implementation.

3) Opportunity: Innovative Business Model as Enabler of Human-Centered Innovation: While human-centricity is the cornerstone of Design Thinking, it has to be in balance with business viability [13]. In Project 10, we observed digital solutions to facilitate new business models, which in turn enabled the team to better address user needs.

The team had collected positive user feedback on the proposed functionality of personalized light displays, but deemed hardware costs unviable. Hardware-based products are commonly sold to a customer or, in a more contemporary approach, form part of a product-service-system [31]. In both cases, a constant core functionality is provided in exchange for either a one-time payment or a continuous revenue stream. In this traditional logic, covering the high hardware cost via the purchase price or leasing fee seemed unviable.

Reckoning that digital control enabled the key feature of personalization, the team turned to exploring options in the business model, which led to an innovative approach alleviating the limitations of purchasing and leasing. The final business model incorporated three traits common in the digital realm: pay-per-use-servitization, ad-based monetization, and a platform mechanism. In pay-per-use servitization, which digital technologies can enable, customers do not pay for the product but its use [32]. The team changed the business model from quoting a feature price to quoting a price for *using* the feature in, for example, car rides. While servitization may stretch the time for payments, customers still have to bear the feature cost. To alleviate the issue of high overall cost, the team adopted an ad-based strategy. In ad-based business models, such as implemented in Google search, customers benefit from functionality by accepting the display of ads or gathering of their data instead of paying money. Hence, the team made the display feature of the prototype usable for displaying ads, which, if users chose this option, would subsidize overall cost. To match customers looking for subsidized feature price with those seeking to display ads, the team adopted a platform approach, that is a multisided market in which the platform owner acts as a facilitator to match diverse parties [33], [34].

In this platform- and ad-based business model, the high hardware cost could be, at least in part, passed on to ad sponsors, while users got to keep most of the benefits of personalization. Digital features enabled an innovative business model, which in turn made addressing the observed need for personalization viable. It has to be noted, though, that the effort required to develop and test the business model partly shifted the focus of work from elaborating and testing a high-resolution prototype to detailing the business model.

In other projects: We mostly observed this opportunity in projects set in the fully digital realm. Project 9, on roadside assistance, worked on more direct interaction between stakeholders within a quasi-platform, whereas Project 13 on connected services was inherently set to work with multiple providers.

4) Challenge: Networked Stakeholders in the Business Model: To tackle "wicked" issues involving high levels of ambiguity and a complex interaction of effects [14], [35], Design Thinking puts much emphasis on identifying and managing stakeholders [12], [13]. While design always acts within a network of stakeholders [36], we observed the digital context to lead to complex, networked stakeholder relationships related to the business model, which require adequate management.

Even hardware-based business models may exhibit multitiered value chains, which make addressing user needs complex. For example, Project 10 was set in a B2B context: While investigating user needs, the business model did not plan for a direct relationship between LightCorp and users. Hence, the approach to addressing user needs became more complex: Instead of directly addressing user needs, they had to be integrated with the interests of intermediaries along the value chain, especially those of automotive OEMs.

By embedding organizations in an increased number of dependencies [37], which results in a networked ecosystem [33] as opposed to a value chain, digital innovation further increases the complexity of stakeholder management related to the business model. Since digital artifacts commonly interact with each other and draw on existing technologies [27], procurement dependencies mount beyond ordering mechanical parts. Similarly, digital solutions frequently act as building blocks for customers to develop their own solutions [27] and thus propagate dependencies. Moreover, digital technologies change frequently [38], which renders all technological interactions and relationships inherently *dynamic* and thus further adds to complexity.

By including the stakeholder category of complementors, platform business models, such as the one developed in Project

10, add yet another layer of complexity. A platform business model is not only embedded in an ecosystem of dependencies but constitutes a multisided market bringing together diverse entities co-creating value with the platform owner [33], [34]. Providing adequate resources for complementors and defining their role is a complex issue in what has been called platform governance [39]. Hence, addressing user needs becomes more complex by requiring their integration in the co-creation network. The personalization prototype of Project 10 illustrates this challenge: In addition to managing intermediaries in a multitiered value chain and managing dependencies of (digital) building blocks, the platform business model required orchestrating ad- and content-providers as complementors. Without their contribution, the business model would not have been feasible. Work on the business model thus was much more complex and effortful compared to projects without a digital platform business model.

Overcoming this challenge: The team in Project 10 coped with this challenge by expending a lot of effort on stakeholder management throughout the project. The team interacted frequently with selected intermediaries and other stakeholders to gather their motivations and interests, which they integrated into prototype development and assessment. As evaluation criteria, the team emphasized actual user needs. In our observation, it was especially beneficial the team considered the needs of OEMs early in exploring the multitiered value chain: it made the transition to orchestrating complementors in the platform business model an extension to instead of an onslaught of complexity.

In other projects: We observed similar, if lesser, challenges, for example, in Project 13, which aimed at the development of solutions for mobility users in collaboration with internal and external stakeholders. Especially since the parties involved differed by country, the team was at points unsure to what extent they could take required building blocks and relationships with partners for granted. In Project 13, however, the corporate partner was able to provide guidance on how to deal with these open questions, which enabled the team to either readily address these challenges or to go on with working hypotheses while focusing on user needs.

B. *Fully Digital Innovation (Project 13, Automotive Inc.)*

Showcasing a number of opportunities and challenges to applying Design Thinking in a digital context, we chose Project 13 as an exemplar of fully digital innovation. Automotive Inc., a leading international producer of passenger vehicles, posed the challenge “How might we design the ultimate connected experience for future Automotive Inc. mobility users considering seamless, device-independent customer connectivity?” The challenge was set in a B2C context and aimed for direct use by Automotive Inc.’s customers. Fig. 4 depicts an overview screen of the final prototype app.

Project 13 was a Long Industry Class Project lasting nine months. The newly formed team, consisting of five graduate students with backgrounds in computer science, information systems, robotics, and management, collaborated with an international partner team of four students. The partner team was located on another continent—requiring a flight of more than ten hours to meet. While the teams met for an initial kickoff and

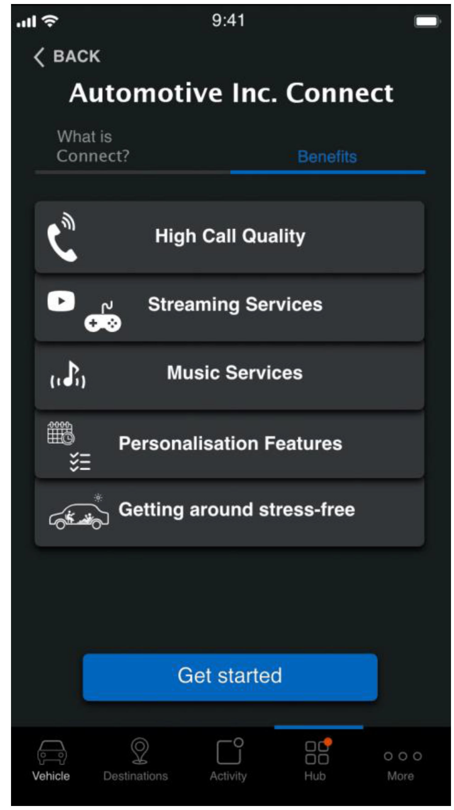

Fig. 4. Screenshot of final prototype app from Project 13 (edited for anonymity).

two intermediate meetings, collaboration centered on Skype and exchanges of documents.

By calling for a “connected experience” considering “device-independent […] connectivity,” Project 13 implies a fully digital solution, that is, all innovative features are software-based without specifically considering hardware details, from the outset. Hence, while sometimes including hardware elements as necessary enablers, ideation and prototyping throughout the project focused on software features. Since the project converged on a fully digital solution and resulted in an app as the final prototype, it lies on the fully digital end of the technology spectrum. This context allowed us to observe opportunities and challenges to Design Thinking traceable to fully digital innovation. We observed opportunities in needfinding through engagement at a distance and in greater potential for individualization. At the same time, we observed challenges related to imagining intangible features, estimating feasibility, and the choice of medium and resolution for prototypes.

1) Opportunity: Immersive Engagement at a Distance: In Project 13, the boundaryless availability of digital artifacts facilitated immersive needfinding through engagement. Digital artifacts, such as services or apps, can be used virtually irrespective of physical location, which improved the understanding of stakeholder needs while working at a distance.

In any project, online sources, such as discussion forums, blogs, or product reviews, can provide rich information in the voice of the customer [22]. This ability comes in especially handy whenever direct access to the target group or the context of use proves difficult due to, for example, physical distance. The data may, however, provide only limited insights—especially when compared to experiencing a situation first-hand by taking the place of stakeholders, as is recommended for needfinding [22]. For example, if one were to gain insights on the actual use of turn indicators in China, harnessing online sources may prove difficult since they do not allow for unfiltered observation, let alone immersion in the context of use.

Compared to only consuming information about the experiences of others, a digital context can, however, enable immersive needfinding through engagement in the actual activity, which is recommended for Design Thinking [22]. Given their intangible nature, digital artifacts, such as apps or services, are easily transferable [3] using electronic means. It is thus possible to use and explore a digital artifact nearly irrespective of location. For example, while it may not be possible to engage in Chinese traffic to investigate the use of turn indicators, it is well possible to access a Chinese e-commerce site and try out the user flow. In this sense, the focus on a "connected experience" enabled the team in Project 13 to engage in the target group's actual behavior. To understand the use of social networks in Asia, for example, the team explored social media aimed at Asian users. Without having to travel to Asian countries, the team was able to experience the actual digital artifacts and their features for themselves. This ability allowed the team to quickly gain insights into how the target group likes to be seen and interact, which in turn helped in ideation on connected solutions in the mobility context. Insights gained in this manner complemented on-site research by the team, which was inherently limited by physical distance.

In other projects: We observed similar opportunities in, for example, Projects 2 and 7. The team in Project 2 on documenting wounds tested a number of existing apps for that purpose in benchmarking, which enabled them to gain an in-depth understanding of the shortcomings of existing solutions. In particular, the team was able to trace complaints of current users and to evaluate the degree to which needs have been fulfilled. Engaging with physical artifacts in the same manner would not have been possible considering the effort needed for traveling to facilities or shipping devices. Similarly, Project 7 engaged with a number of existing smart services without having to bear the effort of engaging with physical artifacts.

2) Opportunity: Potential for Individualization: Compared to hardware products, digital solutions make offering individualized products easier. For example, although the exterior of cars can be individualized with different colors, offering such customization based on producing different *physical parts* is effortful and can incur high cost [40]. By providing a common basis for content, features, or behaviors, digital solutions afford scalable individualization without changes in hardware at near-zero marginal cost. Hence, a digital solution can address highly individualized needs of different user groups or even serve as a canvas for self-expression of individual users.

In its initial exploratory needfinding, the team in Project 13 identified several needs applicable to larger user groups. These needs, such as "personalization," were, however, very generic and not concrete enough for creating prototypes. At the same time, they identified niche needs for specific target groups, which in turn limited general appeal. Considering the cost and effort involved in offering individualized versions [40], it would only have been viable to work on a few promising hardware features. The digital context, however, enabled the team to consider the entire "long tail," that is, highly individualized needs [41]. Thus, they built a prototype addressing the generic need, which, serving as a canvas for personalization, offered different options to fulfill individual niche needs according to, for example, context or user profile.

This prototype journey, which integrates user needs at different levels of abstraction, exemplifies the dichotomy of diverging and converging activities in Design Thinking [12]: While the team diverged to observe and accommodate many needs, they had to converge on appropriate generic features at the same time. Creating generic groups made concise introductions in testing and complexity in prototyping manageable. To differentiate generic and individualized aspects, the team focused on finding universally well-received elements, e.g. personal entertainment, and personalized individual features such as the music played.

In other projects: We made similar observations in several other projects. While revolving around a common online platform, Project 7 devised very different value propositions and features for users based on their technical proficiency concerning smart home products. Project 9 developed a common digital platform for roadside assistance, which offered different information and features to different stakeholder groups such as truck drivers and repair workshops. The team in Project 10 developed a prototype centered on individualization, which offered a platform for different designs based on user preferences. In all of these projects, the digital core was implemented as a canvas for users to fulfill their individual needs.

3) Challenge: Imagining Intangible Digital Features: The team in Project 13 experienced difficulties in imagining and creating tangible prototypes of digital features, which were additionally set in a future context. While the team sought to adhere to the key Design Thinking principle to make ideas tangible [12], [13], the fact that digital innovation is either not perceivable at all or, in many cases, only as screens on existing devices, proved challenging. The team in Project 13 had to imagine and prototype digital features in the context of future mobility, which added a layer of complexity by having to anticipate future developments in mobility. While this situation provided a blank canvas for ideating features, we observed that the team was overwhelmed by the breadth of the potential solution space that contained only few or even no physical elements as boundary conditions.

This challenge was exacerbated by having to consider multiple levels of abstraction: The user experience as a key outcome, user interaction, and prior set-up, for example, by installing apps. A prototype in Project 13 integrating several needs such as in-car entertainment and relaxation exemplifies this challenge: After initial set-up, the critical user experience relied not only on interaction via voice but also on automatically registering underlying user needs, which does not relate to a discernable interface. To enable user testing, the team had to expend much effort to come up with an experienceable, perceivable embodiment of the intangible digital solution. This was especially difficult, since testing aimed at gaining feedback on the automated, unperceivable part of the prototype.

Overcoming this challenge: To overcome or at least ameliorate this challenge, the team constantly renewed its focus on user needs: What kind of experience would users appreciate? In particular, they tried to trigger the respective reactions without considering implementation. In hardware-based or mechatronic projects, this is possible by mimicking the intended shape and feature using materials such as cardboard, which makes the core feature experienceable and directly tangible. In the fully digital context, the ability to recreate the overall experience is more limited. To create rough prototypes, the team used paper prototypes showing wireframes of screen-based solutions. As the team reported, the prototypes were, however, not self-explanatory as testing required describing the context. While this approach worked well to start conversations, we consider it a deviation from the "show don't tell" principle [19, p. 35]. As an even greater deviation, a Design Thinking project in the context of autonomous driving prepared mock-ups as abstractions of both the feature and its use context, which worked well to make fully digital features experienceable, even if still not tangible. For example, a cardboard scenario featuring toy cars illustrated the experience of sensing and sharing data on parking spots. Team members would then present the envisioned scenario to testees and collect comments. These observations are in line with findings that rudimentary, low-fidelity prototypes are sufficient to conduct initial tests of digital innovation [42].

For increasing fidelity and to collect rich feedback, the team in Project 13 inched closer to recreating the actual experience by, for example, testing paper prototypes inside car cockpits or by developing a tangible wizard-of-oz prototype catering to entertainment and relaxation needs. Thus, we conclude that, after overcoming the initial challenge of imagining features on the blank canvas of digital innovation, the continuous evolution of prototypes in Design Thinking [19], [22] worked well to iteratively refine ideas.

In other projects: We made similar observations in other projects. In Project 3, for example, the team identified an Augmented Reality solution to display the number of pills to be distributed to medical dispensers as the most promising experience. Testing this proposition without developing a fully implemented solution was possible by using paper mockups. Placing these below actual dispensers emulated the experience of having necessary information right on the dispenser as a wizard-of-oz prototype, which allowed for rich feedback early on. By placing it in the use context, the team successfully translated the digital experience of virtual augmentation into a physical one. With the dispenser as a clear physical reference, the approach in Project 3 worked better than the one in Project 13 but still required explanation to users and thus violated the "show don't tell" principle [19, p. 35].

4) Challenge: Correctly Estimating Feasibility: We observed that adequately estimating technical feasibility was a challenge in Project 13. While the team struggled with ideation on intangible digital solutions, see above, they conversely showed a tendency to overestimate feasibility in implementation. Drawing on inspiration gained from digital assistants such as Amazon Alexa, they intended to not only show but actually implement personalized services using sensors and artificial intelligence. Despite warnings that even the general state of technology would not allow for such a solution, they pursued a full-fledged prototype, which contained a broad feature set. After failing in implementation, the team relied on a mostly wizard-of-oz prototype with far fewer features than initially planned, but which still allowed for gathering rich user feedback.

While estimating feasibility is also a concern in hardware implementation, the specifics of digital artifacts make it more challenging. Software is made up of interdependent modules, which all have to work together to achieve the overall outcome [43]. As a consequence, whereas a failed hardware implementation may be considered "quite close," inadequate performance of one of the software modules can more easily obliterate all functionality—making the implementation of a feature a binary outcome. Overestimating feasibility had several negative effects. Trying to force implementation took much time, which the team could have used instead to build several prototypes to gather feedback and "fail quickly and cheaply" [19, p. 4]. In addition, the team focused a lot on this idea and considered it as the only solution for some time, which inhibited creative ideation.

Overcoming this challenge: To overcome this challenge, the team had to take a step back and reevaluate their goal in building the prototype. Declaring the user experience the most important aspect, they were able to reduce the feature set. They then assessed the feasibility of different system designs ranging from safe bets to moonshots. Based on such a more conservative estimate of feasibility, they were able to implement features in prototypes. They did, however, leave features needing much effort in implementation as wizard-of-oz experiences by adjusting controls themselves. This approach allowed the team to return to iteratively refining prototypes to address user needs instead of obsessing with technical feasibility.

In other projects: We observed related, if not entirely similar, issues in other projects. Unlike in Project 13 *over*estimating feasibility, Project 9 on improving roadside assistance suffered from *under*estimating feasibility. The technically skilled team member did not believe the envisioned solution of a shared online platform could be implemented. This engaged all team members in the search for a solution, in spite of the fact that implementation of the database backend of a web application was straightforward.

5) Challenge: Adequate Medium and Resolution for Prototyping: Iterative prototyping to make ideas tangible and thus readily understandable is a key aspect of Design Thinking [12], [13]. The fidelity of prototypes should evolve over the course of the project [19], [22]: To evaluate initial ideas, it is advantageous to demonstrate core features using only low-fidelity prototypes. In the fully digital context of Project 13, we repeatedly observed team members, especially those with a background in computer science, to be inclined to forego in-depth user testing and needfinding in favor of developing a fully coded solution right away. Showing these prototypes of a higher-than-necessary level of fidelity to stakeholders repeatedly led to the sobering insight that the solutions did not address user needs.

Even at a preproject stage, one of the members solved a warm-up challenge as an app without considering actual user needs. In developing a late-stage prototype app to introduce customers to the "connected experience," the team used an existing Automotive Inc. app as a template without considering whether the existing layout and user experience address user needs. Showing such full-fledged solutions in testing changes

TABLE III
OVERVIEW OF OPPORTUNITIES AND CHALLENGES OF DESIGN THINKING IN A DIGITAL CONTEXT

Opportunity	Description	Observed in	Challenge	Description	Observed in
Immersive Engagement at a Distance	Ability to try existing digital solutions allows for immersive needfinding even at a distance.	Mechatronic: 2, 14 **Fully Digital: 13**, 5, 7	**Imagining Intangible Digital Features**	Intangibility of digital artifacts poses issues in ideation and prototyping.	Mechatronic: 2, 3 **Fully Digital**: **13**, 5, 9
Improved Collaboration in Prototyping and Testing	Digital features enable frequent changes and easy transfer of prototypes.	**Mechatronic: 10,** 12, 2 Fully Digital: 7, 9, 13	**Correctly Estimating Feasibility**	Nature of interdependent artifacts of knowledge work makes feasibility hard to assess and a discrete event.	Mechatronic: 2, 4, 8 **Fully Digital**: **13**, 9, 21
Potential for Individualization	Easy adaptability of digital solutions allows for fulfilling even niche needs.	Mechatronic: 8, 10, 17 **Fully Digital**: **13**, 5, 6, 7, 9	**Adequate Medium and Resolution for Prototyping**	Inclination of technical experts to leap into implementation without considering user needs.	Mechatronic: 2, 15 **Fully Digital**: **13**, 7, 9, 21
High-Quality Prototypes with Low Effort	Availability and easy integration of high-quality building blocks enable fast creation of prototypes, which can be reused in later implementation.	**Mechatronic**: **10**, 2, 3, 4, 8, 12 Fully Digital: 5, 6, 7, 9, 13	**Networked Stakeholders in the Business Model**	Digital solutions as enablers of innovative features and parts of platform business models increase complexity in stakeholder management.	**Mechatronic**: **10**, 2, 8 Fully Digital: 1, 5, 6, 9, 13, 16, 19
Innovative Business Models to Make Addressing Human Needs Viable	Digital features aid implementation of innovative business models based on pay-per-use servitization, ad sponsoring, and platforms.	**Mechatronic**: **10** Fully Digital: 9, 13, 16, 18, 20	Opportunities and challenges ordered by project phase. Projects used as representative examples put in **bold.**		

interaction [44] and risks evoking reactions from stakeholders on details rather than the core idea [13], [30]. Feedback on polished details may thus fail to answer the key questions [13], [30], for example, whether features are desirable for users.

Overcoming this challenge: To overcome these issues, the team was forced to adhere to Design Thinking principles, that is, to focus on desirability in early project phases using low-resolution prototypes without considering technical feasibility and details. During later stages, they separated testing for feasibility, the "how" in implementation, and desirability, the "what." After experiencing lackluster results from testing with the high-fidelity prototype, they reverted to testing desirability using a stripped down, less functional prototype. A next iteration may thus have included fewer features to focus on understanding user concerns in depth. This helped the team to at least lessen the issue of drawing user comments on technical aspects.

In other projects: We observed similar challenges in other projects. For example, in Project 2, team members developed a fully functional tablet app, only to find that the key issue was to devise a solution that could be used handsfree. In this case, the effort wasted was substantive and enough of a shock to lead the team to fully embrace a needs-driven approach.

C. Summary of Results

To investigate opportunities and challenges arising for Design Thinking in a digital context, we detailed critical incidents in two projects representative of the opposing cases mechatronic, that is hardware- and software-based, and fully digital, software-based, innovation. In the mechatronic Project 10 with LightCorp, we found that the digital context improved prototyping through efficient collaboration and the opportunity to quickly generate high-quality prototypes. In addition, we observed that the digital context enabled innovative business models making fulfillment of previously unsatisfiable needs viable. The fully digital Project 13 with Automotive Inc. highlighted new opportunities in needfinding through engagement in the use context–even remotely. Moreover, the digital context made offering highly individualized solutions easier. The digital context also gave, however, rise to several challenges. In the digitally enabled mechatronic project with LightCorp., devising a platform-based business model presented a challenge in terms of adequately managing stakeholders. The fully digital Project 13 exposed issues in imagining intangible, digital features and correctly estimating their feasibility. In addition, finding the right level of fidelity in prototyping proved difficult.

Ordered by project phase, Table III summarizes the prevalence of opportunities and challenges. We observed opportunities, which run the gamut from early needfinding to elaborating business models, in both mechatronic and digital-only projects. In our recollection of critical incidents, the contrast between digital elements and hardware features, however, made them much more salient in mechatronic projects making greater use of hardware. Except for the challenge of managing stakeholders in innovative business models, challenges are most pronounced in dealing with digital artifacts during ideation and prototyping. Although we observed each challenge in both project types, we found that critical incidents in mechatronic projects led to less severe effects. In these cases, working on hardware may have ameliorated some of the issues with imagining and assessing digital features. This line of thought is supported by our observations on the challenge of imagining intangible digital features: It was prevalent only in fully digital projects and mechatronic Projects 2 and 3, which contained a large share of digital features. While presenting different contexts, we did not note differences based on whether projects were Research or Class Challenges. As discernable from Table III, we observed nearly all opportunities and challenges in both settings.

V. Discussion

Design Thinking has become a popular approach to problem solving and innovation [13], [16]. With innovation shifting to digital features [2]–[4], the question arises which opportunities and challenges are unique to applying Design Thinking in a digital context. Drawing on 21 Design Thinking projects, we reported on critical incidents in one mechatronic, that is, software and hardware forming an integrated solution, and one fully digital, software-based, project. In the following, we discuss our observations on the intangibility of digital artifacts as an enabler or inhibitor of Design Thinking. These considerations lead us to propose implications for Design Thinking projects in a digital context before we position our results in extant research on Design Thinking.

A. *Intangibility of Digital Artifacts: Enabler or Inhibitor?*

Taken together, our observations lead to the insight that the intangibility of digital artifacts can either boost or inhibit Design Thinking projects. As an artifact of digital innovation, software is the result of pure knowledge work [5] and is thus intangible. This characteristic enabled key opportunities we observed. First, software features of prototypes could be easily adjusted, which allowed for creating broad variety in testing. Even core functions of software can be changed quickly without the need for any additional material. While this trait was taken as given in fully digital projects, the restrictions in adjusting hardware components in mechatronic solutions emphasized the difference: Adjusting major hardware components entailed considerable effort from procuring parts, through integration, to ensuring the long-term physical stability of the prototype. In comparison, in many cases, while software changes presented a headache for the coder, they did not exhibit as many external dependencies causing delays.

Second, intangibility makes software easily transferable [3]. This trait enabled immersive needfinding by engaging in the use context and effortlessly sharing artifacts among collaborators, no matter where they were located. In particular, this ability allowed for frequent iteration on prototypes, for example, by sharing unfinished states and subsequently addressing any bugs. Taken together, the ease of changes and the inherent transferability allowed for scalable, decentralized prototyping and testing: By creating a digital solution once and transferring it instantly, the team in Project 10 could test at two locations simultaneously. This advantage is again emphasized by the direct opposition to work on the hardware components in Project 10 on exterior lighting: Whereas the software could simply be transmitted online, hardware problems in the collaborating team were much more difficult to resolve remotely.

Opposing these positive traits, we can trace the root cause of several of the challenges we observed to the inherent intangibility of digital innovation. Located at the fully digital, software-based end of the continuum, the team in Project 13 had a hard time imagining intangible features. In fact, these difficulties may have set off a vicious circle: Our observations imply that only considering a use context, without hardware components as a reference, may have made the scope of the problem space too broad, which, in turn, prevented the team from coming up with concrete ideas of what the user experience ought to be. While the team was able to describe the prototype idea of an artificial intelligence solution in abstract terms, it struggled with creating a low-resolution prototype embodying what made their idea desirable. The absence of a universally clear picture of the "what" subsequently led to problems in defining the "how" of technical implementation due to underestimating the effort needed for implementation—our second observed challenge. This lack of insight into actual feasibility most likely contributed to the third observed challenge: Choosing an appropriate level of fidelity in prototypes. The team may implicitly have considered building a high-resolution prototype, which would also answer the "how" of technical feasibility, as the only way to get a grip on the intangible feature. As a violation of key Design Thinking principles, they would have used a fully implemented feature to test whether the feature was desirable. The drive to build high-resolution prototypes thus relates back to the root cause of the difficulties related to imagining intangible digital features.

B. *Implications for Design Thinking Projects in a Digital Context*

Our findings have implications for conducting Design Thinking projects in a digital context. Especially when compared to hardware, we observed that digital features presented opportunities related to, for example, prototyping and testing. If a project contains hardware elements, incorporating digital features may open up opportunities in design and new business models. This can involve either shifting an existing feature to the digital realm [3] or including additional features as a way of exploiting the opportunities we observed. Conversely, managing the observed challenges of digital features is a key consideration. While requiring increased effort, the challenge of managing stakeholders in digitally enabled business models could be adequately addressed by embracing the Design Thinking mindset to empathically investigate actual needs using tools, such as stakeholder maps.

Unfortunately, the challenges posed by the intangibility of digital features were more difficult to overcome. Since projects working on mechatronic solutions exhibited the challenges to a lesser extent, we suggest that hardware should be included at least as a boundary consideration in projects, which makes applying the Design Thinking principle to "make it tangible" [12], [13] easier. A fully digital context without elaborating any hardware elements may lead to difficulties in making ideas tangible: for example, if the relevant features are intended to run automatically based on sensors. In these instances, we suggest splitting up the task of prototyping: projects may for a relatively long time strictly focus on the question of which experience is desirable—the "what" in development. To accomplish this goal, we found that, in early stages, using a very basic prototype abstracting from a use scenario works well. Such a prototype, for example, a cardboard with toy cars, may not provide any functionality but may serve as a graphic description of the context. Even though these prototypes required explanation during testing and thus violated the "show don't tell" principle [19, p. 35], they functioned well to start conversations. In later stages, projects *also* have to estimate technical feasibility—"how" the feature is going to work, which requires a technical proof-of-concept of an artificial intelligence solution, for example.

The right medium and resolution for prototypes in later stages may lie in a dual approach: Continued use of low-resolution prototypes to ascertain desirability and the development of prototypes as technical proof-of-concepts to iteratively update estimations of feasibility. Technical proof-of-concept prototypes are especially meant for use within the team. Using proof-of-concept prototypes in user testing may lead to the issue of users commenting on aspects "under the hood" instead of providing feedback on the desirability of features [13], [30]. In user testing, projects can continue using relatively low-fidelity prototypes for corroborating "what" the features should do. While these prototypes aimed at "what" to develop also evolve—from a paper mock-up of a scenario to, for example, a full website layout showing the user interface, they may remain far less detailed in terms of functionality. Based on our observations and experiences, we see such a dual approach as a promising way to handle the intangibility of fully digital artifacts in prototyping and testing.

C. Contribution to Design Thinking Research and Limitations

Drawing on a rich and diverse history in design studies, Design Thinking now acts as a managerial approach to problem-solving [16]. With its ability to address "wicked," hard-to-grasp problems [14], it has drawn much interest as an approach to innovation in a range of different contexts [1], [13], [28]. Increasingly, innovation has, however, shifted to the digital realm [2]–[4], which implies specific changes in artifacts and working style—calling for adopting Design Thinking [6], [17].

Extant research into Design Thinking in the digital context has, for example, investigated the potential benefits of introducing Design Thinking into IT organizations [20] or those derived from its ability to improve requirements engineering [45]. As a specific example, combining Design Thinking with agile software development may lead to superior outcomes [46]. Embracing the notion that Design Thinking is a valuable approach to innovation in the digital context, we add to this stream of research by providing initial insights on *how* the digital context affects conducting Design Thinking projects. By reporting on our observations of opportunities and challenges, we hope to contribute to the evolution of tools in Design Thinking. Our results highlight areas that may benefit from additional methodical support. The observed dual nature of intangibility, which both drives opportunities and poses challenges, especially links to previous findings on how prototypes and their characteristics shape interactions in design [29], [44]. We moreover add to propositions to further develop the role of prototyping as a key activity of Design Thinking in treating wicked problems [47]. Such developments may also position Design Thinking as a go-to approach in areas of digital innovation that are currently lacking adequate support. For example, there have been calls for more methodical support in embracing digital solutions for providing services [48]. In our expectation, a digital-aware toolset in Design Thinking, that is sufficiently developed, may help to overcome such issues.

As with any research endeavor, this study is subject to limitations. To identify opportunities and challenges of a digital context for Design Thinking, we iteratively identified and analyzed critical incidents from 21 projects. While the projects exhibit thematic variance, the joint involvement of the authors and similarities between the cases limit generalizability. Our sample and methodological approach are exploratory and further research may help in achieving comprehensive coverage of the effects of a digital context. Our observations of specific traits of the digital context in part rely on comparisons with hardware features in our projects. Since all projects comprise at least some digital features, a comparison with hardware-only projects would be fruitful future research. To render as accurate an account of critical incidents as possible, we sought to provide detailed, rich descriptions [23] including information on antecedents and effects [24]. As stated in the method section, the involvement of several, but not all, authors in each of the projects improved reliability in iteratively identifying and categorizing critical incidents. Similarly, by taking several roles in multiple projects, each author was able to take multiple perspectives in judging incidents, which should improve reliability. Despite such efforts, personal biases may still have influenced our results.

VI. Conclusion

The locus of innovation has shifted from purely mechanical advances to hybrid hardware- and software-based or fully digital forms. Design Thinking is an established methodology for creating human-centered innovation, which is independent of the application context and therefore suitable for use in a digital context. Drawing on 21 Design Thinking projects, we identified opportunities and challenges related to applying Design Thinking in a digital context. We reported on critical incidents in two projects positioned at opposing ends of the technology spectrum ranging from digitally enabled mechatronic solutions to fully digital projects. In the mechatronic project, we observed opportunities in improved collaboration in prototyping, high-quality prototypes, and innovative business models. Complex relationships of stakeholders in the business model did, however, present challenges. In a fully digital context, we observed opportunities in improved needfinding and the ability to offer individualized solutions. However, the fully digital project showcased several challenges associated with imagining intangible digital features, correctly estimating feasibility, and finding the right medium and fidelity in prototyping. In discussing our observations, we identified the intangibility of digital innovation to drive both opportunities and challenges. We would like to initiate a discussion on how existing tools in Design Thinking can be best used or supplemented for innovation in a digital context.

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Leonard Przybilla received the master's degree in management and technology from Technische Universität München (TUM), Germany, in 2017.

He is currently a Researcher at the Chair for Information Systems at TUM. His research interests include project management for innovation, such as design thinking, and team processes. His research has been published in conference proceedings such as ICIS, ECIS, PACIS, and ACM SIGMIS CPR.

Kai Klinker received the master's degree in informatics from Technische Universität München (TUM), Germany, in 2016.

He is currently a Researcher at the Chair for Information Systems at TUM. His current research interests include augmented reality, smart glasses, passive trust and design science. His research has been published in journals and conference proceedings such as ISF, DESRIST, MKWI, ECIS, INFORMATIK, GMDS, PVM and PACIS.

Michael Lang received the master's degree in finance and information management from Technische Universität München (TUM), Munich, Germany, and Universität Augsburg, Augsburg, Germany, in 2014 and the doctoral degree in information systems from TUM in 2019.

He is currently a Project Manager at MSG nexinsure ag, developing and implementing insurance platform solutions. His current research experience and interests include decision-making in cloud sourcing projects, certification of cloud services, and information privacy in online environments. His research has been published in Information & Management and a number of refereed conferences such as ICIS, ECIS, and HICSS.

Maximilian Schreieck received the master's degree in management and technology and the doctoral degree in information systems from Technische Universität München (TUM), Germany, in 2014 and 2020, respectively.

He is currently a Postdoctoral Researcher at the Chair for Information Systems, TUM. His research interests include platform governance and enterprise software systems. His research has been published in the IEEE TRANSACTIONS ON ENGINEERING MANAGEMENT, ELECTRONIC MARKETS, INFORMATION TECHNOLOGY FOR DEVELOPMENT, JOURNAL OF INFORMATION TECHNOLOGY TEACHING CASES, and conference proceedings such as ICIS, AOM, ECIS, HICSS, AMCIS, and PACIS.

Manuel Wiesche received the Diploma in information systems from Westfälische Wilhelms-Universität, Münster, Germany, in 2009 and the doctoral and habilitation degrees from the TUM School of Management, Technische Universität München, Munich, Germany, in 2014 and 2019, respectively.

He is currently a Full Professor and Chair of Digital Transformation at TU Dortmund University, Dortmund, Germany. His current research interests include digital platform ecosystems, IT workforce, IT project management, and IT service innovation. His research has been published in MISQ, EJIS, JMAR, CACM, IEEE TEM, I&M, EM, and MISQE.

Helmut Krcmar received the master's degree in business administration with majors in information systems and taxation and the doctoral degree Dr. rer. oec. from Universität des Saarlandes, Saarbrücken, Germany, in 1978 and 1984, respectively.

He is currently a Professor Emeritus of Information Systems with the Department of Informatics, Technische Universität München (TUM), Munich, Germany, with a joint appointment with the School of Management, where he is currently the Founding Dean and Delegate Officer of the President – TUM Campus Heilbronn. He has been a Postdoctoral Fellow with IBM Los Angeles Scientific Center, and an Assistant Professor of Information Systems with the Leonard Stern School of Business, NYU, and Baruch College, CUNY. From 1987 to 2002, he was the Chair of Information Systems, Hohenheim University, Stuttgart, where he was the Dean of the Faculty of Business, Economics and Social Sciences. From 2002 to 2020, he was the Chair of Information Systems with the Department of Informatics, TUM, where he was the Dean from 2010 to 2013. Interdisciplinary work incorporates areas such as accounting, mechanical engineering, and health care. He has coauthored a plethora of research papers published in major IS journals including *Management Information Systems Quarterly, Journal of Management Information Systems, Journal of Information Technology, Information Systems Journal, Journal of Strategic Information Systems, European Journal of Information Systems*, IEEE Transactions on Engineering Management, *Business & Information Systems Engineering, Communications of the ACM, Information and Management, MIS Quarterly Executive, Information Systems Frontiers, EM, ACM Transactions on Computer-Human Interaction, and Communications of the Association for Information Systems*. In Germany, his book *Information Management* is now in a 6th edition (2015). He collaborates in research with a wide range of leading global organizations. His research interests include information and knowledge management, engineering, piloting, and management of innovative IT-based services, computer support for collaboration in distributed and mobile work and learning processes.

Prof. Krcmar is a Fellow of the Association for Information Systems (AIS), (cf. https://aisnet.org/) and a Member of Acatech National Academy of Science and Engineering.