Engineering of Digital Innovation in Edge Computing and Industry 4.0: An Experience Report

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Abstract: This paper illustrates the use of an innovative process model that represents a systematic and scientific approach, using well-established methodologies and techniques from the field of Information Systems and telecommunications. Organizations in the field are pushing for innovation and proposing new technologies and standards, but these proposals often have fundamental differences and tend to primarily target industrial consumers, which have use cases that require reliable and stable systems and methodologies. Despite the known potential benefits of Edge Computing in industrial settings, there is still a lack of scientific rigor in related research and development processes. We contribute to the field by addressing this shortcoming, and by providing a scientific evaluation and a tailored version of a pre-existing method, which allowed us to build a practical solution that tackles the needs of industrial partners, while following a scientific approach. As a result, we managed to build an innovative design for a large industrial company operating in Edge Computing, while thoroughly assessing the progress from idea formulation to the complete solution.

1 INTRODUCTION

1.1 Problem Statement and Motivation

In recent years we have experienced an increasing push for digital transformation in industry, and more often the enabling technologies of this innovation are rooted in the field of Telecommunications. Industry 4.0 (or the fourth industrial revolution) is more than ever characterized by a strong reliance of "traditional" industries (e.g. manufacturing, logistics, etc.) on the Internet of Things, which implies the use of devices, network technologies and distributed infrastructures to achieve automation through the exchange and processing of (often very) large amounts of data, in a quasi-real-time manner. The major industry verticals that operate in the field of telecommunication are not idle on the matter. In fact, they are the major proponents of technologies and standardization efforts that are meant to bring Cloud Computing much closer to the users, in the paradigm known as Edge Computing (and even further, with IoT Edge). Such include companies that are mostly operating as parts of large standardization consortia, of the likes of GSMA, ETSI, 5GFF, and CAMARA, which are organizations built to promote the standardization and practical implementation(s) of Edge Computing. Academia and governmental bodies are also participating in the technical research, and a notable example is represented by the OpenFog Consortium, a worldwide ecosystem trying to push the creation and adoption of Fog Computing platforms, architectures and use cases (fog an "intermediate layer" between cloud and edge) (OpenFog Consortium Architecture Working Group et al., 2017). Some further examples are listed here. The International Telecommunication Union (ITU) coordinates operations and research at a global scale, and has dedicated major efforts to the design of standards for edge computing on 5G and mobile networks (Gupta et al., 2016). The European Telecommunications Standards Institute (ETSI) and the Edge Computing Consortium (ECC), independent non-profit organizations, have been working on standardizing communication protocols, network infrastructures and interfaces at the application level for edge computing, especially targeting use cases that involve IoT, Industry 4.0, and smart cities (Khan et al., 2019; Hamm et al., 2019). Notable mentions regarding highly heterogeneous networks and Machine-to-Machine(M2M) communications are the Open Net-

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working Foundation (ONF) and the Industrial Internet Consortium (IIC). The ONF has worked on standards for Software Defined Networks (SDN) and Network Function Virtualization (NFV), while the IIC worked on advancing industrial human-computer interaction, by promoting a large-scale adoption of interconnected intelligent machines, and real-time analytics.

While they do share many of their fundamental aspects, some of the standards proposed by these organizations often also come with fundamental differences, e.g. related to how the user data is handled, or what type of integration should be realized with the Virtual Network Functions (VNFs) that constitute the 5G core network. Therefore independent research groups are often proposing converging models (Yannuzzi et al., 2017). Most experimental use cases are developed in controlled industrial environments, often with dedicated on-premise 5G network setups, and target applications such as VR/AR, multimedia streaming, geo-localized services for smart cities and possibly Cellular Vehicle-to-Everything (C-V2X) communication. In industrial settings, there has always been a strong need for highly available and reliable systems to perform tasks such as monitoring, actuation and general infrastructure management. Modern Edge Computing proposals offer the technological baseline (e.g., having the 4G LTE/5G network as the core networking infrastructure) to allow this sort of application, and also to cover use cases that can be mission-critical. Nonetheless, there exists research that is already defining the foundations for 6G networks and Extreme Edge Computing infrastructures (You et al., 2020). Moreover, as these advancements happen quickly, they are often based on many parallel efforts, based on a lot of trial and error, that end up being potentially very time-consuming and often redundant (across enterprises, many organizations strive to achieve the same things, in different manners). In short, there are some methodical approaches in this research field, but hardly scientifically grounded ones.

1.2 Proposed Contributions

While working with a prominent telecommunications company, we saw an opportunity to define an innovative concept for industrial partners that were interested in a solution to automatically manage devices that belong to their general infrastructure. The innovative idea was to have a mechanism that would allow machinery of any type and embodiment to connect to the premise's internal network and, in a secure manner, perform an automated setup with minimal human interaction. This would be a baseline for a technology that provides a private cloud of industrial equipment, in which management and operations could be highly automated, as in a complement/substitute for SCADA. An example use case would be for robots that are meant to roam warehouses that need to be set up, to perform monitoring and actuation tasks (e.g., moving around cargo, alerting in the occurrence of accidents, fires, etc.). The tasks would be deployed as any cloud/edge-native application, and the devices would know "by themselves" which computing infrastructure they should join. This innovative concept for the physical infrastructure is what we called the "Edge-native device".

As mentioned in the previous subsection, though, one of the main problems in this field is the seemingly widespread lack of scientific rigor in innovative processes. This is a problem that has been discussed since the 1990s, and is best explained by (David et al., 1992) as the "problem of translation", that afflicts especially the field of research in Information Systems. The issue can be summarized as the difficulty of transforming an invention into real innovation (something that brings benefits to business and society), which often results in long periods of time spanning between an idea proposal and its actual productization.

Therefore, we wanted to contribute in this regard, by providing an experience report, showing that it is possible to carry out an innovative effort in the field of Edge Computing for Industrial IoT (IIoT), in a way that follows scientific rigor. The discipline that seemed most suitable to fulfil this, is Design Science Research (DSR). In particular, the approach we followed is strongly based on the work described in (Huseynli et al., 2022), which integrates the Stage-gate process (Cooper, 1990) with foundational design theories, and follows the DSR process through the three main stages Problem Identification, Solution Design and Evaluation, as described in (Offermann et al., 2009). Moreover, we practicalized the knowledge extraction tasks of (Huseynli et al., 2022) by using the main building block of the framework described in (Ogbuachi et al., 2022), the Reduced Fragment Descriptor (RFD).

2 LITERATURE REVIEW

In this section, we outline some of the literature that represents state-of-the-art research on the matter of Digital Innovation. Some of these works propose frameworks and tools for innovation process management, showing use cases for Digital Innovation/Transformation.

(Nylén and Holmström, 2015) propose a framework for supporting digital innovation management

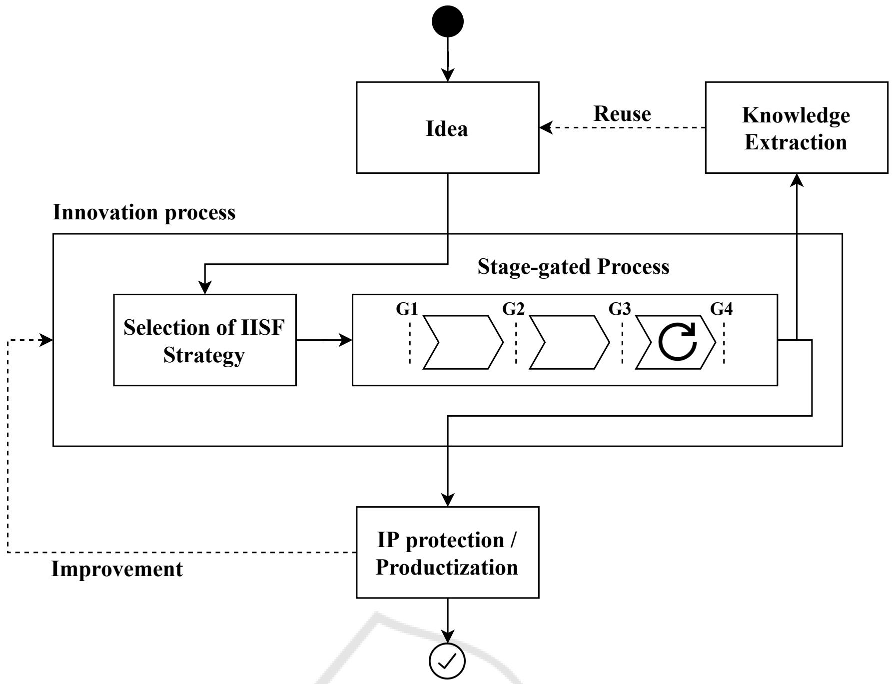

Figure 1: Implementation of (Huseynli et al., 2022) for DI in Edge Computing.

as a solution for controlling and predicting emerging product and service innovations in organizations. The managerial framework that resulted from this research encompasses the five areas "user experience, value proposition, digital evolution scanning, skills, and improvisation". Another notable contribution from the paper is a diagnostic tool that assists firms in identifying areas that need technological improvement and, thus, shows possibilities to start applying digital innovation practices. Furthermore, (Wang, 2019) notes that the environment in which digital innovations are shaped can be intuitively called an "ecosystem". The author writes about the main similarities between sociotechnical and natural ecosystems and suggests the idea that digital innovation research could gain an advantage if the research took the ecological perspective seriously by treating it as part of the theory. The paper contributes to research in digital innovation by building a comprehensive theory – a multilevel framework for digital innovation ecosystems which can allow practitioners to figure out digital innovation prospects in their organizations.

In addition, (Häikiö and Koivumäki, 2016) build a value generation process framework in order to improve understanding and promote the formation of a knowledge base for value creation and service innovation within the digital service innovation process. The framework is assessed by checking its applicability in an actual networked retail service innovation context. The study shows that in digital service innovation, multiple business, process, and information technology-related factors have an impact on value creation.

A notable study applied in industry is described in (vom Brocke et al., 2017), which is about the journey that the company Hilti went through for its digital transformation and innovation process. As a result of a successful endeavour, Hilti became a globally integrated enterprise and ended up with greater operational and customer-service excellence by further redefining business processes and the way their work was performed. Hilti used several phases to transform itself into a digital enterprise: firstly a digital basis was established, and then an actual utilization of the resulting digital potential followed. The authors show that digital innovation needs a backbone, putting it as a prerequisite for further development. Moreover, they show that a strategy is a vital player to direct, and encompasses "related actions, key objectives, and expected developments".

Likewise, (Anderson et al., 2012) explore the relationship between Innovation and DSR by focusing particularly on Information Systems. They investigate the synergies between the research streams of two topics and concentrate essentially on how to identify the differences and common aspects. They then perform a case study in Chevron where an innovation process is implemented, and the findings from this process show that key insights arising from DSR guidelines (Hevner et al., 2004) can potentially improve innovation processes within organizations. The paper identifies five potential areas of DSR that can benefit innovation processes.

Similarly to the work outlined in these papers, we also conducted innovation process management, but with a focus on Edge Computing for Industry 4.0, addressing both scientific rigor and practical relevance.

3 METHODOLOGY

As explained in Section 1.2, a DSR process was adopted from the planning to the design phase of this innovation project. This followed through the final submission to the internal enterprise stakeholders, who accepted to invest in the solution through a patent filing (Figure 1).

The strategy we adopted is based on the application of two DSR tools: the Method for the Engineering of Digital Innovation proposed by (Huseynli et al., 2022) for the constitution of the whole research and development process, and the construct proposed by (Ogbuachi et al., 2022) to aid the documentation of the process steps. The RFDs were also used to aid part of the knowledge extraction efforts from (Huseynli et al., 2022).

Specifically, (Huseynli et al., 2022) presents a method to guide enterprises through a process for Digital Innovation, using Design Science Research. The team(s) involved in the process should first identify a problem and define the initial proposal for an Idea, categorizing it also in terms of design range. These design ranges were originally described in (Offermann et al., 2011), and were applied with some modifications in the Integrated Innovation Strategies Framework (IISF) proposed in (Huseynli et al., 2021). They define an initial conceptual focus of the innovation project (or research) within Narrow-, Mid-, and Wide-range innovation strategies, where the terms do not identify a temporal scope, but rather a high-level estimation of feasibility and efforts. The choice of a target design range and a specific innovation strategy allows to produce the first output of this process: an abstract that introduces the idea to stakeholders.

This abstract is one of the initial documents submitted at the "entry" of the stage-gated innovation process and is considered in the evaluation that happens at Gate 1. The innovation process itself takes strong inspiration from the original work of (Cooper, 1990), the Stage-gate process, and expands it by adding phases based on the DSR process of (Offermann et al., 2009) between each gate.

(Huseynli et al., 2022) deals with the process definition at a high level, and it is up to the team to decide how to implement each intermediate stage, and produce the documentation required at each gate, namely:

- Gate 1: Idea proposal (including design range, innovation strategy, and the corresponding abstract).
- Gate 2: Project Scheme
- Gate 3: Project Plan
- Gate 4: Results of the Agile project execution (e.g, report of the fulfilled milestones)

In the case of this innovation process, to aid a team that approached the method of (Huseynli et al., 2022) for the first time, we integrated the use of a Method Engineering (ME) construct, the Method Fragment.

In particular, we decided to use the construct proposed in (Ogbuachi et al., 2022), the Reduced Fragment Descriptor (RFD). This is a representational tool meant to visually simplify the illustration of ISO/IEC 24744 method fragments (ISO/IEC 24744:2014, 2014; Henderson-Sellers et al., 2008), by highlighting the key aspects of the proposed fragment, to make them easily digestible also to people that are more conversant with development, rather than business. In addition to the information provided by traditional Method Fragments, RFDs highlight sequentiality by the describing Input (requirements to actuate the method described by the fragment) and Output (results of the method fragment) in the visual representation (valid for both process and product Fragments (Henderson-Sellers et al., 2008)). This makes it so that RFDs can be used for the constitution of processes, where they act as "building blocks" of temporal/functional sequences, similarly to the approach used in Business Process Modeling.

The next section will explain in detail how a practical implementation of the DSR process and the method from (Huseynli et al., 2022) was performed in this specific scenario. It will use the structure proposed by (vom Brocke and Mendling, 2017) to describe the conducted innovation process and evaluate the aforementioned method.

4 INNOVATION PROCESS

4.1 Situation Faced

Innovation Process. A notable telecommunication company working on Edge Computing and Industrial IoT solutions faced the problem of proposing a standardizable method for the constitution of computational clusters in private networks. The Edge computing paradigm, as of now, does not target User

Equipment (UE) as direct computational nodes of an Edge Computing infrastructure, but rather just as the end-users of Edge-native services, which produce/consume information either in the form of streamed data or responses to/from pre-defined exposed services. In Industrial IoT (IIoT), needs differ from those of the typical consumer, and it is important that data is transmitted consistently, at high rates, and in a manner that can allow for a trustworthy and coherent representation of the status of the equipment (resource observability and monitoring). The connected devices, therefore, need to be active providers of information that can help manage the infrastructure that resides at the industrial premise. Another "nice to have" feature of this research stemmed from ideas such as (Kang et al., 2017; Chen et al., 2018), where the operational costs for an industrial partner would be decreased by enabling an automated configuration of the equipment, lifting part of the setup work from human labour. This additional feature was given the preliminary name of "cluster autoconfiguration". The telecommunication company wanted to make sure that all the devices capable of connecting to the internal network infrastructure of an industrial premise, having enough logical hardware resources to perform extra computational tasks, could join a cluster of devices. Said cluster would be based on MicroK8s (a lightweight version of Kubernetes for IoT devices) and managed by an orchestrator node running the control plane, and the devices would receive applications packaged as Kubernetes "Pods". The infrastructure would allow for tasks such as telemetry reporting, task actuation and occasionally performing unrelated computing tasks (to make the devices useful while in their "idle" state).

Research Process. The major stakeholders in this project were Experts and Heads of the Technology & Innovation group within the company. These people were particularly knowledgeable about trends in the industry, being in direct contact with industrial partners that rely on the services of their company to satisfy specific networking needs. They had enough insight not only to tell if the proposed idea was viable, but also to estimate marketability in the short/mid-term. Throughout the innovation process, they helped keep the idea development realistic both in terms of technology and expected efforts/resources.

We also observed that, though current edge computing (and similar) standards do not specify a baseline for the technologies to be used in the orchestration of services running on the edge infrastructure, big industrial players such as Intel have been working on implementations based on the production-grade orchestrator Kubernetes, to deploy not only the Edge applications, but the virtualized Network Access Infrastructure itself (Intel Smart Edge Open). By targeting UE as the final computing node, the company wanted to push things even further, and contribute to the state of the art with a solution that could be a precursor to highly distributed Edge applications in 6G.

4.2 Action Taken

Innovation Process. Our process followed the structure described in Figure 1. The first step was to produce a Gate 1 proposal for the stakeholders. This proposal would describe the general statements/claims and show that the team had gathered enough background knowledge to justify the feasibility of the idea and its practical relevance. These claims would later be fundamental for the actual patent claims, in case the idea and project went through successfully. The experts that followed the team's work provided enough insight to help build a high-level view of the requirements and a potential system design. After successfully passing Gate 1, a similar strategy was followed to satisfy Gate 2.

For this second gate, the level of detail required by the stakeholders (who acted as "gatekeepers") was higher, leading to the drafting of a Project Scheme. The role of this second stage is to ensure that the team has a clear strategy for the rest of the DI process and that the members know and are able to communicate the expected design outputs of the innovation project. The output could be DSR artifacts, and one or more selected (or entirely new) development processes. The final decision at this stage is also of the "go/no go" type (as a "filtering gate"), and the outcome was successful.

At Gate 3 the expectation is a finalized project plan, including an estimation of required resources for the design proposal and prototypes, the definition of a budget to satisfy such requirements, a stable definition of the human resources (team members and idea owners), and a project timeline (mostly based on the quarterly meeting held in the company for the evaluation of patentable ideas). The plan included also the first architectural and functional definitions for a more detailed design of the proposed system, in the form of sequence, class, and components diagrams in the Unified Modeling Language (UML). These diagrams outlined the base features of the system and a clear definition of the characteristics of a successful proof of concept.

Finally, at Gate 4 the stakeholders evaluated the consistency of the submitted artifacts to the original plan. The evaluation included the proof of concept (implementation of the main features of the system), metrics for the satisfaction of the detailed project plan and consistency with the initial proposal and the suggested novelty/business relevance.

Research Process. The scientific contribution of Gate 1 was an assessment of the state-of-the-art in regard to Multi-access Edge Computing (MEC) and the industrial needs for industrial distributed computing and real-time operations. The assessment served as justificatory knowledge to motivate the proposal of our innovation idea. The idea itself was then framed through an IISF strategy, specifically as a mid-range Exaptation of the type "Derive from", and the corresponding abstract was added to the documentation for the stakeholders (Table 1, 2).

The phase preceding Gate 2 focused on the DSR steps of Problem Identification (following from phase 1) and Solution Design (at a relatively high level), and the expected output was an artifact of the type *Method* (Bucher and Winter, 2008). At this stage, the idea was also "refreshed" and structured to accommodate the needs of two types of users: industrial IT managers setting up on-premise clusters of computational devices, and telecommunication operators wanting to create future-proof hybrid clouds, hosting the UE of their cell plan subscribers into their clusters to create highly available and super-low-latency networks. Therefore, the design was split into two different "Facets", the second design was framed into a mid-range Exploitation of the type "Increase scope", and the corresponding abstract was added to the documentation (Table 1, 2).

Gate 3 required settling the team members and their responsibilities in a timely manner. This meant having a definition of a set of sequential milestones and corresponding deadlines (following an Agile design paradigm). These milestones were defined on a per-feature basis. Another important aspect of this phase was establishing contacts with "complementary teams". These were the teams that could provide specific information or even practical help in terms of networking, security and development. This last part was especially important to find people/resources from which the main innovation team could gather knowledge about embedded systems development, since the UE were expected to be resource-constrained devices, based on hardware such as ARM microcontrollers). During this step, the decision to rely on MicroK8s was finalized.

Finally, the work for the presentation at Gate 4 targeted an implementation of the core functionalities of the system, meaning the definition of user functions, security (e.g., key exchange and storage), APIs for automated network discovery, and the protocols for automated UE evaluation and onboarding. This part of the process was conducted through multiple iterations of design, development and evaluation, typically meant to fulfil the milestones that were defined in the Project Plan. Gate 4 was concluded with the final evaluation, in which internal stakeholders were present, together with the Heads of the Patent Development unit at the company.

4.3 Results and Lessons Learned

This strategy brought several benefits. Having a stage-gated background allowed for keeping the project in focus, especially during the definition of the core functionalities, while also enabling a flexible development workflow, thanks to its compatibility with the Agile lifecycle model (Cooper, 2014). This proved particularly true for the innovation team in the Project Plan and Project Execution phases, during the definition of the structural and functional details of the system. Following (Offermann et al., 2009; Huseynli et al., 2022), the iterations and evaluations in the Project Execution phase also allowed the extraction from the development efforts of experiential design knowledge of the prescriptive type (vom Brocke et al., 2020), that could be stored and reused for future projects or as a base for improvements. This prescriptive knowledge could be stored as DSR artifacts as well, namely in the form of method fragments (using RFDs) and Design Principles.

5 CONCLUSIONS

A telecommunications company faced the challenge of proposing a standardizable method for the formation of computational clusters in private networks for Edge computing and industrial IoT solutions. The company aimed to ensure that all devices capable of connecting to the internal network infrastructure of an industrial premise and having enough logical hardware resources, could join a cluster of devices. The cluster would be managed by a MicroK8s control plane-based orchestrator node and devices would receive applications in the form of Kubernetes "Pods" to perform workloads such as telemetry reporting and task actuation. The research process involved key stakeholders from the company's Technology & Innovation group, who were knowledgeable about the direction of the edge computing industry and had insight into the viability and marketability of the proposed solution. As a result, the project was devel-

Table 1: Application of the IISF Strategies (Huseynli et al., 2021).

Design Contributions	Applied Innovation Strategy	Implementation
Design of an infrastructure to support direct utilization of UE in an industrial Edge Computing infrastructure	Exaptation: Derive from	Derive core characteristics of Multi-access Edge Computing and apply them to Industry-specific use cases, to innovate IIoT infrastructures with novel, hardened networking capabilities
Extension of the proposed design to support Telco operators in creating highly dynamic and highly reliable clusters of UE	Exploitation: Increase scope	Take the proposed design and improve it in terms of security, scalability (e.g., federation of control planes) and infrastructure management , for potential massive IoT Edge use cases.

Table 2: Innovation strategies and corresponding abstracts.

Chosen Innovation Strategy	Corresponding Abstract
Exaptation: Derive from	In the field of distributed systems, the idea of Edge Computing proposes solutions to the centrality of modern cloud computing, which still relies heavily on massive computing infrastructure handled by Hyper-scale cloud providers. This can cause issues related to security (e.g., data ownership and distribution) and performance (e.g., latency that can be too large for sensitive industrial applications). Based on these issues, we developed a new solution for the IoT Edge, in form of a mid-range design: an infrastructure scaling model that can facilitate control and expansion of industrial computing and actuation facilities.
Exploitation: Increase scope	In the field of Multi-access Edge Computing, Edge infrastructure is meant to bring the computing power much closer to the User Equipment, to decrease latency and the load on the Hyperscale providers. This design though doesn't allow the provider to offload computation. In this paper, we propose a model inspired by Extreme and IoT Edge, in which the UE can participate in the computational power of the Edge cloud, under the supervision of the network provider.

oped within the expected time limits, and passed all the stages of the gated process, resulting in the company investing in a patent filing. Future work on this topic will include further development and testing of the proposed solution and/or extended method in other real-world industrial environments. This could involve conducting pilot studies with industrial partners to gather feedback on the solution's performance and identify any areas of improvement. Additionally, research could be done to evaluate the scalability and robustness of the solution proposed here in large-scale deployments and investigate potential security risks and develop mitigation strategies. Another direction could be to investigate the integration of other technologies, such as Artificial Intelligence, to enhance the solution's functionality. Additionally, it would be important to evaluate the potential cost savings and efficiency improvements that can be achieved by using this solution in diverse industrial environments.

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