Instituto Alberto Luiz Coimbra de Pós-Graduação e Pesquisa de Engenharia
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AN EVIDENCE-BASED ROADMAP TO SUPPORT THE INTERNET OF THINGS SOFTWARE SYSTEMS ENGINEERING

Rebeca Campos Motta

Tese de Doutorado apresentada ao Programa de Pós-graduação em Engenharia de Sistemas e Computação, COPPE, da Universidade Federal do Rio de Janeiro, como parte dos requisitos necessários à obtenção do título de Doutor em Engenharia de Sistemas e Computação.

Orientadores: Guilherme Horta Travassos
Káthia Marçal de Oliveira

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TESE SUBMETIDA AO CORPO DOCENTE DO INSTITUTO ALBERTO LUIZ COIMBRA DE PÓS-GRADUAÇÃO E PESQUISA DE ENGENHARIA DA UNIVERSIDADE FEDERAL DO RIO DE JANEIRO COMO PARTE DOS REQUISITOS NECESSÁRIOS PARA A OBTENÇÃO DO GRAU DE DOUTOR EM CIÊNCIAS EM ENGENHARIA DE SISTEMAS E COMPUTAÇÃO.

Orientadores: Guilherme Horta Travassos
Káthia Marçal de Oliveira

Aprovada por: Prof. Guilherme Horta Travassos

Profª. Káthia Marçal de Oliveira

Prof. Óscar Pastor Lópes

Profª. Sophie Dupuy-Chessa

Profª. Flávia Coimbra Delicato

Prof. Cláudio Miceli de Farias

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“Mas, buscai primeiro o reino de Deus, e a sua justiça,

e todas estas coisas vos serão acrescentadas.”

Mateus 6:33

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Rebeca Campos Motta

Novembro/2021

Orientadores: Guilherme Horta Travassos
Káthia Marçal de Oliveira

Programa: Engenharia de Sistemas e Computação

O paradigma da Internet das Coisas (IoT) traz muitas expectativas, desafios e uma multidisciplinaridade do conhecimento técnico. Envolve várias áreas ou facetas do conhecimento que devem ser combinadas de forma precisa e coerente para desenvolver sistemas de software mais autônomos e inteligentes. Neste trabalho, um conjunto de 117 recomendações distribuídas em 29 categorias foram organizadas em instrumento chamado de *IoT Roadmap*, para apoiar o desenvolvimento da IoT. O *IoT Roadmap* é um artefato baseado em evidências que compreende diferentes experiências para lidar com a IoT de uma maneira multifacetada. O Roadmap é um guia do que considerar ao especificar, projetar e implementar sistemas IoT. O ciclo de vida do Corpo de Conhecimento em Engenharia de Sistemas (definição conceitual, definição e realização do sistema) oferece suporte à organização dos elementos do roteiro e à dimensão temporal para orientar a engenharia de sistemas IoT de maneira eficaz. As análises e estudos experimentais resultaram em um grande conjunto de informações sobre IoT multidisciplinar, organizado em um corpo de conhecimento que pode beneficiar pesquisadores e profissionais envolvidos na IoT.

Abstract of Dissertation presented to COPPE/UFRJ as partial fulfillment of the requirements for the degree of Doctor of Science (D.Sc.)

AN EVIDENCE-BASED ROADMAP TO SUPPORT THE INTERNET OF THINGS SOFTWARE SYSTEMS ENGINEERING

Rebeca Campos Motta

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Advisors: Guilherme Horta Travassos
Káthia Marçal de Oliveira

Department: Computer Science and Systems Engineering

The Internet of Things (IoT) paradigm brings many expectations, challenges, and a multidisciplinarity of technical knowledge. It involves several knowledge areas or facets that should be combined precisely and coherently to develop more autonomous and smarter software systems. In this work, 117 recommendations distributed in 29 categories were organized in an IoT Roadmap instrument to support IoT development. The IoT Roadmap is an evidence-based artifact to comprise different expertise to deal with IoT in a multi-faceted way. The IoT Roadmap guides what to consider while specifying, designing, and implementing IoT systems. The Systems Engineering Body of Knowledge life cycle (concept definition, system definition, and realization) supports the roadmap elements' organization and temporal dimension to guide IoT systems engineering effectively. The analyses and experimental studies resulted in a large set of information on multidisciplinary IoT, organized into a body of knowledge that can benefit researchers and professionals involved in IoT.

Résumé de la thèse présentée au l’Université Polytechnique Hauts-de-France dans le cadre des conditions nécessaires à l'obtention du Doctorat en Sciences (D.Sc)

AN EVIDENCE-BASED ROADMAP TO SUPPORT THE INTERNET OF THINGS SOFTWARE SYSTEMS ENGINEERING

Rebeca Campos Motta

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Directeurs: Guilherme Horta Travassos
Káthia Marçal de Oliveira

Programme: Génie Informatique et Systèmes

Le paradigme de l'Internet des objets (IoT) apporte de nombreuses attentes, des défis et une multidisciplinarité des connaissances techniques. Il implique plusieurs domaines ou facettes de connaissances qui doivent être combinés de manière précise et cohérente pour développer des systèmes logiciels plus autonomes et plus intelligents. Dans ce travail, un ensemble de 117 recommandations réparties dans 29 catégories ont été organisées dans un instrument nommé la feuille de route IoT, pour soutenir le développement de l'IoT. La feuille de route IoT est un artefact fondé sur des preuves qui comprend différentes expertises pour traiter l'IoT de manière multiforme. La feuille de route est un guide des éléments à prendre en compte lors de la spécification, de la conception et de la mise en œuvre des systèmes IoT. Le cycle de vie du corpus de connaissances en ingénierie des systems prend en charge l'organisation et la dimension temporelle des éléments de la feuille de route pour guider efficacement l'ingénierie des systèmes IoT. Les analyses et les études expérimentales ont abouti à un large ensemble d'informations sur l'IoT multidisciplinaire, organisé en un corpus de connaissances pouvant bénéficier aux chercheurs et aux professionnels dans l'IoT.

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1 Introduction

This chapter describes what motivated this investigation, defining the research goals and questions. Besides, it presents an overview of the research approach, highlighting the main results. Finally, it presents the outline of this document.

1.1 Context and Motivation

In the past, software applications were not integrated, with much effort to customize and maintain since they were independent of each other. A solution was to go for the “big software,” more extensive and extended projects with standardized processes. Such projects end up with a more expensive one-size-fits-all approach to technology that fails due to overwhelming technical complexity and inflexibility (Andriole, 2017). However, even with such limitations, the advancement of technologies made society rely more on software-based systems.

In this scenario, the interest in software development grows for contemporary paradigms such as the Internet of Things. Through software, current solutions offer the opportunity for a reality where physical and virtual worlds are connected, where "things" can act, products can "command" production lines, and other features that extend the original purpose of computing solutions (Bisio, Garibotto, Grattarola, Lavagetto, & Sciarrone, 2018).

Our interest as a research group in emerging and contemporary software technologies started with an investigation concerned with **Pervasive** and **Ubiquitous Systems** (Spínola, Massollar, & Travassos, 2007; Spínola & Travassos, 2012). These two terms are intimately connected, and some authors have addressed them interchangeably. The working on these topics is usually motivated by the idea that "the most profound technologies are those that disappear," as stated in (Weiser, 1991). In his seminal work, Weiser defines ubiquitous computing as being the use of the computer through its availability in the physical environment, making it effectively invisible to the user, and proposes that in the future, computers should be embedded in the environment, invisible to the users, becoming ubiquitous and creating a new paradigm to access information and to interact with devices. A software system can be considered ubiquitous according to its adherence to ubiquity characteristics (Spínola & Travassos, 2012): context awareness, adaptable behavior, service omnipresence, heterogeneity of devices, the capture of experience, spontaneous, interoperability, scalability, privacy and trust, fault tolerance, quality of service, and universal usability. Ubiquity becomes a transversal property of software systems as they fulfill these ubiquity characteristics. The beginning of a new paradigm changed the style and form of interacting with software beyond the traditional desktop, bringing it to the larger real world. It is a challenge since it is not a well-understood or well-controlled environment. However, it is complex and dynamic, with an ever-changing context of use.

Following our research motivations, we delve deeper into the context-awareness feature investigating **Context-Aware Software Systems**. Several works have been developed in this direction, primarily concerned with testing and interoperability in this type of system (Matalonga, Rodrigues, & Travassos, 2017; Motta, de Oliveira, & Travassos, 2019). “Context” is defined as any piece of information that may be used to characterize the situation of an entity (physical objects present in the systems environment) and “context-awareness” as a dynamic property of the system that can affect the overall software system behavior when realizing interaction between an actor and the system (Abowd *et al*., 1999). Context-Aware software systems usually are equipped with identification and sensing capabilities, bridging the physical to the virtual world. It leaves systems closer to what is proposed for ubiquitous systems since it becomes more embedded in the environment.

Another related area is the **Machine-to-Machine (M2M)** domain, where devices communicate end-to-end without human intervention (Madakam, Ramaswamy, & Tripathi, 2015). M2M refers to technologies allowing both wireless and wired systems to communicate with the capability of acting (Wan, Chen, Xia, Di, & Zhou, 2013). M2M systems are meant to operate in a specific application, which means that M2M solutions do not allow the broad sharing of data or opened connection of devices into the Internet (Holler *et al*., 2014). We see M2M as a leading paradigm towards the idea of IoT (Atzori, Iera, & Morabito, 2010).

One more area is represented by **Cyber-Physical Systems** (CPS) that aims “to bring the cyber-world of computing and communications together with the physical world” (Madakam, Ramaswamy, & Tripathi, 2015). According to (Miorandi, Sicari, De Pellegrini, & Chlamtac, 2012), “a Cyber-physical infrastructure is the result of the embedding of electronics into everyday physical objects, making them ''smart'' and letting them integrate seamlessly within the global.” CPS is the evolution of M2M systems, contributing to the bridge between the physical and virtual world in the same manner but introducing more intelligent and interactive operations (Chen M., 2012).

Moreover, a more recent concept is the **Internet of Things (IoT),** where the pervasive presence around us of a variety of things which through unique addressing schemes, can interact with each other and cooperate with their neighbors to reach a goal (Atzori, Iera, & Morabito, 2010). IoT has emerged as a new paradigm where software systems are no longer limited to computers but can materialize into a great variety of different objects or to specific users' goals and closed environments. The interaction between humans and the cyber-physical world is changing since the software can be deployed everywhere and in everything, such as cars, smartphones, refrigerators, watches, and clothes (Giusto, 2010; Weber, 2010; Zorzi, Gluhak, Lange, & Bassi, 2010). This perspective enables pervasively connecting things (like what is proposed in ubiquitous systems) with identification, sensing, or actuation capabilities, making it possible to interact with our environment (like what is expected in CPS).

The IoT paradigm is closely related to the context of **Industry 4.0.** In this case, IoT is deployed in factories and production environments, turning them more "intelligent," leading toward the fourth industrial revolution (Wortmann, Combemale, & Barais, 2017). Other examples are **smart cities**, **smart homes,** and other **smart environments** (Aziz, Sheikh, & Felemban, 2016; Cicirelli *et al*., 2018), where the *smartness* is directly related to IoT proposal of enhancements in the things, extending their original behaviors or purpose.

Through the years, the IoT grew from a theoretical concept to a priority for many organizations. In this sense, there are many statistics available regarding both devices and investments for IoT. By the end of 2018, an estimated 22 billion connected devices were in use, and forecasts suggest an increase to 50 billion by 2030, creating a massive web of interconnected devices[1]. IoT investments reached 100 billion dollars in market revenue in 2017, and forecasts suggest that this figure can grow to around 1.6 trillion by 2025.[2] According to a Gartner survey, 75% of companies had by the first half of 2019 already deployed at least one use case of IoT with adoption focused on the use of digital twins, virtual representations of physical objects that allow for more efficient, real-time

[1] https://www.statista.com/statistics/802690/worldwide-connected-devices-by-access-technology/

[2] https://www.statista.com/statistics/976313/global-iot-market-size/

monitoring and despite the disruptive impacts of COVID-19, 47% of organizations plan to increase their investments in IoT (Gartner, 2020).

With so much interest and investments from academia and industry, new challenges are emerging as a result of IoT possibilities, such as the higher need for the software to be embedded in the product (Miranda *et al*., 2015; Lu A., 2017) and technology diversity to deliver the variety of possible solutions (Chapline & Sullivan, 2010; Gubbi, Buyya, Marusic, & Palaniswami, 2013) considering communication and interoperability, essential for their materialization (Gyrard, Serrano, & Atemezing, 2015; Lin *et al*., 2017). Thus, attention to software development with a holistic vision integrated with different disciplines can represent an excellent differential for the development of such systems since complex systems require systems engineering that integrates across each part to meet requirements (Chapline & Sullivan, 2010). It is necessary given the high uncertainties about the system and its problem domain, the multidisciplinarity among the solution, and the business needs. Therefore, multidisciplinary solutions are essential for this development since knowledge from different disciplines and skills should be used. Furthermore, this scenario promotes a high degree of innovation where software engineers need to build new software technologies to solve new problems, many of which are still unknown (Atzori, Iera, & Morabito, 2010; Haller, 2011).

These engineering issues justify the need for evolving knowledge, skills, and technologies distinct from those offered to support the traditional engineering of software (Skiba, 2013; Zambonelli, 2016; Larrucea, Combelles, Favaro, & Taneja, 2017) being this the motivation for our research. Therefore, new software engineering research and development challenges emerge in the IoT paradigm, without prejudice to the original software life-cycle concerns with deadlines, costs, and quality levels of products and processes (Pfleeger & Atlee, 1998; Fitzgerald & Stol, 2017), but involving the intensive internalization of software into the products, high distribution of solutions, diversity and technological multidisciplinarity, communication and systemic interoperability.

1.2 Problem Definition and Research Question

The development of IoT solutions is complex since it embodies physical, networked, software, and human-interactive systems characteristics. Moreover, physical and virtual components are intertwined, overlapping related engineering areas, and integrating different skills and technologies for its realization (Nguyen-Duc, Khalid, Shahid Bajwa, & Lønnestad, 2019). Therefore, IoT drives us to "engineer"

multidisciplinary solutions involving, in addition to Software Engineering, different disciplines for the accomplishment of successful systems and by its purposes, including the presence of software, essential for the materialization of systemic solutions.

Unlike traditional systems, IoT enables the networking of several devices that can reach ultra-large-scale. In this scenario, there might be hardware and software components, each with its internal process, that should run smoothly in a highly dynamic and distributed environment (Fahmideh & Zowghi, 2020). However, some of the intrinsic **IoT characteristics**, such as autonomy, heterogeneity, and mobility, are orthogonal to the disciplines, challenging its development and quality (Zambonelli, 2017). Furthermore, it is also important to consider technical issues and human resources (Microsoft and Hypothesis Group, 2020; van Deursen *et al.*, 2021). Therefore, the **lack of knowledge** is also one of the considerable IoT challenges.

Our vision in this research seeks to be more comprehensive in the sense of Systems Engineering. During the activities, we strive to see the possible disciplines and areas of knowledge involved in IoT, which we call **facets**. We understand facets as "one side of something many-sided" (Oxford Dictionary), "one part of a subject, a situation that has many parts" (Cambridge Dictionary), representing the multidisciplinarity required in such systems. We want to consider the particularities required by IoT software systems and deal with the system as a whole, considering the properties that can emerge from the interconnection of the individual elements (BKCASE Governing Board, 2014). The improvement of IoT development involves new technologies, a better understanding of the problem, and new strategies for development to accomplish IoT solutions.

Our motivation to investigate and contribute to the evolution of IoT engineering is therefore supported by:

- The relevance of IoT in the national and international environments (BNDES, 2017; Microsoft and Hypothesis Group, 2020).
- The need for a holistic approach and multidisciplinary view for developing new software solutions (Higgins, 1966; BKCASE Governing Board, 2014; Bauer & Dey, 2016; Aniculaesei, Grieser, Rausch, Rehfeldt, & Warnecke, 2018).
- Different practitioners demand technical competencies and skills to engineer IoT software systems (Microsoft and Hypothesis Group, 2020).
- The demand for software technologies to engineering IoT software systems (Larrucea, Combelles, Favaro, & Taneja, 2017; Jacobson, Spence, & Ng, 2017; de Farias *et al.*, 2017).

We argue that the engineering of IoT software systems needs more than a single perspective since these solutions usually cover other disciplines (network, hardware, and others) alongside the software. Thus, our concerns are configured in a multidisciplinary way. The notion of IoT departs somewhat from a pure and straightforward software system, demanding approaches more closely to the comprehensive view of Systems Engineering. The purpose of Systems Engineering is to embrace multidisciplinarity, uniting the areas necessary for the realization of successful systems according to its goals, including the part of Software (BKCASE Governing Board, 2014). Therefore, the principles of Software Engineering should intertwine with those of other disciplines to deliver contemporary and adequate engineered solutions with a strong software emphasis, composing a comprehensive view of Software Systems Engineering.

This thesis addresses the problem to support the engineering of IoT software systems considering its multidisciplinarity and characteristics. Therefore, the main research question of this thesis proposal is formulated as follows:

What to consider while specifying, designing, and implementing IoT software systems?

1.3 Research Goal

The main objective of this work is to propose an evidence-based instrument that can help development teams be aware of what to consider while specifying, designing, and implementing IoT software systems. Considering IoT immense potential, in addition to presenting a characterization of the area and organizing the existing challenges, with this work, the proposed instrument should be:

- Generic enough, at a higher level of abstraction, to represent the particularities and characteristics of the IoT paradigm.
- Flexible enough to be extended and evolved so that it continues to represent contemporaneity.
- Adaptable enough so that it can be instantiated more concretely in the different applications in the IoT paradigm.

Thus, this work comes as an initial effort to introduce an IoT Roadmap in the context of IoT software systems. This objective can be broken down and better detailed in the following sub-objectives:

- Investigate the characteristics that define IoT software systems and differentiate them from conventional ones.
- Investigate the challenges of engineering IoT software systems.
- Investigate the disciplines involved in the development of IoT software systems.
- Organize a body of knowledge regarding the engineering of IoT software systems and their life cycle.
- Define an instrument on top of such a body of knowledge to support the engineering of IoT software systems, considering their characteristics, challenges, and involved disciplines.
- Evaluate the proposed instrument through experimental studies to assess its feasibility and applicability.

Therefore, this work proposes an IoT Roadmap to support the Engineering of IoT Software Systems. The IoT Roadmap is an evidence-based instrument that comprises different expertise to deal with IoT in a multi-faceted way, working as a guide for recommendations to support specifying, designing, and implementing IoT software systems. We hope such a Roadmap can reduce technical complexity and the lack of knowledge about building and deploying high-quality IoT solutions to society.

1.4 Methodology

According to (Kitchenham, Dyba, & Jorgensen, 2004), the use of quality processes for software engineers is insufficient to improve quality in the development. Therefore, it is recommended to characterize the software technology before its adoption to determine its feasibility, contributing to Evidence-based Software Engineering.

The research methodology has been proposed by (Shull, Carver, & Travassos, 2001), incremented by (Spínola, Dias-Neto, & Travassos, 2008), and tailored for this work. This methodology relies on primary and secondary studies to support the conception of new software technologies. We selected this methodology because it is adequate for the research purpose since it is an evidence-based approach to the conception, development, and evaluation of software technologies. The methodology's first stage, the **Conceptual Phase**, involves executing a secondary study to obtain an initial proposal for the software technology. In the second phase, named **Development Phase**, the idea is to define a software technology to support the gaps observed in the

Conceptual Phase. Finally, feasibility and observational studies are planned and executed for the **Evaluation Phase** to give us evidence of the proposal's feasibility, applicability, and validity, contributing to an incremental development with its improvement (Figure 1).

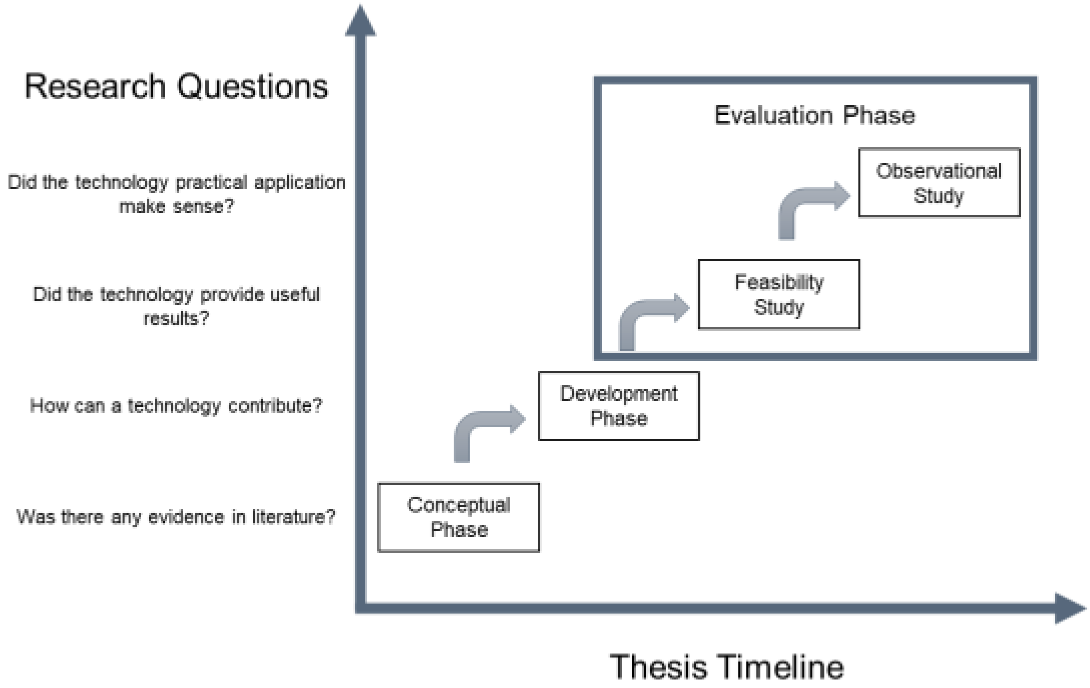

Figure 1. The methodology followed in the research

Adapted from (Spínola, Dias-Neto, & Travassos, 2008).

We adapted this methodology for our research executing different activities for each phase. For the **Conceptual Phase**, described in Chapter 3, four activities were performed:

1. Secondary Study – to characterize IoT about its definition, attributes, and current applications. We followed adequate procedures focusing on secondary studies.
2. Investigate IoT Challenges – to recover issues based on technical literature, field professionals, and public initiative. In this way, it is possible to find research gaps and the main problems that need an effort for IoT development.
3. Investigate IoT Facets – the IoT Facets represent the disciplines and knowledge areas involved in IoT development. We also present the challenges for IoT development, mapping the concerns for each facet.

4. Structured Interviews – We conducted a study to characterize the pertinence of the facets identified according to software practitioners' perception of IoT software systems engineering.
5. Propose the IoT Conceptual Framework – the study's results lead to a conceptual organization of all the concepts recovered so far.

For the **Development Phase**, described in Chapter 4, three activities were executed:

1. Literature Reviews – A set of Rapid Reviews (RRs) were executed to characterize each IoT Facet regarding applications, tools, methods, and techniques that can clarify *what, how, where, who, when*, and *why* to manage such facets contemplating the different perspectives involved in IoT.
2. Propose the IoT Roadmap – The IoT Roadmap materializes the body of knowledge organized in the research, operationalized in an instrument that addresses IoT multidisciplinarity and supports the IoT paradigm's understanding.

For the **Evaluation Phase**, described in Chapter 5, two activities were executed:

1. Feasibility Study – We executed an online survey to characterize the IoT Roadmap's viability, considering the artifacts generated in the context of the design of IoT software systems already concluded.
2. Observational Study – A second study was performed to improve the proposed approach concerning its application and usefulness in real case scenarios.

With the activities performed, we identified evidence that led to the IoT Roadmap technology proposition. This software technology was later evaluated, providing evidence on its usefulness and practical application, therefore providing all the answers to the research questions defined by the original methodologies (Shull, Carver, & Travassos, 2001; Spínola, Dias-Neto, & Travassos, 2008). Thus, the methodology we followed provided an evidence-based approach, and the resulting IoT Roadmap is grounded on the experimental results achieved. The IoT Roadmap is presented in an instrument that delivers research concepts and a practical guide to support IoT development (Figure 2).

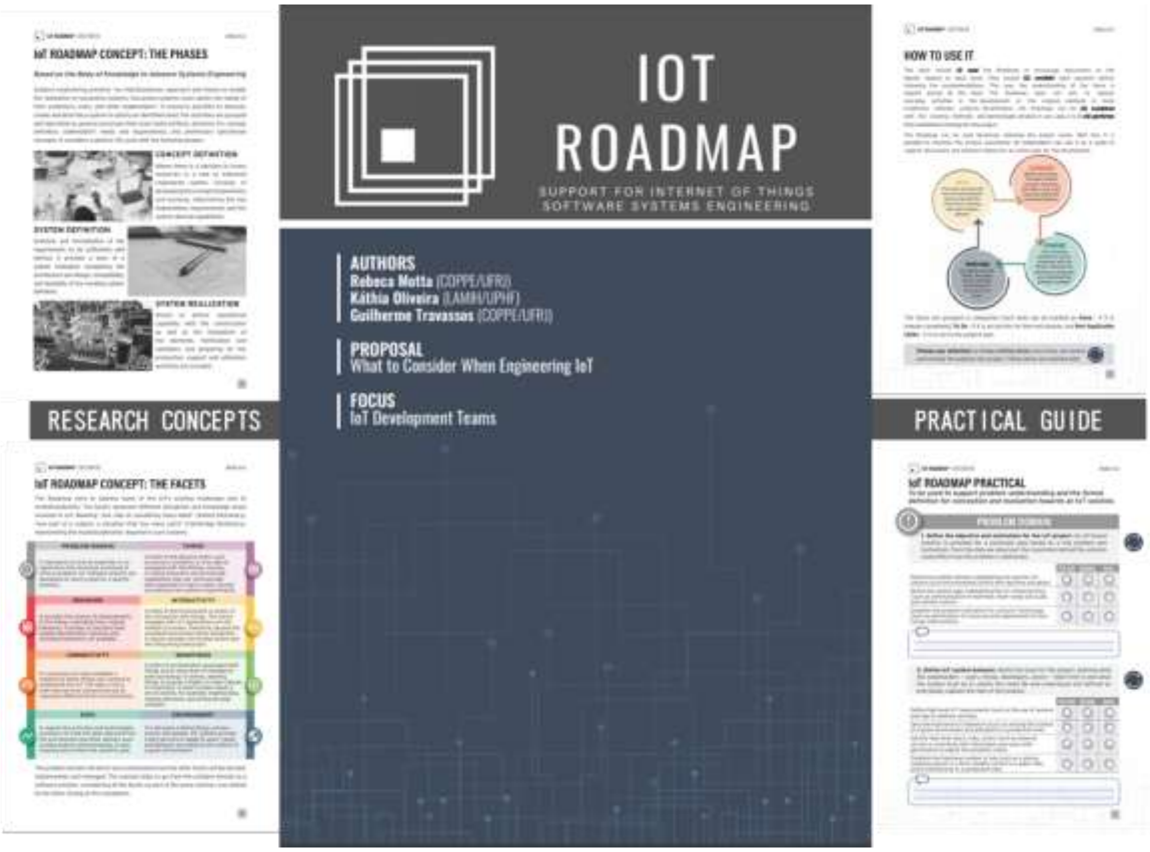

Figure 2. IoT Roadmap Overview.

1.5 Main Results

Different contributions were achieved throughout this research and are presented in this manuscript, from which we highlight the published works:

- Rebeca Campos Motta, Káthia Marçal de Oliveira, Guilherme Horta Travassos: On challenges in engineering IoT software systems. In Proceedings of the XXXII Brazilian Symposium on software engineering, pp. 42-51 (2018).
- Rebeca Campos Motta, Valeria Silva, Guilherme Horta Travassos: **Towards a more in-depth understanding of the IoT Paradigm and its challenges.** J. Softw. Eng. Res. Dev. 7: 3 (2019)
- Rebeca Campos Motta, Káthia Marçal de Oliveira, Guilherme Horta Travassos: **On Challenges in Engineering IoT Software Systems.** J. Softw. Eng. Res. Dev. 7: 5 (2019)

- Rebeca Campos Motta: **Towards a strategy for supporting the engineering of IoT software systems.** EICS 2019: 20:1-20:5
- Rebeca Campos Motta, Káthia Marçal de Oliveira, Guilherme Horta Travassos: **A framework to support the engineering of internet of things software systems.** EICS 2019: 12:1-12:6
- Rebeca Campos Motta: **An Evidence-Based Framework for Supporting the Engineering of IoT Software Systems.** ACM SIGSOFT Softw. Eng. Notes 44(3): 22-23 (2019)
- Bruno Pedraça de Souza, Rebeca Campos Motta, Daniella de O. Costa, Guilherme H. Travassos: **An IoT-based Scenario Description Inspection Technique.** SBQS 2019: 20-29
- Bruno Pedraça de Souza, Rebeca Campos Motta, Guilherme Horta Travassos: **Towards the Description and Representation of Smartness in IoT Scenarios Specification.** SBES 2019: 511-516
- Bruno Pedraça de Souza, Rebeca Campos Motta, Guilherme Horta Travassos: **The first version of SCENARIotCHECK: A Checklist for IoT based Scenarios.** SBES 2019: 219-223
- Rebeca Campos Motta, Káthia M. de Oliveira, Guilherme H. Travassos: **A conceptual perspective on interoperability in context-aware software systems.** Inf. Softw. Technol. 114: 231-257 (2019)
- Rebeca Campos Motta, Káthia Marçal de Oliveira, Guilherme Horta Travassos: **Towards a Roadmap for the Internet of Things Software Systems Engineering.** MEDES 2020: 111-114
- Rebeca Campos Motta, Káthia Marçal de Oliveira, Guilherme Travassos: **IoT Roadmap: Support for Internet of Things Software Systems Engineering.** CoRR abs/2103.04969 (2021)
- Rebeca Campos Motta, Káthia Marçal de Oliveira, Guilherme Travassos: **Technical Report: Rapid Reviews on Engineering of Internet of Things Software Systems.** CoRR abs/2101.05869 (2021)
- Rebeca Campos Motta, Káthia M. de Oliveira, Guilherme Travassos: **A Preliminary Study of IoT Multidisciplinary View in the Industry.** INFORSID 2021: 143-148
- V. Maia, R. C. Motta, K. M. de Oliveira, and G. H. Travassos: **Exploring Interactivity concerns on the Internet of Things Software Systems.**

Submitted to Journal of Software: Evolution and Process (2021 – *under review*)

- R. C. Motta, K. M. de Oliveira, and G. H. Travassos: **An Evidence-Based Roadmap for Engineering IoT Software Systems.** Submitted to Journal of Systems and Software (2021 – *under review*)

1.6 Thesis Outline

This thesis proposal is organized into six chapters. In this first one, we have presented the motivations that led to work on this topic, the research problem, questions, and the followed research methodology.

Chapter 2 presents a theoretical background of this work, presenting concepts of Systems Engineering and System Architecture and related works for this research.

Chapter 3 presents the studies conducted in the conception phase to characterize and support the present research. It corresponds to the IoT Characterization, recovery of IoT Challenges from technical literature, practitioners, a Brazilian government report, and the definition of the related areas in the IoT Facets.

Chapter 4 discusses how these concepts were organized in the IoT Conceptual Framework, and it presents the materialization of the IoT Conceptual Framework operationalized in a Roadmap format. Finally, we present the definition process and the recommendations on how to use the IoT Roadmap.

Chapter 5 presents the experimental studies conducted to evaluate the IoT Roadmap. Finally, it presents a Feasibility Study and an Observational Study detailing the planning, execution, and presentation of results.

Chapter 6 presents the final considerations, objectives achieved, and the activities for future work and concludes this manuscript.

2 Theoretical Background

This chapter presents the basic concepts of the theoretical foundations of this work: Systems Engineering and System Architecture. We also present different propositions from literature to support the development of IoT Software Systems as Related Work.

2.1 Systems Engineering

"Increased complexity of systems recently being developed in the fields of communications, instruments, computation, and control has led to an emphasis on the field of systems engineering." (Schlager, 1956) This sentence seems to fit right into our vision for IoT. However, it is from this seminal work in the field of Systems Engineering.

Systems Engineering is a multidisciplinary and integrative approach to enable the successful realization, use, and retirement of engineered systems, using systems principles and concepts and scientific, technological, and management methods (Walden, Roedler, & Forsberg, 2015).

Other definitions are:

> *Systems engineering is a discipline that concentrates on the design and application of the whole (system) as distinct from the parts. It involves looking at a problem in its entirety, taking into account all the facets and all the variables, and relating the social to the technical aspect* (Booton & Ramo, 1984).

> *Systems engineering is an iterative process of top-down synthesis, development, and operation of a real-world system that satisfies, in a near-optimal manner, the full range of requirements for the system.* (Eisner, 2008).

The foundation of Systems Engineering is justified for being a knowledge-driven process, unlike a manufacturing process that is based on repetitive activities that achieve quality outputs. It focuses on designing, integrating, and managing complex systems over their life cycles and relies on systems thinking principles to organize the knowledge. The outcome is an engineered system defined as "a combination of components that work in synergy to collectively perform a useful function" (Walden, Roedler, & Forsberg, 2015). The scope of Systems Engineering entails several activities that are managed in the Life Cycle.

2.1.1 Life Cycle

Due to its multidisciplinary nature, we argue that IoT software systems should consider Software Engineering intertwined with other disciplines to deliver engineered solutions, configuring a broader Systems Engineering vision. The scope of Systems Engineering is composed of three complementary areas that contribute to the realization of a successful system (BKCASE Governing Board, 2014):

Systems Engineering: it concerns activities to discover, create, and describe a system to satisfy an identified need. The activities are grouped and described as general processes covering build artifacts, concept definition decisions, stakeholders' needs and requirements, and preliminary operational concepts.

Systems Implementation: it uses the structure created during the architectural design and system analysis to construct the system elements that meet the stakeholder requirements and system requirements developed in the early phases. These elements are then integrated to form intermediate aggregates and, finally, the complete system-of-interest.

System management: this area is about managing the resources and assets allocated to perform systems engineering, often in the context of a project, a system, or a service. Implementing systems engineering requires the coordination of technical and managerial endeavors. Management provides the planning, organizational structure, collaborative environment, and program controls to ensure that the stakeholder needs are met.

Alongside the areas, System Engineering presents a life cycle that can be composed by different phases depending on the model - some examples are presented in (Forsberg, Mooz, & Cotterman, 2005; ISO/IEC/IEEE International Standard 15288, 2015; and Walden, Roedler, & Forsberg, 2015). Since "no single one-size-fits-all" system life cycle model can provide specific guidance for all project situations," the BKCASE Governing Board, 2014) proposal covers the following generic phases:

Definition: this phase includes **Concept Definition**, with the need to build or change an engineered system where activities involve developing the main concepts of operations and business, and **System Definition**, where requirements are sufficiently well defined to define a solution

Realization: it begins with the commitment to deliver operational capability and activities include the construction of the developmental elements as well as their integration. System Production (improvements), Support (maintenance), and Utilization (operation) stages follow the System Realization.

Retirement: this stage is often executed incrementally as the systems become obsolete or is no longer economical to support and therefore undergo disposal or recycling of their content.

From the problem statement, our vision in this work is that IoT software systems involve more than Software Engineering. The System Engineering in this vision motivated us to have a multidisciplinary view of the problem. In this section, we briefly presented the proposed areas and phases. With our work, we seek to contribute to the System Engineering area, following the **Concept Definition**, **System Definition,** and **System Realization** phases with the IoT Roadmap that embraces multidisciplinarity and presents a guideline for action based on the initial project characterization reflecting principles of Systems Engineering.

2.2 System Architecture

All human-made systems are composed of interacting components, each with its own identity and characteristics arranged in a certain way to accomplish a goal (Wasson, 2005). The system architecture is a specification of the components of a system and the communication between them, providing the conformity constraints to the components (Luckham, Vera, & Meldal, 1995). Its architecture can define a system if it conforms to these constraints and meets the given requirements. The architecture guarantees the behavioral properties, configuration, and relationships present in the whole process of system engineering.

Developing the system architecture is a paramount activity in systems engineering since it relies on a creative process with no unique solution to satisfying user requirements (Walden, Roedler, & Forsberg, 2015). The system architecture is critical because it provides the groundwork for system development.

This work does not delve into architectural issues but proposes promoting a multidisciplinary vision and broader concepts in IoT software systems. In this work, this conceptual organization was inspired by the Zachman Framework (see section 2.2.1).

2.2.1 The Zachman Framework

The Zachman Framework (Zachman, 1987) is a widely used technology in information and business architecture. It was introduced in 1987 to comprehend the scope of control within an enterprise and provide a holistic view of the enterprise architecture used as a base for its management. It still is an essential reference for enterprise architecture, and it is still supported by many types of modeling tools and languages (Goethals, Snoeck, Lemahieu, & Vandenbulcke, 2006). The framework enables a complex thing, like architecture, to be defined for different purposes from different perspectives with different descriptions.

Zachman's motivation to develop the framework was that "with increasing size and complexity of the implementation of information systems, it is necessary to use some logical construct for defining and controlling the interfaces and the integration of all of the components of the system" (Tang, Han, & Chen, 2004).

This framework is primarily defined considering a table, crossing perspectives, and interrogative questions as presented in Table 1 (Zachman, 1987; Sowa & Zachman, 1992).

Table 1. Zachman Framework.

		INTERROGATIVES					
		What	How	Where	When	Who	Why
PERSPECTIVES	Planner						
	Owner						
	Designer						
	Builder						
	Implementer						
	User						

The framework formalization is presented as a metaphor from the building architecture to system architecture. The perspectives are therefore described as (Sowa & Zachman, 1992):

- **Planner** - The first architectural sketch depicts the size, shape, spatial relationships, and primary purpose of the final structure in gross terms. In the framework, it corresponds to an executive summary for a planner or investor who wants an estimate of the scope of the system, what it would cost, and how it would perform.
- **Owner** - Next is the architect's drawings that depict the final building from the owner's perspective, who must live in it. They correspond to the enterprise business model, which constitutes the design of the business and shows the business entities and processes and how they interact.
- **Designer** - The architect's plans translate the drawings into detailed specifications from the designer's perspective. They correspond to the system model designed by a systems analyst who must determine the data elements and functions representing business entities and processes.
- **Builder** - The contractor must redraw the architect's plans to represent the builder's perspective, considering the constraints of tools, technology, and materials. The builder's plans correspond to the technology model, which must tailor the information system model to the details of the programming languages, I/O devices, or other technology.
- **Implementer** - Subcontractors work from shop plans that specify the details of parts or subsections. These correspond to the detailed specifications given to programmers who code individual modules without being concerned with the overall context or structure of the system.
- **User** - The user perspective was added later and represents the view of the functioning building, or system, in its operational environment.

The framework presents six fundamental questions in the columns to outline each perspective:

- <u>Some entity</u> is the answer to the question of **what**. The entities are real-world objects for Rows 1 and 2 (Planner's and Owner's perspectives). For Row 3 (Designer's perspective), they are logical information types in the model. For Row 4 (Builder's perspective), they are physical data types in the technology model. Finally, Row 5 (Implementer's perspective) has more specialized data types for each component.
- <u>Some process</u> is the answer to the question of **how**. Rows 1 and 2 are real-world processes. For the lower rows, they are computational functions that model the process.

- Some type of location is the answer to the question of **where**. The top two rows are locations in the world. For the lower rows, they are logical or physical nodes in a computer network.
- Some role played by a person or a computational agent answers the question of **who**. Rows 1 and 2 are persons who play some role in the enterprise. For the lower rows, they may be programs that act for the user at a higher level.
- Time is the answer to **when** a subtype such as a date or time coincides with some event.
- Some goal or subgoal that provides the reason that motivates the model for that row is the answer to **why**.

The framework does not prescribe a process, notation, tool, or method. Instead, the primary purpose is to represent an organization holistically, keeping it simple but comprehensive as a classification scheme. To remain straightforward, Zachman defines seven rules for using the framework:

Rule 1: Do not add rows or columns to the framework.

Rule 2: Each column has a simple generic model.

Rule 3: Each cell model that specializes in its column is a generic model.

Rule 4: No Meta concept can be classified into more than one cell.

Rule 5: Do not create diagonal relationships between cells.

Rule 6: Do not change the names of the rows or columns.

Rule 7: There is no column order. However, the rows should be fulfilled from top to bottom.

The definitions presented here are related to the formalization of the original framework. Since its proposal (1987) and formalization (1992), the framework evolved, and it was implemented for different uses being the base for several adaptations. In its evolution, the initial name of perspectives was updated for new names: Planner has been named Executive, Owner has been named Business, Designer has been named Architect, Builder has been named Engineer, and Implementer has been named Technician.

The Rational Unified Process - RUP (de Villiers, 2001) used the Zachman Framework for its assessment. The RUP is defined regarding roles, artifacts, activities, and workflows, presenting its lifecycle in temporal terms, using phases and iterations.

The four phases are Inception, Elaboration, Construction, and Transition. The idea of the study was to observe RUP`s effectiveness regarding its coverage of software development deliverables using the Zachman Framework. In the paper, the authors tailor the perspectives and questions initially proposed by the framework to fit their purposes (de Villiers, 2001). In conclusion, the authors claim that the Zachman Framework cannot assess the full capabilities of RUP because, despite its adequate cover of the static part (addressing the artifacts and their relationships to one another, plus roles and activities and their relationship to artifacts), the framework does not capture the dynamic point of view (how the static aspects relate to each other across the lifecycle).

The Zachman Framework was also used to support a method to infer business activities to support business processes modeling to facilitate the consistent representation of business processes (Sousa, Pereira, Vendeirinho, Caetano, & Tribolet, 2007). It proposed rules to identify business process activities by analyzing the framework dimensions with the questions.

Another work aims to support product traceability along the product lifecycle and presents the Zachman framework as a guideline for applying the IEC 62264[3] standards balancing conceptual and implementation information (Panetto, Baïna, & Morel, 2007). The authors claim that the framework could define different models at different abstract levels for other purposes with different views.

The framework has also been used for requirements engineering (Chen & Pooley, 2009; Lee, Ahn, & Lee, 2014). Both studies use the Zachman Framework for requirements engineering and provide alternatives for a meta-model to fill each framework cell and recommendations for a modeling method.

Zhang *et al.* used this framework for safety analysis in Avionics Systems (Zhang, Shi, & Chen, 2014). They justified its use by describing "a system composed of the interconnected physical and functional elements. The difficulty is the mixture of the physical and functional layers while no structure defines the relation instantiation", which was achieved through the framework.

The Zachman framework was also applied to Systems of Systems - SoS (Bondar, Hsu, Pfouga, & Stjepandić, 2017), where the framework guided the development of SoS architecture, including emergent behavior. In the paper, the essential features of the framework, no specific models, no methodology, and no notation, are considered

[3] From the International Organization for Standard - IEC 62264-1:2013 for Enterprise-control system integration.

advantages since it enables a certain level of freedom to the architects and developers to incorporate different modeling techniques.

More evidence on using the Zachman framework can be observed in different case studies (Panetto, Baïna, & Morel, 2007; Nogueira, Romero, Espadas, & Molina, 2013; Aginsa, Matheus Edward, & Shalannanda, 2016), the latter claiming that "*Zachman framework continues to represent a modeling tool of great utility and value since it can integrate and align the IT infrastructure and business goals.*"

Because of its flexibility and customization (McGovern *et al.*, 2004), the Zachman Framework was selected as a structure that could support the organization of the concepts in this research. Furthermore, with its extensive use and adaptation, such a framework demonstrated suitable for working with complex software systems such as IoT.

2.3 Related Works

For this Thesis, we present an actionable instrument in the form of a Roadmap that gives a holistic view for the realization of IoT software systems based on the principles of Systems Engineering. The IoT is a prominent area, with interest from academia and industry, motivating growing research and investigation. We recovered some works dealing with IoT Challenges, IoT Engineering, and IoT Requirements as related work.

2.3.1 IoT Challenges

IoT is an under-construction domain, so, understandably, many works present an overview of challenges and opportunities. Throughout the research carried out in this thesis, we came into contact with several works that show the IoT challenges, many of which focus on challenges for an application area and challenges for specific features of IoT (Borgia, Gomes, Lagesse, Lea, & Puccinelli, 2016; Motta, de Oliveira, & Travassos, 2018).

Regarding works that list challenges for a specific domain, we highlight IoT for **agriculture** (Tzounis, Katsoulas, Bartzanas, & Kittas, 2017)**; IoT for wearable applications** (Dian, Vahidnia, & Rahmati, 2020); for **Industry 4.0** (Khan *et al*., 2020; Sisinni, Saifullah, Han, Jennehag, & Gidlund, 2018) and challenges in **Healthcare** (Thilakarathne, Kagita, & Gadekallu, 2020). Despite the differences in application, most of the listed challenges are shared since they are related to IoT characteristics.

Different works provide an overview of IoT characteristics, its challenges, and initiatives to deal with some of them, such as **security** (Kouicem, Bouabdallah, & Lakhlef, 2018; Mohamad Noor & Hassan, 2019; Macedo *et al*., 2019); **interoperability** (Motta, de Oliveira, & Travassos, 2019; Yang *et al.*, 2020; Negash, Westerlund, & Tenhunen, 2019); and **data** (Saleem & Chishti, 2019; Diène, Rodrigues, Diallo, Ndoye, & Korotaev, 2020) – often cited as top IoT challenges.

Each of these IoT challenges requires a specific mechanism, and for the sake of IoT evolution, the research must tackle them. However, we argue that a broad view is also necessary to deal with them combined. Otherwise, we still see product silos from big companies, heterogeneous solutions, even terminology not clearly defined (Guth *et al.*, 2018). Hence, for the IoT paradigm to thrive, there is a need to make an integrated vision of the problem available and develop good IoT products. As proposed in this work, this vision should be considered at the early stages of the IoT problem definition and reflected in the design, architectures, and technologies used for IoT software systems (Pfleeger & Atlee, 1998). This overview on the IoT challenges was an important initial step towards understanding our research problem and directing the future of our research. In this work, we also researched the challenges in IoT, but we did not delve into their details. Instead, we decided to focus on the broader view of supporting IoT engineering through the IoT Roadmap.

2.3.2 IoT Requirements

With a view to IoT challenges, we realized that projects could benefit from a better understanding and definition of the problem domain and the formalization of its needs. Therefore, we looked for related works that dealt with the issue of requirements for IoT systems.

An interesting work (Costa, Pires, & Delicato, 2017) more than just presenting the requirements and needs of an IoT application focuses on these challenges. It proposes an approach to support the requirements specification for IoT software systems named the IoT Requirements Modeling Language (IoT-RML). We share some of the motivations with this work since it states that different perspectives and the heterogeneous nature of IoT should be considered in the development. The Domain Model composes their proposal for the abstraction and a SysML profile for the specification (Costa, Pires, & Delicato, 2016). A stakeholder expresses a requirement as a proposition in their model, which may influence or conflict with other requirements. Their approach supports both functional and non-functional requirements, which is crucial in this scenario. A proof of concept is presented to illustrate the use of the approach in the context of a smart building, focusing on employees' safety and energy efficiency.

Our proposal somehow relates to the IoT-RML approach (Costa, Pires, & Delicato, 2017). However, we aim to address the problem understanding in the conceptual phase, which focuses on a step before the specification requirements considering a multi-perspective and multidisciplinary strategy.

Another work on IoT requirements is the SCENARIoT specification technique (de Souza, Motta, de O. Costa, & Travassos, 2019), a requirement specification technique for describing IoT scenarios based on interaction arrangements. In this technique, the IoT desired solution fits in one of the nine interaction arrangements and produces a particular scenario description with the related IoT characteristics.

In a similar context, there is the Requirements Engineering process for IoT systems (Silva, Gonçalves, & da Rocha, 2019). The process follows the ISO IEC/IEEE 12207:2017 structure and defines activities for the Business process, Stakeholder Needs and Requirements Definition process, and System/Software Requirements Definition process.

We share some of the motivations with SCENARIoT and the Requirements Engineering process for IoT systems (Silva, Gonçalves, & da Rocha, 2019) since they consider the multidisciplinary view on IoT.

The presented requirements methods work well in what they propose to define what must be implemented in an IoT software system. However, their performance is limited to the initial moment of the project, acting only in part of the life cycle. With this, we saw a possibility to extend the understanding and support of IoT software systems in different engineering phases.

2.3.3 IoT Engineering

Through the research, we also found some works that tackle engineering issues, mainly the activities and processes related to the conceptualization and realization of IoT solutions, that we understood as IoT Engineering. The idea is that the realization of IoT systems requires adaptations to existing processes and technologies or the proposition of new processes and technologies (Zambonelli, 2017). The works listed here address precisely this issue.

For example, Patel and Cassou (Patel & Cassou, 2015) propose supporting IoT applications' implementation. Their approach is designed to address essential challenges (lack of division of roles, heterogeneity, scale, different lifecycle phases) that differentiate IoT software systems from others. In the methodology, the proposal is based on the separation of concerns: domain, functional, deployment, and platform. Each concern has specific steps to guide the development, implemented in a defined process with the suggestion of five different roles. This work (Patel & Cassou, 2015) focused on the development and deployment phases, using model-driven development and specific modeling languages. Despite the comprehensive proposal, their work differs from the IoT Roadmap presented in this thesis. As they focus on code generation, the proposed methodology is not concerned with understanding the problem itself or the engineering organization at the project level. Thus, the methodology is directly linked to **how** to make IoT applications, not addressing the knowledge behind the realization. It also has the limitation of using the editor and the language defined in the proposal, which can inhibit the wide use of their proposal.

Two interesting works (Alegre, Augusto, & Clark, 2016; Sánchez Guinea, Nain, & Le Traon, 2016) are literature reviews, focusing on engineering strategies to develop IoT Context-Aware Software Systems (CASS) and Ubiquitous Systems, respectively.

In (Alegre, Augusto, & Clark, 2016), the results are based on a literature review, and a questionnaire carried out with specialists in CASS. It presents extensive work in the CASS area, analyzing and characterizing the concept of context and their interaction types and main features. The most exciting part for the perspective of our work is that they search the literature for developing techniques and methods that have been adapted from conventional systems to CASS throughout the most common stages of a development process: Requirements Elicitation, Analysis & Design, Implementation, and Deployment & Maintenance. The paper presents a brief analysis of the different techniques found and concludes that the proposals usually focus on addressing a specific issue in the development independent of each other. Several aspects were presented to justify a lack of a unified vision, such as diversity (many alternatives require many developments type in different possible scenarios) and a lack of a shared understanding.

With similar motivation, (Sánchez Guinea, Nain, & Le Traon, 2016) performed a systematic review to investigate development strategies but focusing on Ubiquitous Systems. The authors conclude the review by indicating that one of the main challenges is the lack of support for developers due to a lack of techniques and methodologies that help developers design and deploy their applications to different ubiquitous systems. In addition, there is no support for the entire development cycle. Some of the other challenges presented show the need for a multidisciplinary strategy to deal with software alongside connectivity, interactivity, and other concerns in a unified way.

These two works fit into the context of IoT, addressing concepts of context-aware and ubiquitous systems. Although they do not propose solutions, they present an overview of the area that corroborates the motivation of our work regarding multidisciplinarity and the need for a holistic vision.

Another related work from 2018 is from Aniculaesei *et al.* They argue that conventional engineering methods are inadequate for providing some of the challenges specific to autonomous systems, such as the dependability focus of their work (Aniculaesei, Grieser, Rausch, Rehfeldt, & Warnecke, 2018). Some of the main points discussed are the possibility of adaptive behavior present in IoT, as they adapt their behavior to better interact with other systems and people or to solve problems more effectively, and variations in the context, the formerly closed and valid development artifacts may not capture the changes and be inadequate since the environment. From this, the system's behavior can no longer be fully predicted or described in advance. In response to these challenges and gaps, the authors propose an approach based on Dependability Cages. Their approach deals with development and operation risks, external (uncertainties in the environment), and internal (system changing behavior). One of the limitations observed in the proposal is related to multidisciplinarity. The authors identify this aspect of the systems, but the proposed approach does not present a mechanism to deal with it. Another missing point is a breakdown of the necessary initial content (say, the requirements) to use the approach.

A review by Giray *et al.* provided us valuable insights on IoT software systems development methods (Görkem *et al*., 2017). They reiterate that IoT software systems are more complex than usual software systems and possess challenges from the process perspective. In the review, they provide an overview and evaluation of the Ignite Methodology (Slama, Puhlmann, Morrish, & Bhatnagar, 2015), the IoT Methodology (online), ELDAMeth (Fortino, Rango, & Russo, 2014), a Software Product Line Process to Develop Agents for the IoT (Ayala, Amor, Fuentes, & Troya, 2015), and a General Software Engineering Methodology for IoT (Zambonelli, 2016). The methods were evaluated against 14 criteria, such as defined steps to execute the method, metrics provided, artifacts, documentation, and tool support. The evaluation concluded that none was considered a complete method to cover all the criteria and phases necessary for developing IoT software systems.

The identified works present advances regarding the challenges, requirements, and methods for developing IoT applications. Despite the limitations pointed out, the works presented meet what they propose. The IoT Roadmap does not intend to replace them, as it aims to guide and support IoT engineering based on a multifaceted understanding of a problem. The IoT Roadmap can be used in combination with the works presented, acting in conjunction with existing techniques on the three highlighted fronts: challenges, requirements, and methods.

2.4 Chapter Considerations

Our proposal supports IoT software systems' engineering process, considering its multidisciplinarity, to enrich the previous research for IoT and contribute to the area. The proposed Roadmap materializes the IoT Conceptual Framework and presents directions, activities, and recommendations to support IoT unified development. In the execution of this thesis, we found a lack of more concrete proposals for the materialization of this paradigm. We aim to address some of the challenges presented in the related works, and in this proposal, we intend to focus on multidisciplinarity. Besides, to support the project's understanding and definition for the Concept Definition, System Definition, and System Realization Phases.

This chapter presented the theoretical foundation necessary for the understanding and realization of our proposal. We aim to address IoT, with its particularities, with a multidisciplinary approach based on **Systems Engineering** in a structure inspired by the **Zachman Framework**. In this chapter, we also presented **Related Works** to our theme.

3 Conceptual Phase

This chapter presents different studies performed to retrieve the fundamental conceptual elements to define our proposal with an IoT Characterization, IoT Challenges, and IoT Facets. Those conceptual elements were the base for the definition of the IoT Conceptual Framework to be used in our proposition.

3.1 Internet of Things Characterization: A Systematic Literature Review

Before any decision to direct the proposal, the first activity was to characterize the IoT paradigm to observe research opportunities. Thus, it was defined as one of the specific objectives to identify the characteristics presented by IoT and give an overview of the area, aiming to promote a better perception of current development needs. A systematic literature review (SLR) was undertaken, which is described in this section. In addition to the characterization, we also wanted to investigate the status and concerns in developing IoT software systems. The results of this study are available in (Motta, Silva, & Travassos, 2019).

The SLR reported in this section is focused on secondary studies and was conducted to investigate IoT. We followed a defined methodology and guidelines to provide a formal and well-defined process with planning, execution, analysis, and packing steps (Mian, Conte, Natali, Biolchini, & Travassos, 2005). With the review, we aim to summarize the technical literature related to IoT, identify possible research gaps, and expand the conceptual background of this investigation, focused mainly on the characterization of IoT. The following sections of this chapter expose a summary of the used protocol, the data retrieved, and the review contribution. The complete protocol of this review was documented as a technical report[4].

Planning. The main goal of the planning step is to prepare the SLR protocol based on the research questions. The search string should be formulated considering possible terms and synonyms. Study selection and inclusion criteria are also decided.

[4] https://goo.gl/cZVVDc

Finally, the protocol approval must proceed to the execution step. The summary of the protocol is presented in Table 2.

Table 2. Protocol Summary.

Goal	**Analyze** Internet of Things **With the purpose of** Characterizing **Regarding** its definitions, characteristics and application areas **From the point of view of** software engineering researchers **In the context of** knowledge available in the technical literature	
Research questions	(RQ1) What is Internet of Things? (RQ2) Which characteristics define IoT applications? (RQ3) Which are the applications for IoT?	
Search string	Population	("*systematic literature review" OR "systematic* review*" OR "mapping study" OR "systematic mapping" OR "structured review" OR "secondary study" OR "literature survey" OR "survey of technologies" OR "driver technologies" OR "review of survey*" OR "technolog* review*" OR "state of research") **AND**
	Intervention	("internet of things" OR "iot")
Search Strategy	SCOPUS (www.scopus.com) + Backward and Forward Snowballing (Wohlin, 2014)	
Inclusion Criteria	- To provide an IoT definition; OR to provide IoT properties; OR to provide applications for IoT.	
Exclusion Criteria	- Not provides an IoT definition; AND not provides IoT properties; AND not provides applications for IoT; AND studies in duplicity; AND register of proceedings.	
Study type	Secondary Studies	
Acceptance Criteria	Three distinct readers: - all readers accept => paper is accepted - all readers exclude => paper is excluded - the majority of accept, others in doubt => paper is accepted - else => discuss and consensus	
Technical Report	Detailed information about the planning and execution - https://goo.gl/cZVVDc	

Execution. This step is carried in trials where the search string iteratively evolves, aiming to improve precision and recall. Each trial involves reading and consensus from the readers' part in the studies retrieved. Decisions encompass whether to continue and include papers considering the criteria established in the planning step or refine the search string and perform a new trial. Next, the reader's consensus needs to proceed with the analysis step. After applying the final search string to Scopus in December 2018, 76 articles were returned, of which 24 remained after using the inclusion and exclusion criteria defined in the SLR protocol. After a detailed reading of them, seven were kept for analysis. From these seven, we performed Snowballing procedures. It refers to using an article's reference list of citations to identify additional material (Wohlin, 2014). We performed Backward and Forward Snowballing Sampling in this step, tracking down references in the seven articles selected in the previous step and their citations. It was performed following the selection procedure established (Filter by Title, Abstract, and Full-paper reading). This step resulted in the inclusion of five new articles.

In total, 12 articles compose our final set for the review: (Atzori, Iera, & Morabito, 2010; Bandyopadhyay & Sen, 2011; Miorandi, Sicari, De Pellegrini, & Chlamtac, 2012; Gubbi, Buyya, Marusic, & Palaniswami, 2013; Xu, He, & Li, 2014; Borgia, 2014; Singh, Tripathi, & Jara, 2014; Whitmore, Agarwal, & Da Xu, 2015; Madakam, Ramaswamy, & Tripathi, 2015; Gil, Ferrández, Mora-Mora, & Peral, 2016; Sethi & Sarangi, 2017; Trappey, Trappey, Hareesh Govindarajan, Chuang, & Sun, 2017).

We used an extraction form to retrieve the following information from the secondary sources: Reference information, Abstract, IoT definition, IoT related terms, IoT application features, IoT application domain, Development Strategies for IoT, Study Type, Study Properties, Challenges, and Article focus.

Analysis. The readers agree upon a set of candidate papers, considering the inclusion/exclusion criteria. After full reading, the candidate papers extract relevant data based on the extraction form. In this step, based on the results, we performed a qualitative analysis inspired by Grounded Theory (GT) coding procedures (Strauss & Corbin, 1990) in part of the findings. This approach is widely used for qualitative research in the Software Engineering area (Carver, 2007). We found 28 IoT definitions, 28 characteristics, and several application domains to answer our research questions in the analysis phase.

Packing. This step is performed throughout the review process, aiming to document every decision in each activity and the information collected and analyzed.

The results are presented in the following sections, reporting the findings for each research question.

3.1.1 What is the "Internet of Things"?

The 12 selected papers supported the extraction of 28 different IoT definitions to answer RQ1. From the analysis of these 28 definitions, we noticed that the existing definitions followed a specific pattern in their structure, explaining the actors involved, the requirements, and the consequences of relations among actors as part of a system - not necessarily presented in all definitions. We considered this structure not to limit our interpretation but to support a more thorough IoT concept understanding, thus finding an appropriate and updated definition for this work.

We organized some of the definitions found in chronological order to observe how the concept has evolved. The IoT concept has evolved and changed from its first appearance in 1999 (Ashton, 2009). This section presents some of the IoT definitions found throughout our SLR, organized chronologically to observe how the concept has evolved through the years (timeline in Figure 3).

In the 2001 definition, we can observe that the idea is to connect objects, information, and people, the actors in this system. Therefore, it clarifies the network's necessity to connect the actors, and the realization was limited by RFID, representing the starting point of IoT discussions.

Considering the definition of 2005, it does not propose the use of any technology, like RFID. Still, it includes the idea of expanding the initial capabilities of an object through technology and brings attention to objects' behaviors. However, to perceive changes in the objects' state is only possible by identifying the object first. Therefore, it leads to an effort to make the things identifiable.

Once identifiable, it is possible to make things communicate automatically (Dunkels & Vasseur, 2010). We consider this as a concept an evolution since this kind of autonomy was not previously discussed. This definition is also introducing the purpose-idea and reinforces it.

As we progress to 2009, we can see that the central concept of communication and integration remains. Still, we noticed the introduction of requirements such as interoperability and integration in a seamless way. Moreover, this definition also details the *things* in IoT, as *things* being virtual or physical, that can have different personalities and may use different communication protocols.

The 2010 IoT definition is one of the most used IoT definitions, and we consider it complete regarding a rationale involving actors, relations among actors, requirements, and what it enables. It presents the vast amount and heterogeneity of actors that can engage interaction and achieve that through unique addressing schemes. In this case, new actors are included, and we can observe that sensing and acting are other possible behaviors that a system can possess, differing from previous definitions. Therefore, these actors can cooperate to reach some goals.

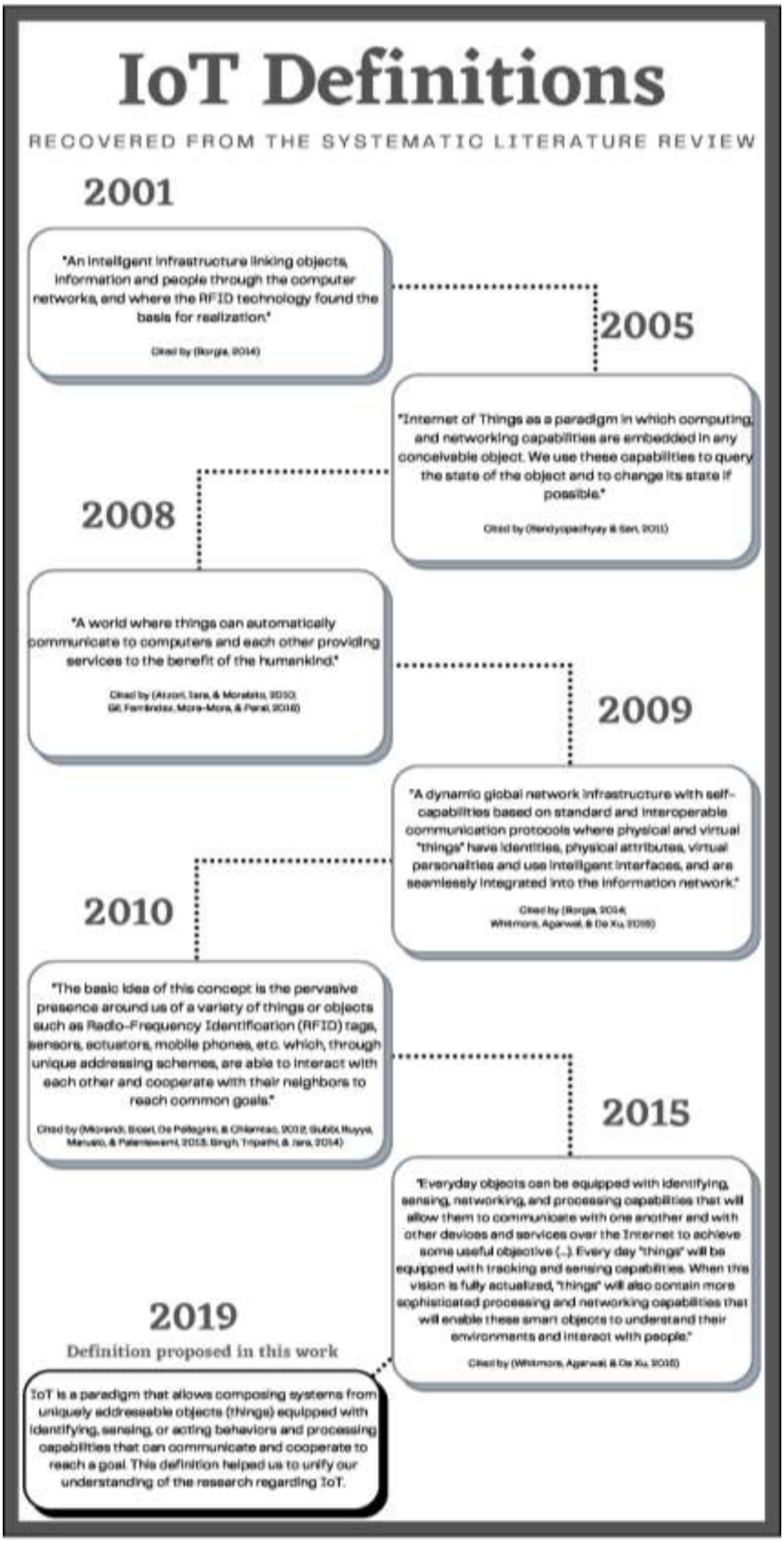

Figure 3. IoT Definitions recovered from the SLR.

Once the everyday *things* can sense the environment, they become more aware of what is around them, which characterizes context-awareness. In this definition, we again see that IoT's primary concern is to leverage the connection among different things to achieve a system objective. Also, the authors explain that *things* in the IoT context are those objects equipped with identifying, sensing, networking, and processing capabilities. In contrast, other definitions exemplify *things* as providers of such capabilities: tags, sensors, and actuators. Finally, it represented the IoT vision in 2015.

In general, IoT software systems have multidisciplinary and innovative characteristics in the most diverse areas (Fizza *et al.*, 2021; Dash & Prusty, 2021). IoT is planned to have exponential growth with the expectation to play a vital role in industry, cities, and agriculture, creating new market opportunities and business models. Many IoT applications are available, including automation, monitoring, and wearable devices (Dian, Vahidnia, & Rahmati, 2020) based on identifiers, sensors, and actuators (Gómez-Chabla, Real-Avilés, Morán, Grijalva, & Recalde, 2019). These applications are wrapped with software solutions and security, privacy, interoperability, and performance, among other quality aspects essential in engineering IoT software systems (Ahmed, Bures, Frajtak, & Cerny, 2019).

In our understanding, the *things* in the IoT context exist in the physical realm, such as sensors, actuators and anything that is equipped with identification (tag reading), sensing or actuation capabilities, which excludes entities in the Internet domain (hosts, terminals, routers, among others). The *things* should also have communication, networking, and processing functionalities varying according to the system's requirements. In the beginning, the *things* in IoT software systems were objects attached with electronic tags, so these systems present identification behavior. Subsequently, with the evolution of the concept, sensors and actuators became part of the paradigm and enabled the Sensing and Actuation behaviors. It means that an IoT software system may have Identification, Sensing, Actuation behaviors, or a combination of them. We can observe the evolution of the paradigm over the years and what it currently represents, clarifying points of multidisciplinarity, heterogeneity, and other characteristics that motivate the proposal of this work. In addition, we note other concepts such as context-awareness and ubiquity in a broader sense in IoT definitions.

To answer RQ1, from the understanding of all definitions, we define **IoT as a paradigm that allows composing software systems from uniquely addressable objects (*things*) equipped with identifying, sensing, or acting behaviors and**

processing capabilities that can communicate and cooperate to reach a goal. This definition helped us to unify our understanding of the research regarding IoT. Furthermore, it motivated us to follow the direction taken, and from this definition, other activities were carried out.

3.1.2 Which characteristics define IoT?

The 12 papers provided 211 excerpts, coded following coding procedures (Strauss & Corbin, 1990), from which we identified 28 characteristics (Table 3) to answer RQ2. One point of discussion is that the authors do not define all the articles' characteristics or refer to the original work defining them. The lack of definitions hinders the research and understanding of the area since we cannot know the characteristic's meaning or what the author meant by that. It is challenging to characterize IoT and develop more suitable solutions that contemplate the desired characteristics since they were not defined, only listed. For the same reason, it is not possible to infer that the authors are discussing the same issues regarding cost, size, resources, or energy, such as efficiency, for instance. Therefore, we list the characteristics without definition and detail the defined characteristics in Table 4.

Table 3. IoT Characteristics.

Characteristics	#
Characteristics not defined	19
Characteristics defined	9
Total	28

List of characteristics **not defined** by the papers in the set: Accuracy, Adaptability, Availability, Connectivity, Efficiency, Extensibility, Flexibility, Manageability, Modularity, Performance, Privacy, Reliability, Robustness, Scalability, Smartness, Sustainability, Traceability, Trust and Visibility. Even with the lack of definition, these characteristics are relevant for the characterization scenario of IoT systems.

List of characteristics **defined** by the papers in the set:

Table 4. IoT Defined Characteristics.

Characteristic	Definition	Reference
Addressability	The ability to distinguish objects using unique IDs	(Atzori *et al.* 2010; Bandyopadhyay and Sen 2011; Miorandi *et al.* 2012; Borgia 2014).
Unique ID	It is necessary for unique identification for every physical object. Once the object is identified, it is possible to enhance it with personalities and other information and enable control over it	(Atzori *et al.* 2010; Bandyopadhyay and Sen 2011; Miorandi *et al.* 2012; Gubbi *et al.* 2013; Borgia 2014; Li *et al.* 2015)
Object Autonomy	Smart objects can have individual autonomy, not needing direct human interaction to perform established actions while reacting or being influenced by real/physical world events	(Atzori *et al.* 2010; Gubbi *et al.* 2013; Madakam *et al.* 2015)
Mobility	Object availability across different locations	(Atzori *et al.* 2010; Bandyopadhyay and Sen 2011; Borgia 2014; Sethi and Sarangi 2017)
Autonomy	Refers to systems not needing direct human intervention to perform established actions such as data capture, autonomous behavior, and reaction	(Atzori *et al.* 2010; Miorandi *et al.* 2012; Gubbi *et al.* 2013; Borgia 2014; Whitmore *et al.* 2015; Sethi and Sarangi 2017)
Context-awareness	The use of context to provide task-relevant information and services to a user	(Atzori *et al.* 2010; Bandyopadhyay and Sen 2011; Miorandi *et al.* 2012; Gubbi *et al.* 2013; Borgia 2014; Li *et al.* 2015)
Heterogeneity	Several services taking part in the system, which present very different capabilities from the computational and communication standpoints	(Atzori *et al.* 2010; Bandyopadhyay and Sen 2011; Miorandi *et al.* 2012; Gubbi *et al.* 2013; Borgia 2014; Madakam *et al.* 2015; Li *et al.* 2015; Sethi and Sarangi 2017)
Interoperability	Interoperability is of three types: Network interoperability that deals with communication protocols. Syntactic interoperability ensures the conversion of different formats and structures. Semantic interoperability deals with abstracting the meaning of data within a particular domain	(Atzori *et al.* 2010; Bandyopadhyay and Sen 2011; Miorandi *et al.* 2012; Gubbi *et al.* 2013; Borgia 2014; Madakam *et al.* 2015; Li *et al.* 2015; Sethi and Sarangi 2017)
Security	To ensure the security of data, services, and entire IoT system, a series of properties, such as confidentiality, integrity, authentication, authorization, non-repudiation, availability, and privacy, must be guaranteed	(Atzori *et al.* 2010; Bandyopadhyay and Sen 2011; Miorandi *et al.* 2012; Gubbi *et al.* 2013; Borgia 2014; Madakam *et al.* 2015; Whitmore *et al.* 2015; Li *et al.* 2015; Sethi and Sarangi 2017)

3.1.3 Which are the applications for IoT?

Several application domains can leverage the Internet of Things advantages to answer RQ3. However, all the application domains are only examples of areas that benefit from IoT or are supposed to do it in the future. As declared in Whitmore *et al.,* "the domain of the application areas for the IoT is limited only by imagination at this point" (Whitmore, Agarwal, & Da Xu, 2015).

Atzori (Atzori, Iera, & Morabito, 2010) describe five domains: (A) Transportation and logistics, (B) Healthcare, (C) Smart environment (home, office, plant), (D) Personal/social, and (E) Futuristic domain (whose implementation of such applications is still too complicated).

Gubbi *et al.* (Gubbi, Buyya, Marusic, & Palaniswami, 2013) describe (A) Personal and Home, (B) Enterprise, (C) Utilities, and (D) Mobile domain. Also, there is a classification of the applications for Consumer (Home, Lifestyle, Healthcare, Transport) and Business (manufacturing, retail, public services, energy, transportation, agriculture, cities, and others) (Trappey, Trappey, Hareesh Govindarajan, Chuang, & Sun, 2017). Those domain categorizations can be a subpart of a categorization, which grouped the applications in three major domains (Borgia, 2014): (A) Industrial domain, (B) Smart city domain, and (C) Health well-being domain. They are not isolated, but there is a partial overlapping since some applications are shared across the contexts. For example, tracking of products can be a demand for both Industrial and Health well-being domains.

This review addressed the purpose of a general IoT characterization, presenting a definition and identified characteristics. It was an initial step in the Conceptual Phase of the proposal, and one of the first contributions in this work is the knowledge organized and presented in the Technical Report.

3.1.4 Threats to Validity

It is important to highlight some threats to this study's validity (Wohlin *et al.*, 2012). Since only Scopus was used as a search engine, it may be missing some relevant studies. Still, from our experience, it can give fair coverage when performing together with snowballing procedures (backward and forward) (Motta, de Oliveira, & Travassos, 2019). In addition, a recurrent issue in SLR regards inconsistent terminology and restrictive keywords. We searched for other reviews and observed the terms used to compose our search string to reduce the researchers' bias. The cross-checking between two researchers and having a third researcher revise the results mitigated data extraction and interpretation biases. All phases of this review were peer-reviewed; any doubt was discussed to reduce selection bias among the readers. We have not performed a Quality Assessment regarding the research methodology of the selected studies due to the lack of information in the secondary reports. It is a threat to this study's validity.

3.2 Internet of Things Challenges

After the IoT characterization, we performed different studies to complement our knowledge and identify the main issues, concerns, and challenges when dealing with IoT. Each study was planned considering a specific perspective on the subject. Initially, we contemplate the perspective of the academy, recovered through the literature review previously presented. Then we decided to broaden the range to represent two other perspectives collected from practitioners and a government report, contributing to a more comprehensive representation of IoT Challenges (Figure 4). The results of this study are available (Motta, de Oliveira, & Travassos, 2018)

Figure 4. The three perspectives considered to recover the IoT Challenges.

Although academia, government, and practitioners are different visions, they discuss the same topic. Thus, they become complementary, giving us a more comprehensive view of the area. Throughout the following sections, we show the impressions of each perspective, and each study is detailed with planning, execution, and results.

To analyze the data resulting from each study, we rely on qualitative analysis and coding procedures based on GT (Strauss & Corbin, 1990). The idea is that the analysis arises from and is grounded in research data through constant comparison and has been extensively used and adequate to Software Engineering research (Seaman, 1999; Carver, 2007; Badreddin, 2013). This approach was selected since GT provides reference support for the procedures and is adequate to work with a large amount of information, such as the data extracted from a literature review and other sources, and interpret data. Furthermore, considering that some concepts have different meanings, this methodology is suitable for establishing similarities and differences. The same analysis strategy was used throughout the study and is based on **coding** - the process of breaking down, examining, comparing, conceptualizing, and categorizing data.

3.2.1 Challenges from Literature

In the SLR presented in the previous section, we followed a structured process, divided into different steps (Figure 5).

Figure 5. Literature Review Process.

Alongside the analysis to answer the proposed research questions, we also recovered information from issues, challenges, gaps, and open questions regarding IoT development. We are calling here challenges. First, the 12 papers provided 38 excerpts regarding IoT challenges. Then we used codes to assign concepts to a portion of data, with a constant comparative analysis to identify patterns from similarities and differences emergent from the data. This procedure was based on GT coding procedures (Strauss & Corbin, 1990). Two researchers with cross-checking conducted this textual analysis to achieve consensus. The 38 excerpts were organized into seven main challenges:

- **Architecture** - Issues and concerns regarding design decisions, styles, and the structure of IoT software systems.
- **Data** - It refers to managing a large amount of data and recovering, representing, storing, connecting, searching, and organizing data generated by IoT from many different users and devices.
- **Interoperability** - Related to the challenge of making different systems, software, and *things* interact for a purpose. Standards and protocols are also included as issues.
- **Management** - The application of management activities, such as planning, monitoring, and controlling, raise the interaction of different things in the IoT software system.
- **Network** - Technical challenges related to communication technologies, routing, access, and addressing schemes considering the different characteristics of the devices.

- **Security** - Issues related to several aspects to ensure data security in the IoT software system. For that, a series of properties, such as confidentiality, integrity, authentication, authorization, non-repudiation, availability, and privacy, should be investigated.
- **Social** - Concerns related to the human end-user to understand the situation of its users and their appliances.

It is interesting to notice that some challenges can be interrelated, indicating the multidisciplinary nature of IoT. For example: "For technology to disappear from the consciousness of the user, the Internet of Things demands software architectures and pervasive communication networks to process and convey the contextual information to where it is relevant" (Gubbi, Buyya, Marusic, & Palaniswami, 2013), this excerpt is coded for an architectural issue and network as well. Another example is "Central issues are making full interoperability of interconnected devices possible, providing them with an always higher degree of smartness by enabling their adaptation and autonomous behavior, while guaranteeing trust, privacy, and security" (Atzori, Iera, & Morabito, 2010), which was coded both for interoperability and for security issues. However, provided solutions to the problems presented in the technical literature can be tricky to achieve due to the diversity of challenges, variety of devices, and uncertainties in the area.

3.2.2 Challenges from Practitioners

Another perspective used to recover IoT challenges was the practitioners' opinion. From the characterization obtained with the SLR, we had the opportunity to hear people from industry and academia who are interested or already work with IoT.

The intent of capturing the information from this source was to increase our observation dataset and triangulate the challenges found in the SLR with the ones reported by practice. With this new vision, we deal with other relevant aspects and put the research closer to the people working in the area.

We performed qualitative studies during two scientific events from which all the participants were working on the IoT domain. Therefore, we considered the participants representative, insightful, and experienced in the topic. We organized the discussions at the events inspired by a focus group (Kontio, Bragge, & Lehtola, 2008) process and experiences from previous studies. The general process with some details is presented in Figure 6.

Figure 6. Overview of the study.

The questions seek to capture participants' perceptions regarding IoT and parallel the differences between the conventional and these new applications: a) Regarding product **quality** between conventional software and IoT: What is similar? What is different? What needs to be investigated? b) Regarding the software **technologies** between conventional software and IoT: What can be used directly? What needs adaptation? What don't we have?

For the discussions, we were mainly focused on the quality of the product, the technologies used, and the necessary knowledge of software engineering used in conventional software systems projects and IoT projects. Both in planning and execution, a researcher assumed the role of moderator accompanying the whole process. The questions aimed to foster discussions, and participants were free to express their perceptions.

Based on the outlined questions, we had the opportunity to execute the study in two events. The first event was the Quality IoT Workshop at the Brazilian Symposium on Software Quality in August 2017. In this event, the 21 participants were divided by their interests into three discussions groups to deal with the mentioned questions in the following perspectives:

- **People:** Discussion focused on human end-user. This technology's challenges and impact in our daily lives, such as social, legal, and ethical, are composed of five (5) participants.
- **Product:** Discussion focused on IoT products that can be generated, considering the inclusion of software and "smartness" in general objects and

the possibilities of new products in this scenario - a group composed of nine (9) participants.

- **Process:** Discussion focused on the software development process that should be included in the *things* and consider the big picture of organizing the *things* together - a group composed of seven (7) participants.

The groups had one hour for discussion. A representative of each group wrote down the main points identified and later presented the ideas to all the participants.

The second event was a panel in the Brazilian Congress on Software: Theory and Practice conducted by the same moderator of the first event, executed in September 2017. In this panel, five (5) practitioners (experts from academy and industry) and the audience were motivated to discuss the same previous study questions for 1h30. The moderator acted as the reporter in the panel discussion, gathering the central issues and producing a document reporting the notes.

At the end of this round of studies, all the notes from both events were collected and analyzed, leading to the findings and results discussed here. Discussions were reported through text, and the analysis was based on GT coding procedures were used that allowed the identification of nine categories of IoT challenges:

- **Architecture** - More attention is required to the software system architecture since the boundaries between hardware and software are no longer well defined. Also, the architecture should reflect in its conception the concerns on portability and interoperability, including orchestrating the connected devices, which is not trivial.
- **Interoperability** - Aside from the primary concern with the interaction of so many different devices, an important issue is how to address the programming for multi-devices. Thus, interoperability can be considered for development as well.
- **Professional** - The current developers are not entirely prepared to develop for IoT. The professionals should evolve together with the technologies, so an educational evolution and the training of software system engineers are necessary.
- **Quality Properties** - Although some specific properties such as interoperability, privacy, and security are primarily discussed, several other quality attributes are considered different in the IoT domain, such as capacity (device and network), installation difficulty, responsiveness, context

awareness. Contemplate non-functional requirements by considering what the individual sees, feels and how *things* can contribute to that.

- **Requirements** - Considering the IoT nature, with a tendency for more innovation mainly based on ideas, the requirements can be presented less structured. Another concern is that the user can also be a developer since the solutions reach different individuals and devices, and new features can be attached.
- **Scale** - To develop, manage and maintain a large-scale software system is a concern. As the number of devices and the number of relationships in the software system increases, new technologies are needed to maintain the required quality level of a software system.
- **Social** - Aligning the technical with the social, Human-Computer Interaction, and User Experience is of great importance in IoT development. Moreover, it should provide new methods and tools for IoT scenarios.
- **Security** - In the center of many discussions, security-related issues such as privacy and confidentiality are significant concerns, such as the software system scale, mobility, and performance. To balance several dimensions in a secure software system is required to turn IoT into reality, but the current software technologies do not support it.
- **Test** - IoT provides unprecedented universal access to connected devices. Testbed and acceptation tests are sophisticated, and there is a greater need for other types of tests, for example, usability, integrity, security, performance, and context awareness.

3.2.3 Challenges from Government

In 2016, the Brazilian Federal Government and the National Bank for Economic and Social Development (BNDES) began surveys with a prospective vision to conduct diagnoses and propose public policies for IoT. The motivation for this call is based on the tendency of IoT to spread across virtually all sectors of the economy since it is positioned as one of the major technological trends in Information.

The purpose of the Technical Study is to assess the stage and perspectives of implementation of IoT in the world and Brazil, to propose public policies that potential economic, technological, and productive impacts, and those linked to the well-being of Brazilian society. Therefore, in addition to a general diagnosis, the Technical Study should go more in-depth into mapping possible application segments and structural and technical issues, which present the most significant balanced potential between the densification visions of the chain productivity and impact on the economy and well-being. Based on this in-depth diagnosis, public policies should be developed together with competent bodies.

The study was planned and executed by the McKinsey / Fundação CPqD / Pereira Neto Macedo consortium selected through the Public Call BNDES / FEP Prospecção nº 01/2016 - Internet of Things (IoT) and all results are public domain and can be accessed for detailed information[5]. This section presents some information about the conducted study (Study Background and Execution). Our research aims to analyze the results obtained and look for IoT challenges from this perspective.

The consortium conducted the planning and execution. We only added it here for contextualization and based our part on the results discussed in the next section. Diagnosing and proposing public policies in the theme Internet of Things for Brazil was organized in four phases (BNDES, 2017). The study aimed to have a benchmark with successful international experiences (public policies and projects) that could serve as an inspiration and to answer the main questions:

- Which are the primary application segments and structural issues that should be approached?
- What are the technologies to be developed, and which are the leading global players?
- What are the challenges/opportunities in the country that IoT can address?
- What are the skills and opportunities for the industry?

The study was performed between January 2017 and March 2018, where these central questions were investigated. In addition, the study recovery data from several public sources, among them a Public Consultation, also conducted interviews with experts from various sectors relevant to the deployment of the Internet of the Things in Brazil and those obtained five workshops executed during the period. This collaborative effort involving several actors thus constitutes the foundation upon which the results rest.

Both planning and execution were performed by the McKinsey / Fundação CPqD / Pereira Neto Macedo consortium. From our side, in the context of this research, we

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[5] https://www.bndes.gov.br/wps/portal/site/home/conhecimento/pesquisaedados/estudos/estudo-internet-das-coisas-iot/estudo-internet-das-coisas-um-plano-de-acao-para-o-brasil

relied on their results to conduct an analysis based on GT, separated in Figure 7 by the dotted line and detailed in the next section.

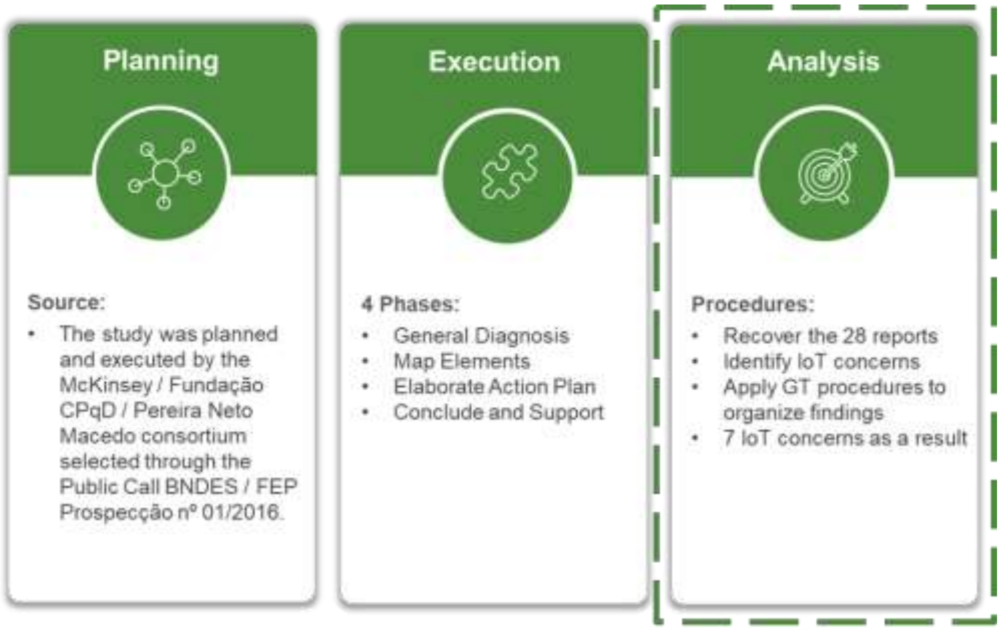

Figure 7. IoT Action Plan - Work division.

Only the dotted line was executed in the context of this research.

The result of the official study comprises a vast amount of information distributed in 28 documents that serve the strategic purposes that led to the conduction of the study in the first place.

Our interest relies on the set of materials available in a textual format and conducts an analysis. The author performed the procedure from the complete reading of the content and extraction of data portions mainly associated with challenges, opportunities, gaps, concerns, and issues related to IoT from a government perspective, performed similarly as in the previous studies. In addition, the extraction of challenges from the data from the government study reports occurred after the execution of the other two studies, contributing to the identification and faster assimilation of the content.

We collected all the resulting material and read and extractions, similar to what was performed for the SLR (Section 3.1). Reading the material allowed extracting information focusing on the presented challenges, analyzing, and similarly organizing them as the two previous information sources (the SLR and practitioners). From this material, seven categories of IoT challenges emerged:

- **Regulation** - Governments are working on crucial issues that require significant investment and coordination between the public and private sectors. Standardization is one of the most critical regulatory issues, and there is no single strategy to follow. In some cases, it is necessary to create laws and institutions that regulate privacy and security issues, which are debated today by all the countries mentioned in the report.

- **Interoperability** - To allow devices to communicate with each other, regardless of model, manufacturer, or industry. There is a concern that, if left free to the market, the standards developed by technology giants may result in monopolies, leading to the exclusion (or cost-intensive inclusion) of technologies in the global IoT ecosystem.
- **Security** - The vast amount of data generated results in numerous challenges regarding security in IoT, such as increasing the network attack, restricting the devices to support robust security techniques and mechanisms, misuse by the user, and even some product design flaws. Thus, security can be considered one of the leading technological concerns of IoT, comprising components of any solution.
- **Professionals** - To invest resources in the training of engineers and other professionals can create a strategic differential. However, the scenario is different, so more than proficiency in programming languages of lower level; the professional who develops software for IoT should be able to customize solutions already developed for specific demands.
- **Things** - For the devices, which includes their access and gateways, several non-functional restrictions inherent to IoT should be present in the products. These restrictions increase the total cost of the objects, such as an energy consumption alternative when connecting to the power grid is impossible.
- **Network** - There are pretty heterogeneous concerns since IoT covers several use cases for which the network requirements are specific, such as: (i) for real-time applications, such as autonomous vehicles, communication latency as well as response time are crucial factors directly related to the network; (ii) applications requiring low data traffic and coexisting with a broad geographic dispersion (e.g., precision agriculture) impose a new paradigm for the evolution of technologies, contrary to what has been developed in the last decade, where the higher bandwidth capacity was predominant. In summary, the IoT access to the network should be heterogeneous, with different technologies composing a vast ecosystem.

- **Data** - The concentration of the data generated and transmitted by smart objects should be processed and analyzed, yielding the expected use cases value. Thus, there is a concern in storing and handling a vast amount of data, especially when there are strict low latency and greater agility in response requirements.

3.2.4 Results

Extracting the perception and challenges of IoT from different points of view was essential for the strengthening and direction of our research. For instance, it is possible to observe that, although there are different perspectives, they become complementary to represent the challenges to produce quality software for this kind of system. Together, the three sources provided 14 different challenges, which must be met in favor of a higher quality IoT software system (Figure 8).

Figure 8. IoT Challenges.

We can see that each source has its particularities, and some are consistent with their origin. It is expected that practitioners have a more technical and in-depth view presenting more individual and software-oriented issues regarding IoT systems. The challenges with **management** and **quality** are transversal to the implementation of such software systems. They can be observed from any point of view. Still, the practitioners have specific quality challenges, such as meeting non-functional requirements, which bring more specificity and definition to this issue. Also, **requirements** and **testing** issues are still somewhat open on representing, describing, and integrating software systems. These three aspects must be met in the software systems regardless of their scale, which in IoT software systems can reach ultra-large-scale, bringing their associated problems. These three challenges are affected by one aspect that we observed in the SLR. From the characteristics extracted, we could observe that properties and characterization are not explicit, neither the characteristics that can affect the development process of such applications. Unclear characteristics can impair requirements, which in turn affects the testing, hindering the overall system quality. This difficulty is partially due to conceptual aspects since IoT, and the related concepts, are not yet established and not enclosed by a single definition. The concept is still under discussion (Shang, Zhang, Zhu, & Zhou, 2016).

Considering the increasing number of interconnected devices, the size or **scale** of IoT can grow consistently. As a result, the software systems can achieve a more extensive scale coupled with complicated structure-controlling techniques, bringing new challenges to their design and deployment (Huang, Duan, Xing, & Wang, 2017). Therefore, new solutions for architectural foundations, orchestration, and management are essential for dealing with scale issues, especially for Ultra Large-Scale Systems such as Smart Cities and autonomous vehicles (Roca, Milito, Nemirovsky, & Valero, 2018).

Concerning **regulation**, some actions are being made, by governments[6] and other institutions[7], to form an adequate legal framework. However, it is necessary to prompt effort to provide guidance and decisions regarding governance and how to operate IoT applications in a lawful, ethical, socially, and politically acceptable way, respecting the right to privacy and ensuring the protection of personal data (Caron, Bosua, Maynard, & Ahmad, 2016; Almeida, Doneda, & Moreira da Costa, 2018). An intensive advance for this challenge has been made since the European Parliament released the General Data Protection Regulation (GDPR) in 2016[8]. However, being compliant with the GDPR is a challenge for organizations (Blanco-Lainé, Sottet, & Dupuy-Chessa, 2019), especially in IoT solutions dealing with a large amount of data.

For the devices, sensors, actuators, tags, smart objects, and all the ***things*** in the Internet of Things, or Everything, these are some of the aspects that should be taken into consideration: a) resources and energy consumption, since intelligent devices should be designed to minimize required resources as well as costs (Delicato, Pires, & Batista, 2017); b) Deployment since they can be deployed one-time, or incrementally, or randomly depending on the requirements of applications; c) Heterogeneity and Communication: different things interacting with others, they must be available, able to

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[6] https://aioti.eu/ *and* https://ec.europa.eu/commission/priorities/digital-single-market_en

[7] https://www.kiot.or.kr/main/index.nx *and* https://www.digicatapult.org.uk/

[8] http://data.europa.eu/eli/reg/2016/679/corrigendum/2018-05-23/oj

communicate and accessible (Li, Xu, & Zhao, 2015; Madakam, Ramaswamy, & Tripathi, 2015).

At the intersection between Industry and Literature, we have **architectural** and **social** issues. Both challenges are open due to the area novelty in which there is still an uncovering of how to deal and what to expect. **Architecture** is a recurrent issue in the literature being point out by (Liao, Deschamps, Loures, & Ramos, 2017) as one of the priority areas for action and reported by (Trappey, Trappey, Hareesh Govindarajan, Chuang, & Sun, 2017) to be one of the official objectives of ISO/IEC JTC1. In general, the status is that there is still no consolidated standard nor well-established terminologies to uniform advancements for architecture in IoT**.**

Regarding **social** challenges, given that the objects, devices, and a myriad of *things* are likely to be connected to many others, being people one of the actors as well (Matalonga, Rodrigues, & Travassos, 2017), it is necessary to explore the potential sociotechnical impacts of these technologies (Whitmore, Agarwal, & Da Xu, 2015). Using such devices to provide information *about* and *for* people is one of the applications. Several challenges and concerns should be addressed to achieve the benefits aimed with IoT. In facilitating the development, data dissemination protocols are designed to evolve the solutions for privacy, security, trust maintenance, and effective economic models (Guo, Yu, Zhou, & Zhang, 2012). As affirmed by (Dutton 2014), if not designed, implemented, and governed appropriately, these new IoT could undermine such core values as equality and individual choice.

At the intersection between Industry and Government, we have the challenges of **professionals**, represented by the preparation of their skills and knowledge as for the teams that should be multidisciplinary to meet IoT premises. If requirements, testing, and other technical activities are under discussion, we need to consider the professional who satisfies and performs such activities (Yan, Jia, Hu, Guo, & Zhu, 2019). With the development of IoT, different people, systems, and parties can have diverse requirements. One of the abilities required is how to translate these requirements into new technologies and products. Other skills are related to managing the frequency of information generated, managing the ubiquity and actors involved in interactions, developing and maintaining privacy and security policies (Tian, Yu, Chu, & Li, 2018). As the area is new and defines the professionals and teams that should work on it too, it is essential to discuss the professional and develop skills and knowledge necessary for this new generation of innovators, decision-makers, and engineers (Kusmin, Saar, Laanpere, & Rodriguez-Triana, 2017; van Deursen *et al*., 2021).

Connectivity, Communication, **Network,** and the multiple related concepts that enable the evolution of interconnected objects are critical for IoT materialization (Gubbi, Buyya, Marusic, & Palaniswami, 2013). One of the main challenges of this scenario is a vast amount of information identified, sensed, and acted upon that must be processed primarily in real- or near-real time with a discreet delivery of personalized manner, ensuring availability and reliability of the data and the channel between devices and between the human and devices (Mihovska & Sarkar, 2018). Many open challenges require new approaches to a quality network in this scenario. Therefore, research should progress into practice to ensure the benefits for the users. Together with Network challenges, we have **Data** issues. In a world with "anytime, anyplace connectivity for anyone and connectivity for anything" (Conti, 2006), we can see how quickly the data can be generated and how vast amounts of information are created. Some of the challenges are related to the continuous and unstructured creation of connection points (devices, things), the persistence of data objects, unknown scale, and data quality such as Uncertainty, Redundancy, Ambiguity, Inconsistency, Incompleteness (Gil, Ferrández, Mora-Mora, & Peral, 2016; (de Aquino, de Farias, & Pirmez, 2019).

However, above these, **security** and **interoperability** challenges are at the center of all IoT-related discussions from the evidence we gathered in these studies. For IoT, for example, it enables computing capabilities in *things* around us, and interoperability is the attribute that allows the interaction among heterogeneous devices with varied requirements of different applications. According to the software system's needs, interoperability can range in various technical, syntactic, semantic, and organizational levels (Motta, de Oliveira, & Travassos, 2019). Complete interoperability is an open question for current software and essential for IoT due to its comprehensive nature. Issues like encryption, trust, privacy, and security-related challenges are of utmost importance since IoT is inserted into someone's personal life or industry. High coverage procedures should guarantee the software system's security and trustworthiness.

3.2.5 Threats to Validity

Like any empirical study, different threats to the validity of our results can be identified (Wohlin *et al.*, 2012). From both the data collected from **industry** and the

government, the interpretation of data was supported by the practices of GT, which allowed to get consistency among researchers and shared understanding of the central concepts. However, other perspectives could be used for data interpretation, imposing a risk of changing the results. Thus, it represents a threat to any qualitative study and constitutes a menace that we cannot completely mitigate. The threats for the SLR were presented in the previous section.

3.3 Internet of Things Facets

To support the multidisciplinary vision proposed in this work, we have analyzed the material extracted from the IoT SLR to arrive at the facets representing this multidisciplinarity. Finally, the union of challenges with the facets is presented at the end of the chapter, which defines the challenges to engineer IoT software systems.

Aiming to identify those different facets that characterize this multidisciplinarity, we analyzed the IoT definitions identified in the SLR. The analysis was based on coding procedures from GT (Strauss and Corbin, 1990) the same way as previously defined. The coding procedure leads us to propose the six facets (Figure 9).

The 28 extracted IoT definitions were organized in a table with one field of “code” to assign an area, topic, discipline (named here as a facet) related to a definition excerpt. This coding process was executed by three researchers separately, using separate and independent documents. An example of the document is presented in Figure 10. It comprises the index with the definition number. Each definition is presented as extracted from the paper, and the code is associated with portions of the definition, with a color scheme to help their identification.

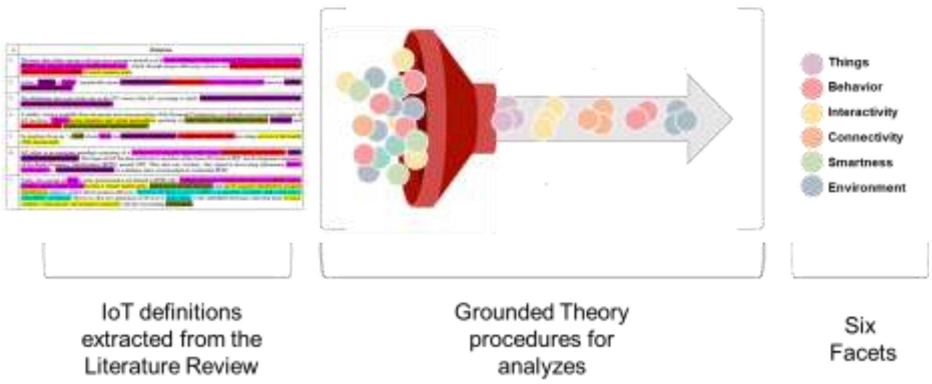


Figure 9. Qualitative Analysis Procedure performed.

Legenda: Caracteristica Hardware Nework Application Domain Software Data

#	Definition
1	The basic idea of this concept is the pervasive presence around us of a variety of things or objects – such as Radio-Frequency Identification (RFID) tags, sensors, actuators, mobile phones, etc. – which, through unique addressing schemes, are able to interact with each other and cooperate with their neighbors to reach common goals.
2	In fact, ''Internet of Things'' semantically means ''a world-wide network of interconnected objects uniquely addressable, based on standard communication protocols''.
3	The definitions above paved the way to the ITU vision of the IoT, according to which: ''from anytime, anyplace connectivity for anyone, we will now have connectivity for anything''.
4	A similar vision is available from documents and communications of the European Commission, in which the most recurrent definition of IoT involves ''Things having identities and virtual personalities operating in smart spaces using intelligent interfaces to connect and communicate within social, environmental, and user contexts''.
5	Its members focus on ''a world where things can automatically communicate to computers and each other providing services to the benefit of the human kind''.
6	IoT refers to an emerging paradigm consisting of a continuum of uniquely addressable things communicating one another to form a worldwide dynamic network. The origin of IoT has been attributed to members of the Auto-ID Center at MIT, the development community of the Radio-Frequency Identification (RFID), around 2000. Their idea was visionary: they aimed at discovering information about a tagged object by browsing an Internet address or a database entry corresponding to a particular RFID. To address the above idea, they worked on the development of the Electronic Product Code (EPC), i.e., a universal identifier that provides a unique identity for every physical object, with the aim of spreading the use of RFID in worldwide networks.
7	Today, the concept of thing is more general and is not limited to RFID only. A thing can be any real/physical object (e.g., RFID, sensor, actuator, spime,2 smart item) but also a virtual/digital entity, which moves in time and space and can be uniquely identified by assigned identification numbers, names and/or location addresses. Therefore, the thing is easily readable, recognizable, locatable, addressable and/or controllable via Internet. Moreover, this new generation of devices is smart things to the embedded electronics allowing them to sense, compute, communicate, and integrate seamlessly with the surrounding environment.
8	A few years later, members of the same MIT group used again this concept, defining IoT as: ''an intelligent infrastructure linking objects, information and people through the computer networks, and where the RFID technology found the basis for its realization''.
9	Specifically, they distinguish three categories: (i) Things oriented, where the focus is on the ''objects'' and on finding a paradigm able to identify and integrate them, (ii) Internet oriented, where the emphasis is on the networking paradigm and on exploiting the IP protocol to establish an efficient connection between devices, while simplifying IP so that it can be used on devices with very limited capacity, and (iii) Semantic oriented, which aims to use semantic technologies, describing objects and managing data, to represent, store, interconnect, and manage the huge amount of information provided by the increasing number of IoT objects. Authors conclude that IoT is the result of the convergence of these different visions.
10	IoT is seen as: ''a dynamic global network infrastructure with self capabilities based on standard and interoperable communication protocols where physical and virtual ''things'' have identities, physical attributes, virtual personalities and use intelligent interfaces, and are seamlessly integrated into the information network''.
11	*In addition, IoT enable people and things to be connected not only ''Anytime'' ''Anywhere'' with ''Anyone'' and ''Anything'', but also use any type of location or network and any available service. Hence, two additional concepts, i.e., ''Any path/network'' and ''Any service'', are introduced to complete the picture forming the so-called 6A vision.*
12	Combining then the various concepts, authors have summarized their own IoT vision as: ''the future Internet of Things links uniquely identifiable things to their virtual representations in the Internet containing or linking to additional information on their identity, status, location or any other business, social or privately relevant information at a financialor non-financial pay-off that exceeds the efforts of information provisioning and offers information access to non-predefined participants''

Figure 10. Example of document filled with the definitions and marked with coding.

There were three rounds of discussions, first with two than with all the three researchers. It was done to discuss the similarity and differences in the coding, support the concepts and reduce bias until reaching a consensus. From this analysis, we would like to have a set of facets, based on the data we had so far, and sort among the most used to present a set of areas that must be considered. After the documents merged, meetings for discussions were held. Some of the discussion was regarding the coding granularity level. For example, network and telecommunication can all be part of a single facet called connectivity, aiming to encompass several concepts and keep the same level of abstraction.

For the identified excerpts, we discussed and organized the understanding in the same level of abstraction for all of them to represent the different needs for realizing IoT software systems. As a result of this process, we came to the consensus (based on the definitions) that for IoT, we should consider six different facets: Things, Interactivity, Connectivity, Behavior, Smartness, and Environment (Figure 11).

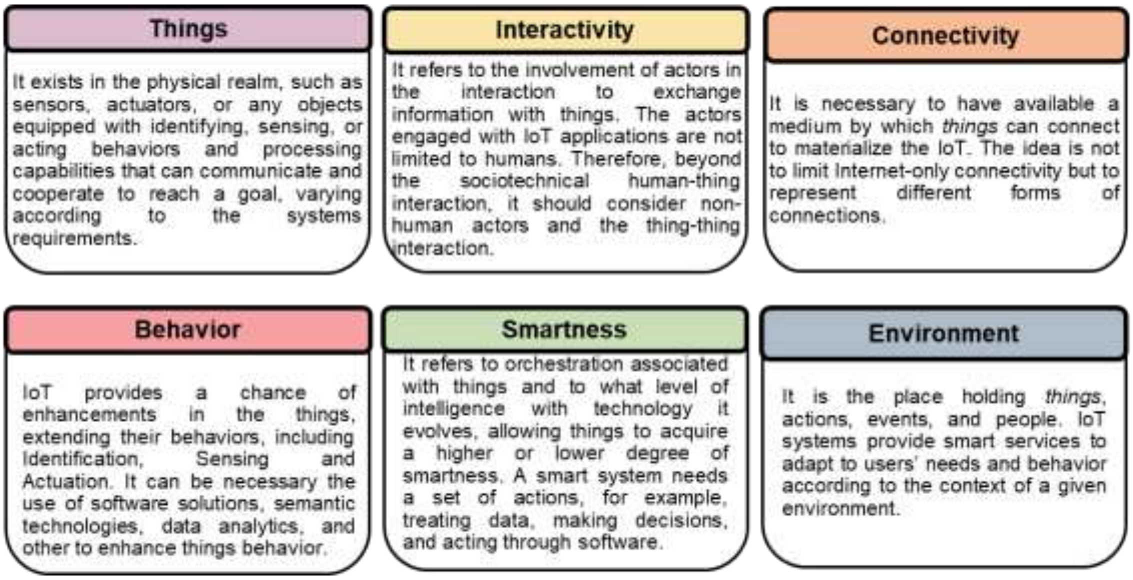


Figure 11. IoT Facets.

1. Things

In this sense, it means the *things* by themselves in IoT. Tags, sensors, actuators, mobile phones, **and all hardware can traditionally replace the computer, expanding connectivity**.

In our understanding, *things* exist in the physical realm, such as sensors, actuators, or any object equipped with identifying, sensing, or acting behaviors and processing capabilities that can communicate and cooperate to reach a goal, varying according to the systems requirements (Whitmore, Agarwal, & Da Xu, 2015). When an object has enhanced capabilities and uses connectivity to interact with others, it can be considered a *thing* in our context. Twenty-five definitions mentioned this facet.

2. Interactivity

It refers to the **involvement of actors in the interaction** to exchange information with *things* and the degree to which it happens. The actors engaged with IoT applications are not limited to humans. Therefore, beyond the sociotechnical challenges surrounding human-thing interaction, we also have concerns with other actors like animals and *thing-thing* interactions (Andrade, Carvalho, de Araújo, Oliveira, & Maia, 2017). The degree to which it happens works together with the medium through which *things* can connect (connectivity) to understand (interoperability) and be connected. Four definitions mentioned this facet.

3. Connectivity

Connectivity is one of the main aspects of IoT software systems. We argue that it is necessary to have a medium by which *things* can connect to materialize the IoT paradigm. It is essential some form of connection, a network for the development of solutions. Our idea is not to limit Internet-only connectivity, but to cover other media such as Intranet, Bluetooth, among others, means **how objects are connected**.

It is important to note that there is no one-fit-for-all solution (Luzuriaga *et al.*, 2015) since it englobes many domains, each of which can have particular characteristics and requirements. However, in the SLR, we can observe that specific requirements are more related to the devices' nature or the application needs, which influence communication directly - such as low latency, bandwidth, and robustness, security, protocols, and standards (Poluru & Naseera, 2017). Even though some of the requirements are not directly related to connectivity, they show aspects that profoundly influence communication. Thus, they are requirements that need to be well understood and addressed to make IoT work. Twenty-six definitions mentioned this facet.

4. Behavior

The existence of *things* is not new, nor their natural capacities. What IoT provides is the chance of **enhancements in *things*, extending their original behaviors**. In the beginning, the *things* in IoT software systems were objects attached to electronic tags, so these systems present identification behavior. Subsequently, sensors and actuators composing the software systems enabled the Sensing and Actuation behaviors, respectively. This facet comprises the realization of the behavior and dealing with the data results[9]. Therefore, it can be necessary to use software solutions, semantic technologies, data analytics, and other areas to enhance the behavior of *things*. In this sense, all data manipulation, analysis, and processing were encapsulated in the Behavior Facet, dealing with the implemented behavior and generated results.

The idea of the system behavior results from its constituent parts. The behavior is generated by the interaction and collaboration of two or more devices, and combining more straightforward behaviors can manage a more complex behavior. Thus, the

[9] At this moment, although we had found some excerpts related to data, in decided to include in one only facet the behavior and the results related from it, that is the data.

behavior of an IoT can be aggregative, emergent autonomous, collaborative, capable of performing different actions. Thirteen definitions mentioned this facet.

5. Smartness

Smartness or Intelligence is related to Behavior but as to managing or organizing it. So, it refers to **orchestration associated with things and what level of intelligence technology can evolve their initial behavior**.

Artificial intelligence and machine learning techniques can enhance intelligence and effective interactions between *things* to manage smartness. It is critical to highlight that only sensors collecting data do not make it smart to develop smart applications. For a system to be *smart*, it needs a set of actions, for example, treating data, making decisions, and acting. The level of smartness depends on the application domain and user need. Fourteen definitions mentioned this facet.

6. Environment

The problem and the solution are embedded in a domain, an environment, or a context. This facet seeks to represent such an environment and how the context information can influence its use. The environment is **the place where *things* are, actions happen, events occur, and people are**. Smart Environments or Smart Spaces provide intelligent services by acquiring knowledge about themselves and their inhabitants to adapt to users' needs and behavior (Aziz, Sheikh, & Felemban, 2016). These systems have a set of *things* capable of sense, reason, collaboration, and act upon the ambient. An essential characteristic of this ambient is the user-centric thinking approach in which all the systems must be developed to attend to the users in the first place. Four definitions mentioned this facet.

Problem domain

In addition to the facets with the vision of conceptualization and realization, we also note the importance of the Problem Domain as usually perceived in conventional software systems. A problem domain is the area of expertise or application that needs to be examined to solve a problem. IoT software systems are developed to reach a goal for a specific purpose. We are starting from a goal (problem domain) to get a solution (software system). Focusing on a problem domain is merely looking at only the topics of interest and excluding everything else. It, in general, directs the objective of that solution. We do not see this concept as a facet since it is presented in any software solution. However, it is important to consider it since it is possible to know if an IoT solution is necessary by analyzing the project needs. From that, the problem domain directs and contextualizes how the other facets should be derived, implemented, and managed. Five definitions mentioned this facet.

From the IoT definition proposed from the findings of the SLR (Section 3.1), we did the exercise to fit it in the facets proposed to exemplify the following demands to develop an IoT software system:

- **A paradigm that allows composing systems:** IoT is not just the *things* by themselves. It represents a more substantial aggregate consisting of several parts, implying no single IoT solution but a myriad of options derived from the *things* and other available systems. In addition, it requires some domain and business-specific strategies.
- **From uniquely addressable objects (*things*):** A unique identification for every physical object should be distinguished using unique IDs. It concerns the network solutions and hardware technologies required to devise the composing parts of the IoT paradigm, representing the *Things* facet.
- **Equipped with identifying, sensing, or acting behaviors and processing capabilities:** Once the object is identified, it can enhance its original behaviors with personalities and other information and connect, monitor, manage and control things. This understanding implies that the "behavior" and "smartness" degree is required for a setting. Therefore, a software solution can be more robust and involve other technical arrangements, such as artificial intelligence.
- **That can communicate and cooperate:** The other part of the paradigm, alongside the *things*, is the connection channel of the available *things*. Together with this network solution, *things* should be able to communicate, but not only that. Also, cooperate, interchange, interact, and share with other actors and humans, therefore the connectivity and interactivity facets.
- **To reach a goal:** This whole scenario is set for a purpose, for a reason, motivated by something. This primary goal guides the development to address the problem inserted in the problem domain.

IoT is a paradigm that allows composing software systems from uniquely addressable objects (*things*) equipped with identification, sensing, or action behaviors and processing capabilities to communicate and cooperate to reach a goal. This understanding encompasses the definitions recovered from the SLR and states the composing and characteristics of IoT.

This element of the IoT Facets is central for our research, and both the IoT Framework and IoT Roadmap are built around it. The facets were extracted from the SLR and cover a set of dimensions that needed to be present, in different degrees, in an IoT software system. This initial set of six facets can be extended if needed since it is limited to the sources dealt with in the studies performed so far. However, we argue that IoT cannot be solved without considering these fundamental paradigm aspects, requiring multidisciplinary technologies and a diverse team to meet them.

3.3.1 Structured Interviews

After defining the multidisciplinary vision with the IoT Facets, we wanted to confirm this proposition and strengthen it with an industry perspective. Therefore, we conducted a study to understand the pertinence of the facets according to software practitioners' perception of IoT software systems engineering (Motta, de Oliveira, & Travassos, 2021).

The pertinence was observed through the applicability, influence, and usage of each facet. For this, we interviewed professionals working on the conceptualization and realization of IoT software systems projects to observe their perceptions.

Material. The study package is available online[10] and includes an invitation explaining its objectives, a consent form to be signed by the participants, and a questionnaire. The questionnaire was divided between a characterization section and an evaluation section with three main questions. The questions were:

- Q1: Are the facets pertinent to IoT software systems engineering at the project's early stages?
    - Q1.1: Are the facets applicable to IoT software systems engineering at the project's early stages?
    - Q1.2: Do the facets influence decision-making in IoT software systems engineering at the project's early stages?
    - Q1.3: Are the facets used in IoT software systems engineering at the project's early stages?

[10] http://bit.ly/3sHDwq9

- Q2: How are the facets considered in the early stages of IoT software systems projects?
- Q3: Is there any additional facet pertinent to IoT software systems engineering at the project's early stages that is not present in this set?

The facets were evaluated individually. According to the dictionary, pertinent is to have clear decisive relevance to the matter at hand (Merriam-Webster) and can be observed through applicability, influence, and usage – as we used in this study. This part of the questionnaire contained the facet definition and a Visual Analogue Scale (continue line with labels in each extreme from "Not Applicable" to "Totally Applicable") to capture the perception expressed in subjective values for the applicability, influence, and usage of such Facet. The Q2 and Q3 were performed as open questions in a structured interview style. It could enable a more accessible discussion and capture information such as the impact of the facets in the development and which facet is harder to achieve or measure.

Pilot interview. Two collaborators with relevant experience in IoT and software development participated in the pilot. The purpose was to verify the materials and procedures before their application. In addition, the feedback from the pilot's participants was used to refine the process before the execution.

Structured Interview. Two researchers performed this series of interviews at the end of 2019. Six participants selected by convenience (using professional contacts) participated in the study from three different enterprises in France. All the participants received the material of the study package. The interviews (lasting one hour, on average) took place between the researchers and participants on different days regarding their schedules. One interview was conducted remotely, and the others were taken in place in the participants' settings.

Institutions Characterization. The first is an R&D project from a university, focused on Human-Machines Cooperation for Flexible Production Systems. The case discussed in the interview is related to remote control of transport systems. The second is a medium-size company focused on inventing ethical, free, and open-source software solutions. The case discussed in the interview is related to voice-activated home-assistant. The third company is a large-size multinational focused on digital payments. The case discussed in the interview is related to contactless payment.

Results. The characterization section presented the participants' experience with IoT; as shown in Figure 12-A, the most presented role was a software engineer with three responses, but we also had researchers from R&D divisions (with two participants) and managers (with one participant). It is interesting to have different roles in capturing more insights on the topic (Figure 12-A).

In Figure 12-B, we can briefly view the organization, with most participants reporting 15 projects. Figure 12-C shows the participant's experience in developing IoT projects. The most experienced participant had 15 years of experience, and the least had four years of experience.

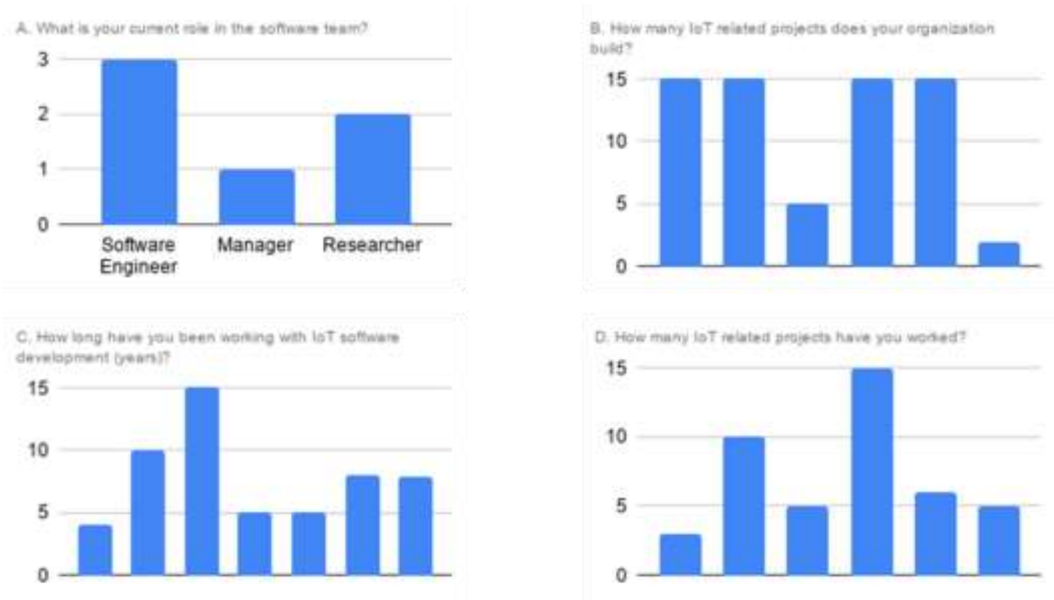


Figure 12. Characterization results.

The pertinence was observed through Applicability, Influence, and Usage (Figure 13). In general, the participants' perception is that all facets are pertinent for IoT projects. From the results, Connectivity, Smartness, and Behavior Facets are the most applicable. Furthermore, Things and Connectivity are the facets the influence the most. Also, Things, Connectivity, and Behavior are the most used facets, according to the participants.

Figure 13. Pertinence results.

Q2 and Q3 were open questions to foster the discussions. With Q2, we observed the technologies (methods, techniques, artifacts) used in practice. From their experience, we retrieved valuable information such as how to decide whether to build or adapt a new device, how the technical limitations (such as a battery) are considered during the development and strategies to deal with the growing project complexity. With Q3, we hoped to observe the completeness of the proposal that relies on the facets. One of the participants reported that "all these concepts are relevant. I do not see anyone working with IoT saying anything different from that". However, a crucial discussion was presented related to Data. "The use, processing, what to do with what was received, how to present it to the user" were some of the issues presented by a participant during the interview.

Our initial idea was that the data would be treated along with the system's behavior. For example, a software system with environmental sensing should capture the relevant data and handle it as valuable. However, we separated behavior and data concepts from the interviews' results, thus creating the Data Facet.

By reviewing our first coding, with an example presented in Figure 10, we realized that Data was also identified, and we had grouped with Behavior. With the study results, we decided on an update to include the Data Facet, separated from Behavior. **Data** is defined as the activities and technologies necessary to treat the data captured from the environment and other devices, such as data analysis and processing, to give meaning and achieve the system's goal. As **Behavior** was redefined as the mechanism of enhancements in the things, extending their original behaviors involving functions that enable Identification, Sensing, and Actuation behaviors, for example.

Together with Problem Domain, the final set has seven facets (Figure 14) representing the multifaceted concerns for IoT software systems development, observed from experimental studies. This section presented the IoT professionals' perception of the pertinence of IoT Facets and inputs for IoT realization. The results strengthen our proposal for a multifaceted view of IoT software systems and the adequate artifacts to deal with it.

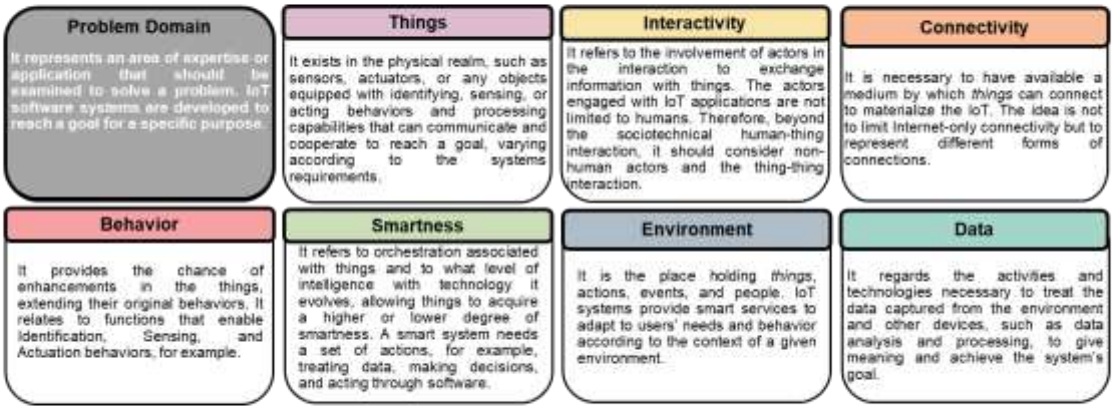


Figure 14. Problem Domain and the Seven IoT Facets.

3.3.2 Threats to Validity

This section presents the threats to the validity identified as proposed by (Wohlin *et al.*, 2012).

The threat to **external validity**: The interview participants had different backgrounds and diverse experiences in industrial applications. Although there is a threat to the generalizability of the results, we consider that this study was a shred of complementary evidence for defining the previously facets defined based on evidence collected from studies analyzed in the systematic literature review.

On the **conclusion validity**: The small sample size is a threatening factor in this study, limiting the generalization and conclusion of the results obtained. As a strategy to mitigate this threat, the participants were from three institutions with different backgrounds reducing bias against sample homogeneity. We recall that we aimed to confirm the pertinence of facets identified, not to validate them once they were already defined based on evidence from the SLR.

Regarding **internal validity**: in this study, a threat refers to the interpretation of the results. To mitigate this threat, we applied a pilot study to observe the materials' application, and there was no comparison on the VAS scale responses – we considered the raw results.

3.4 The IoT Conceptual Framework

Towards the definition of the IoT Roadmap, we looked for a structure that could represent as comprehensive as possible the IoT multidisciplinarity, organize the concepts and information retrieved in our research, and address the temporal perspective proposed with the System Engineering. Furthermore, having such a structure, we can organize the concepts more explicitly and support the conceptualization and realization of IoT software systems throughout the phases. Hence, we named this structure IoT Conceptual Framework.

The discussions in the previous sections have aimed to understand the problem domain, deliberate the work involved in the product being specified, designed, built, deployed, and, afterward, evolved. This initial step clarifies the problem and directs the overall scope by establishing a basic definition of the needs, the people who seek to solve the problem, the type of solution desired, the collaboration with other stakeholders, and the team that oversees the solution (Pfleeger & Atlee, 1998).

For IoT, the problem domain is inherently multidisciplinary (Motta, de Oliveira, and Travassos, 2018). Therefore, it is necessary a way of characterizing and defining it across the different facets. This understanding is necessary since incomplete knowledge and communication flaws constitute the most frequently stated problems in the project conception phase (Fernandez, 2018). Furthermore, the IoT scenario is covered by challenges and requirements seen and treated according to the facets involved. Therefore, the initial alignment should be conducted prospectively to minimize the uncertainty and overcome such challenges in the conception phase.

The IoT Conceptual Framework organization has three core elements: the Systems Engineering Life Cycle (Section 2.1), the Zachman Framework (Section 2.2), and the IoT Facets (Section 3.3). The organization aims to overview IoT requirements and activities considering the knowledge areas and disciplines related to different engineering phases. In this sense, the IoT Conceptual Framework is a structure that can give an overview of the IoT project, seeking to reduce uncertainties and risks by promoting shared knowledge leading to directions based on the context and fitted for the project in question. The results from the framework proposal are available in (Motta R. C, 2019).

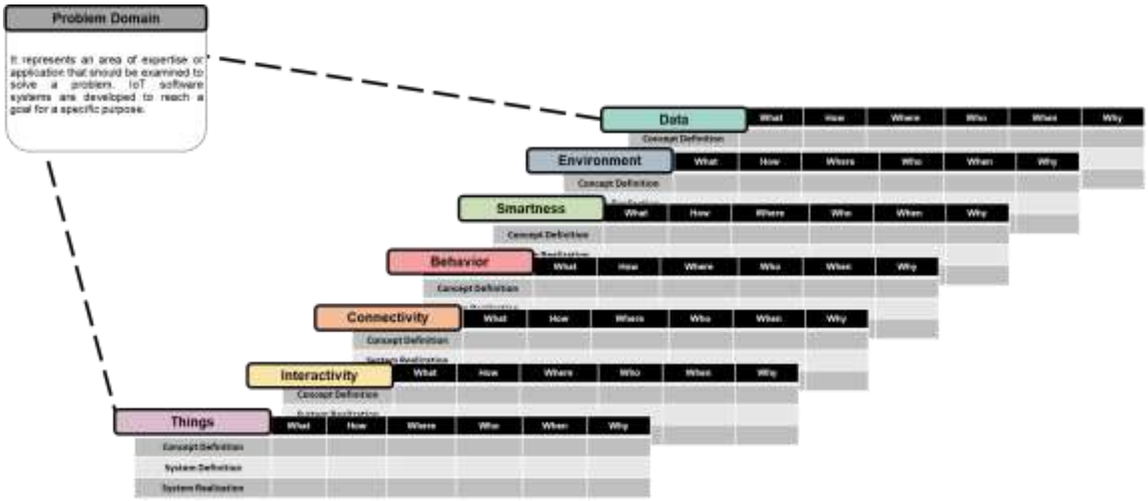


Figure 15. The IoT Conceptual Framework.

As previously described, the Zachman Framework inspired the framework's organization to encompass the facets proposed. This multi-faceted view shows that each facet must be treated according to its particularities and perspectives in IoT. According to the holistic view of systems engineering, the desired solution is more significant than the sum of its parts. To go from the problem to a software solution is the primary challenge in developing IoT software systems.

The original perspectives, with roles, have been replaced by the system engineering **Phases** presented in Chapter 2. Our idea behind this adaption of the Zachman Framework is that the original perspectives in the framework represent the leading roles acting in each system engineering phase. Consequently, the perspectives of Business, Executive, Architect, Engineer, and User who support the definition of the problem domain, were replaced by the **definition** phase (composed of Concept and System definition). Architect, Engineer, Technician, and User perspectives specialize in solving the problem, representing, therefore, the **realization** phase. We consider the User perspective a hybrid because the future vision is that the user actively participates in IoT and smart systems construction (Singh & Kapoor, 2017; Demeure, Caffiau, Dupuy-Chessa, Ta, & du Bousquet, 2019). The Concept and System Definition perspectives lead to understanding, limiting, defining the problem. The Realization perspective leads to the materialization of the solution to the problem. Each of the perspectives has different responsibilities as the project evolves according to the System Engineering phases of Concept Definition, System Definition, and System Realization:

Definition. In IoT projects, the **Concept Definition** refers to defining the problem domain and highlighting the need for an IoT solution. This phase can involve, for example, the identification of the context of use and how this context can affect the solution, identify the resources and restrictions of the project, and if the construction of IoT software system is feasible for what is defined (having a trade-off between physical and virtual capacities, for example). As for the **System Definition** phase, the requirements are sufficiently well defined to define an IoT solution. For the definition, it is important to identify the IoT components (sensors, smartphones, or wearables, for example) and expected system behaviors (sending or actuation, for example) with the expected rules and triggers, considering the interaction among all the actors (things and humans, for example).

Realization. System Realization begins with the commitment to deliver operational capability and activities, including constructing the developmental elements and their integration with each other. Several realizations activities occur to achieve an operational solution, such as physically connecting the components and adjusting the desired behavior parameters according to the use scenarios and environment. For this phase, different skills can be necessary for data and user interaction expertise, for example. This phase also should ensure the IoT solution availability, security, and other quality aspects over its lifetime.

From the guidelines provided in Zachman's framework, we reviewed the communication interrogatives for the IoT context since the answer to each question in each perspective and each facet give us more direct information leading the engineering closer to the solution. These fundamental questions were defined to outline our intention:

- ***What* –** to define which information is required for the understanding and management of the Facet. It begins at a high level, and as it advances in the perspectives, the data description becomes more detailed.
- ***How* –** to describe how abstract goals are translated in solutions using software technologies (techniques, technologies, methods), defining their operationalization and materialization.
- ***Where* –** to locate the activities related to the geographical distribution, even something external to the software system.

- ***Who –*** to identify roles involved in the development of the Facet, including non-human actors.
- ***When –*** to indicate effects of time over the Facet, describing its transformations and sequences of actions.
- ***Why –*** to establish the motivation, goals, and strategies to implement in the Facet.

Each identified Facet is defined and realized, reconsidering the Phases and Communication Interrogatives (5W1H – *what, how, where, who, when,* and *why*) following this structure. This definition is paramount for IoT software systems since some Facets should be part of the same solution, one related to the other aiming at the solution completion. Therefore, during the Facets conception, the integrity of the others could be impacted, and in turn, the overall solution. The IoT Conceptual Framework can help the understanding of this relationship. Therefore, supporting these Facets for IoT engineering is the direction we followed in advancing our research.

3.5 Chapter Considerations

In the activities and studies, we have characterized IoT from the technical literature, extracted IoT Challenges from various sources, and defined the required knowledge areas (**IoT Facets)**. With these activities, we recovered the evidence from SLR and other sources, achieving what was proposed in the Conceptual Phase proposed of the Research Methodology.

In our perspective, the challenges should be addressed in each Facet according to their specificities. Data and Things are presented in challenges but captured as facets from the remainder of the research; therefore, it received an in-depth investigation. A solution for the challenges can be materialized in different ways in the defined Facets. Table 5 presents the high-level challenges collected throughout this work (Figure 8) and shows, in general, how each Facet supports the proposed concerns (Motta R. C., 2019).

Table 5. Challenges in engineering IoT, by Facets.

Challenge	Facet						
	Things	**Interactivity**	**Connectivity**	**Behavior**	**Smartness**	**Environment**	**Data**
Architecture	Software-Designer Network is an emerging network architecture where network control can be decoupled from the traditional hardware. This change and research in network architecture are crucial to connectivity (Bera, Misra, & Vasilakos, 2017).	With the increase in complexity and the number of devices in new architectural styles are necessary to deal with their needs for scalability, fault isolation, and flexibility, for example (Herrera-Quintero, Vega-Alfonso, Banse, & Carrillo Zambrano, 2018).	The architecture should encompass the system's need to visualize/represent behaviors and interactions when dealing with behavior. System dynamics, agent-based modeling, and Monterey Phoenix are commonly used behavioral models to describe the architecture (Giammarco, Giles, & Whitcomb, 2017).	In many cases, what makes a system smart is the devices used and the decision-making process, and the whole solution architecture (Atabekov, Starosielsky, Lo, & He, 2015).	Many discussions are related to architecture for interactivity, especially focusing on decentralized solutions, supporting and monitoring assisted livings in heterogeneous contexts, and integrating existing platforms (Giaffreda, Capra, & Antonelli, 2016).	Activities like system architecture definition are important in Smart Environments and relate to designing and implementing it, providing the reactivity, scalability, extensibility necessary for the environment (Cicirelli, Fortino, Guerrieri, Spezzano, & Vinci, 2016). .	The IoT architecture should communicate internally with millions and perhaps billions of non-homogeneous objects via the internet. Therefore, flexible layers are required in this architecture (Shadroo & Rahmani, 2018).
Interoperability	Conventional IoT deployments based on the simplistic the approach of directly connecting "things" to the Cloud creates "silos," limiting the interoperability between applications. This approach complicates their orchestration and management, increases deployment costs, and does not support the scalability required (Roca, Nemirovsky,	Finally, an intelligent building should respond to all three key components of systems, performances, and services and has to have adaptable and interoperable building control systems (Ghaffarianhoseini *et al.*, 2016)	Then, what matters in HEB is the interoperability between "things," achieved through standardized APIs and interfaces. Once "things" can communicate with each other and their environment, new behaviors emerge by applying the local rules (Roca, Nemirovsky, Nemirovsky, Milito, & Valero, 2016).	D. Roca *et al.* [26] argue that this emergent behavior will improve scalability, interoperability, and cost-efficiency of ultra large scale IoT systems instead of traditional approaches that heavily rely on extensive programming of explicit behaviors (Bosmans, Hellinckx, & Denil, 2018).	Most frameworks and semantic platforms use the existing ontologies, such as SSN and GOname, to solve interoperability problems between sensors and operators. This paper used the neural network algorithm in machine learning to obtain better results and hidden values. In this framework, IoT data are converted into semantic data. The semantic web describes IoT areas using standard protocols and	The use of heterogeneous devices brings interoperability issues which are a very challenging task to deal with. In addition, the heterogeneous environment augments the problem of ambiguity in the identification of data retrieved from different sensors with the same meaning (Babar & Arif, 2017).	Due to this situation, several groups such as ITU, ETSI, OpenIoT, among others, are developing interoperability standards and protocols for the IoT. However, in a multi-standard context, where features, functions, and devices are combined, vertical IoT systems' high fragmentation and development have increased (Palacios & Cordova, 2018).

	Nemirovsky, Milito, & Valero, 2016).				vocabulary. (Shadroo & Rahmani, 2018).		
Management	One of the connectivity concerns is traffic management and control to deal with the enormous data generated by these devices and guarantee the quality of service (Bera, Misra, & Vasilakos, 2017).	This scenario involves distributed systems consisting of hundreds to thousands of devices, involving the coordination of their activities, requiring a high-level ability of reasoning and management (Patel & Cassou, 2015).	In the literature, we have behavior patterns (Haynes *et al*., 2017), separation of concerns, state machines (de Lemos *et al*., 2013), and other solutions to manage behaviors. However, many authors argue that it is still an open issue.	Management issues and smartness are intimately connected. One example is the need to provide power consumption management with analysis and establish rules for optimization (Oliveira *et al*., 2017).	A goal is to allow systems to manage themselves so that human intervention can be minimized. For this, it is necessary to automate management functions according to the behavior of the components defined by a management interface (Dai, Dubinin, Christensen, Vyatkin, & Guan, 2017).	It is necessary to manage functionalities personalization and interpret complex user needs in smart environments (Pons, Catala, & Jaen, 2015; Desolda, Ardito, & Matera, 2017).	These examples of IoT applications reveal the advantage of analyzing smart home data. However, while such data presents valuable opportunities in understanding (…), it also spells out a tremendous challenge regarding data management, storage, and analytics. To ensure that users are not drowning in floods of data, they need systems capable of managing, analyzing, and transforming this amount of data into actionable insights (Yassine, Singh, Hossain, & Muhammad, 2019).
Network	Applications in the IoT domain require extensive connectivity, security, trustworthiness, the ultra-reliable connection, among other requirements for a large number of devices and, though used in IoT scenarios, 2G, 3G, and 4G technologies are not fully optimized for IoT applications (Li *et al*., 2018).	Although connectivity is the core of this new technology, the traditional network infrastructure is not prepared to support IoT requirements. Traditional devices, such as switches and routers, are usually preprogrammed to do particular tasks and follow particular rules. Therefore, it does not meet the IoT application-specific requirements since it	Some behavior emerges that cannot be attributed to a single system but results from the interplay of CPS in the network. Therefore, each system involved must adjust its behavior according to the common goal of the network (Brings, 2017).	The solution encompasses shock sensors, GPS, NFC reader, and cellular IoT. Those combined spontaneously notify the rescue team whenever an accident takes place. As for the higher layers in the IoT protocol stack, the emerged protocols, the Constrained Application Protocol over User Datagram Protocol, and	Current vehicular networks mostly utilize IPv6, which 1) does not support mobility natively and 2) is host-centric, not data-centric. Therefore, we need a datacentric and network-independent approach to IoT mobility (Datta, Häerri, Bonnet, & Costa, 2017).	Wireless Sensors Network, Vehicular Ad-hoc Network, and new network topology and strategies can contribute to achieving a sustainable smart city (Faria, Brito, Baras, & Silva, 2017).	We observe a very delayed data processing: the vertical dashed line on the graph represents the ending of stream ingestion. Most nodes could not perform real-time analysis, and in the worst case, i.e., node 2, the task is completed with a delay of more than 300s. Essentially, data is queued in a

		can be necessary that the devices adapt themselves to multiple different rules (Bera, Misra, & Vasilakos, 2017).		Datagram Transport Layer Security can overcome the limitations of the IoT devices' constraints (Nasr, Kfoury, & Khoury, 2016).			long buffer on the network operators, not consuming in time. It is not acceptable in a system where real-time analysis is essential (Greco, Ritrovato, & Xhafa, 2019).
Professional	Many nodes in IoT undergo constant movement that may result in intermittent interconnectivity between the devices, which may encounter frequent topology changes. Due to these frequent topological changes and limited resources available in the IoT devices, now a day's data routing has become a significant challenge requiring the proper skills and technologies to be overcome (Dhumane, Prasad, & Prasad, 2016).	IoT application development is a multi-disciplined process where knowledge from multiple concerns intersects. Traditional IoT application development assumes that the individuals involved in the application development have similar skills. Thus, it is in apparent conflict with the varied skills required during the overall process involving this engineering (Patel & Cassou, 2015).	Managing an IoT project requires different profiles, each with a different skill (Gabor, Belzner, Kiermeier, Beck, & Neitz, 2016).	Technological solutions can be better achieved in smart cities by making different stakeholders work together (Neuhofer, Buhalis, & Ladkin, 2015).	It is a considerable challenge for the developers to engineer consumer applications as a multidisciplinary ecosystem with no widely followed guidelines (Patel & Cassou, 2015).	To exploit the abundance of the related resources, users could compose the different "behaviors" exposed by the surrounding environment, becoming an active part of the systems, and adding a new perspective in development (Desolda, Ardito, & Matera, 2017).	IoT environment has a high variety of fields generating data, and this flow of information congestion often occurs. Therefore, the development of techniques and tools to assist in extracting useful insights from this constantly growing volume of data is required (Poletti, e Martins, Almeida, Holanda, & de Sousa Júnior, 2019)
Quality	Demanding the diversity of devices and applications, with the most varied quality of service requirements, an IoT access layer must be heterogeneous, with general and niche access technologies making up a vast ecosystem. Report 2B (BNDES, 2017).	It is important to investigate whether multi-touch input on mobile devices and 3D- based user interfaces are appropriate for controlling smart environments. This is because it provides us with the first understanding of interaction quality	For the central unit and measurement node, elements with the communication interfaces are provided to satisfy the communication features specified in the architecture. Integrity is maintained by establishing a dedicated	When a sensor can, for example, only provide a certain quality of data or only measure certain inputs, that can result in a severe constraint on the behavior of the cyber-physical system as it can no longer discern all different states of the physical world and is thus forced to treat	It provides a software-based solution for the user, but it still requires them to be within range of compatible hardware. In addition, regardless of error mitigation methods, it can be challenging to give directions within a building in a way that is both accurate and user-friendly	Transparency is the ability to hide the system, so users may not be aware of it. This ability will happen if the system knows the user very well and both their expectations and environment. Also, the ubiquitous system should hide its computing infrastructure in the	In means to assist the extraction of useful information through datasets created from devices in a real IoT environment as well as verifying the quality and utility of this data and, if possible, estimating the accuracy of previsions of new data (Poletti, e

		(Nazari Shirehjini & Semsar, 2017).	communication channel for the metering elements, thus avoiding information loss (Oliveira *et al.*, 2017).	situations similarly when they yield the same sensor data (Gabor, Belzner, Kiermeier, Beck, & Neitz, 2016).	(Sheppard, Felker, & Schmalzel, 2019).	environment, so the user does not realize that it is interacting with a set of devices (Carvalho, Andrade, & de Oliveira, 2018)	Martins, Almeida, Holanda, & de Sousa Júnior, 2019).
Regulation	RFID operates on several frequency bands. However, the Radio Regulatory body controls the exact frequency in each country (Rezvan & Barekatain, 2014).	Such developments introduce ethical concerns for those whose information is being collected. Finally, some cultures or religions may have a highly restrictive view of all forms of touch, and thus it may be unethical to touch a stranger. Therefore, when designing an effective haptics system, all these concerns should be considered (Eid & Al Osman, 2015).	It may be necessary to revisit M2M communications, an essential concept for the functioning of the IoT specifications. This finding is supported by a series of contributions received on the Internet of Things Public Consultation, which pointed out the need to revisit the concept of machine-to-machine ("M2M") or machine-to-machine communication present in Decree No. 8.234, of 2nd. May 2014.2. Report 8B (BNDES, 2017).	There are numerous possible IoT solutions in mobility, such as cameras and sensors to collect information that allows real-time traffic modulation. However, the assessment of the regulatory environment for mobility will be restricted to two aspects, consisting of (a) centralized and adaptable traffic control; and (b) monitoring of public transport circulation—report 8B (BNDES, 2017).	The "intelligence" of a city cannot be driven solely by central controls coming from government computers, which will try to predict and guide citizens' decisions. Indeed, truly smart cities will consider the contributions of their citizens, who will be able to find new ways to interconnect and make sense of the collected data and information—report 8B (BNDES, 2017).	Standardization and important as well. Ther quite a few studies that deal with the older population. Although a standard approach for developing UIs for the elderly is still lacking, some may argue that a more important problem is acceptance and use of provided standards and not so much their availability. Trust and acceptability is the final ongoing challenge we identify for Ambient Assistance (Grguric, Gil, Huljenic, Car, & Podobnik, 2016).	The approval of specific laws and the creation of the Personal Data Protection Authority can mitigate this problem. Furthermore, it can prevent abuses in collecting and processing personal data from Internet users and the Internet of Things systems. Currently, the legal outlines of protecting personal data in Brazil are provided primarily by the Marco Civil da Internet and by Decree nº 8.771/2016. Report 8B (BNDES, 2017).
Requirements	A set of requirements could be captured that is intrinsically connected to the devices' nature. However, they directly influence connectivity such as efficiency - issues like low power capacity, low memory capacity, low processing (Murakami, Kominami, Leibnitz, & Murata, 2018), and extended coverage -	Regarding things, to deal with heterogeneity and scale (Rojas, Rauch, Vidoni, & Matt, 2017), distribution - geographically distributed and sometimes, in inaccessible and critical regions (Chen *et al.* 2018) as well as mobility – IoT devices are not static; they tend to move between different	An emerging behavior arises from a lack of understanding of the system. For this reason, the initial phases of the project are very relevant, and in IoT, one of the primary emphases is attributed to the initial phase of requirements engineering (Rainey, Mittal, & Rainey, 2015).	Different devices can capture data from the environment. Thus the systems in the future can make decisions and act. It should be planned, and it composes one of the parts of smartness in the systems (Medina, Espinilla, García-Fernández, & Martínez, 2018).	Different IoT devices introduce a wide range of heterogeneity issues. Therefore, standardization is a must but is not enough as no single standard can cover everything. Moreover, some organizations (manufacturers, software companies) would like to follow different standards or	The increasing use of software in embedded devices allows smart spaces development. However, standard software engineering technologies need some modification and defining a systematic process focusing on smart space development (Aziz, Sheikh, & Felemban, 2016).	The main requirement of the proposed system that we wished to test scalability because the amount of data received from sensors could increase depending on the number of sensors connected to a smart farm and the total number of active farms. We considered different

	to attend a large number of devices distributed, an extended coverage area is needed no matter the technology chosen (Chen *et al.* 2018).	coverage areas (Bera, Misra, & Vasilakos, 2017), are issues related to requirements to be covered in IoT.			even proprietary protocols (Dalli & Bri, 2016).		sensors in this use case of smart farming, such as temperature, humidity, and precipitation. (Dincu, Apostol, Leordeanu, Mocanu, & Huru, 2016).
Scale	Standard bridges, unfortunately, still do not scale with the number of standards, and especially the number of IoT devices. Therefore, middleware solutions will play an important role in wrapping the functionalities of the underlying heterogeneous technological layers into well-defined and well-organized services that can be used for communication among IoT devices or used by upper layers (Dalli & Bri, 2016).	However, only a few existing gesture-based control systems have reached end-users because of no scalable and practical solutions that fit into everyday life yet (Alanwar, Alzantot, Ho, Martin, & Srivastava, 2017).	Ad-hoc Network and ZigBee technology need to be connected, and for nodes to be installed, the cost is relatively higher. It is unsuitable for national-scale applications, being more appropriate for a manufacturing plant. Because of their limited coverage, PANs and WLAN are typically for personal use. They are usually affected or interfered with by metal objects' Wireless Sensor Network is a communication standard using radio frequency to communicate between computers and other devices (Dalli & Bri, 2016).	As a result of the increasing scale and diversity and new IoT architectures such as edge computing, the concept of emergent behavior in IoT systems is gaining more attention within the IoT community (Bosmans, Hellinckx, & Denil, 2018).	The various cyber-physical system networks need to be identified and documented before the cyber-physical system's behavior can be verified against the various cyber-physical system networks. As the various cyber-physical system networks can and often will be too large to handle manually, there is a strong need for an automated approach (Brings, 2017).	Users are typically confronted with the full scale of the environments' complexity and can become distracted from their real tasks. It becomes even more difficult in an unknown environment. Target devices must be identified and selected based on 2D-icons, complex menus, or device numbers in most existing user interfaces. It is truly a big challenge to find and activate needed devices, especially in foreign and complex environments (Nazari Shirehjini & Semsar, Human interaction with IoT-based smart environments, 2017).	The classical distributed processing systems (such as Hadoop) use a distributed file system that stores the input, output data, and intermediary results. This type of storing provides scalability for the system, making the processing more difficult in real-time systems and slower. The API interaction with the file system induces large latency (Dincu, Apostol, Leordeanu, Mocanu, & Huru, 2016).
Security	Some protocols guarantee essential data confidentiality and integrity, securing communication channels using cryptography, but	The paper (Dalli & Bri, 2016) highlights some security challenges about things: 1) IoT devices spend most of their time unattended, thus can be easily	There are issues that the IoT community needs to address in order to prevent privacy violation, which includes self-aware behavior of	There are two different opportunities to access a smart home to control functions: network attacks and device attacks. An adversary may	Although there are many challenges in the design and implementation of an effective ambient assisted living (AAL) system, such as information	IoT devices autonomously and continually collect Information about the environment without human awareness (ex., smart home applications	This near-field communications security issue is essentially a form of denial-of-service attack. Rather than just listening to the communications, the

	there are still critical challenges related to network control (Beltrán, 2018).	physically attacked; 2) Wireless communication between Things are vulnerable to eavesdropping; 3) Complex and resource-demanding security mechanisms are not suitable to be implemented on resource-constrained IoT devices.	interconnected devices, data integrity, authentication, heterogeneity tolerance, efficient encryption techniques, secure cloud computing, data ownership, and governance, as well as policy implementation and management (Mendez Mena, Papapanagiotou, & Yang, 2018).	intercept, manipulate, fabricate, or interrupt the transmitted data in network attacks. Device attacks can be classified into software attacks, physical or invasive attacks, and side-channel attacks (Ali & Awad, 2018).	architecture, interaction design, human-computer interaction, ergonomics, usability, and accessibility, there are also social and ethical problems like the acceptance by the older adults and the privacy and confidentiality that should be a requirement of all AAL devices (Marques, Roque Ferreira, & Pitarma, 2018).	recording inhabitants' living habits) that represent a security issue (Dalli & Bri, 2016).	attacker may try to disturb the communications by sending data that may be valid or even blocking the channel so that the legitimate data is corrupted (Rezvan & Barekatain, 2014).
Social	The term "social IoT" refers to objects part of the social community and acting in that environment. Therefore, social services of IoT systems must be reasonably designed to provide the user's requirements and requests and perceive the surrounding environmental context and customized social services to allow for a user's satisfaction (Davoudpour, Sadeghian, & Rahnama, 2015).	We were also interested in exploring whether social context had any effect on gesture preference. To accomplish this, participants were asked to rate their comfort level regarding performing their gestures in different environments and social contexts (Arefin Shimon *et al.*, 2016).	In IoT, every object in the real world can be virtual and has a unique address on the Internet, allowing objects to provide and consume various services. Objects in these scenarios are being connected for a specific goal. The major goal in any social framework is to introduce and use modern techniques to relate the objects to one another (Davoudpour, Sadeghian, & Rahnama, 2015).	Furthermore, many devices in the IoT are based on human behavior; therefore, the social relationships (e.g., friendship and conflict) of people are very critical, which should be considered in the IoT with device-to-device communications (Chen, Tang, & Coon, 2018)	Social inclusion: through the IoT, promote the inclusion of less assisted classes and citizens with special needs, stimulating income generation and improving the quality and access to public services - Report 3A (BNDES, 2017).	Three relevant categories influence the user experience of technology: the broader socio-cultural context, the situational context of use, and the interaction context. The socio-cultural context refers to the context on a societal level (e.g., people's social and cultural background) (Van Hove *et al.*, 2018).	The municipality can increase its decisive role by improving urban spaces (such as public lighting, rehabilitation of public spaces) and the generation of intelligence based on data from social assistance, education, and health policies - Report 7A (BNDES, 2017).
Tests	Traditional testing techniques would not be able to test this global behavior at	An IoT system can have many interfaces (e.g., mobile phones, tablets, desktops)	Many research efforts have been made on challenging topics for the 5G IoT	For the daily chore monitoring scenario, the effect evaluation process takes a	From one perspective, a human actor can be seen as a simple data	Most of the identified literature (62%) deals with the control of medical image	The main requirement of the proposed system that we wished to test was

	scale. Integrating the Emergent-Behavior IoT applications in the real world has a significant impact and therefore requires an incremental means to accept and deploy the application. Ideally, this translates to running the simulation models parallel with the IoT middleware and the actual nodes operating in the real world. The number of nodes can be increased gradually to fully deploy the application in the field (Bosmans, Hellinckx, & Denil, 2018).	and many devices. Thus, there is a difficulty in designing interactions between devices, especially in IoT, where one system will have several components (e.g., mobile interfaces, things, gateways). The lack of tools and methods for testing multi-device user experiences is a research opportunity (Andrade, Carvalho, de Araújo, Oliveira, & Maia, 2017).	in the past few years. The main requirements of IoT include high data rate, the future IoT applications, such as high-definition video streaming, virtual reality (VR), or augmented reality (AR) *et al.*, require higher data rates at around 25 Mbps to provide acceptable performance (Li, Xu, & Zhao 2018).	maximum of around 118 milliseconds to complete the effect evaluation process and send out notifications, in the case of 1609 domotic effects. The "Domotic Effects Evaluation" bundle is quite responsive and responds in near real-time. In most cases, the time for evaluation and sending out notification was less than 150 ms. The number of domotic effects needed for average homes and small buildings will be in hundreds (Corno & Razzak, 2015).	generator, e.g., by walking around with a GPS-sensor embedded in their smartphone, they could broadcast location data to an IoT middleware. However, from another perspective, they can play a very active role in the IoT system by, for example, generating evolving traffic patterns that will influence the behavior of smart traffic lights. Therefore, all these various components and their behavior, interactions, and goals need to be considered and evaluated when developing an Emergent-Behavior IoT system (Bosmans, Hellinckx, & Denil, 2018).	viewers. However, only eight systems (14.5%) were tested in a real clinical environment, and 7 (12.7%) were not evaluated. In the last ten years, many advancements have led to robust touchless interaction approaches. However, only a few have been systematically evaluated in real operating room settings. Further research is required to cope with the current limitations of touchless software interfaces in clinical environments (Mewes, Hensen, Wacker, & Hansen, 2017).	scalability because the amount of data received from sensors could increase depending on the number of sensors that were connected to a smart farm and the total number of active farms (Dincu, Apostol, Leordeanu, Mocanu, & Huru, 2016).

4 Development Phase

This chapter presents the IoT Roadmap to support the engineering of IoT software systems. The Roadmap materializes the IoT Conceptual Framework. It has been defined on top of the body of knowledge acquired from seven Rapid Reviews, representing a significant achievement of this research as it was used to direct the IoT Roadmap structure.

4.1 Defining the IoT Roadmap – An Iterative process

The purpose of the development phase of our methodology is to translate the IoT Conceptual Framework to a more practical level by turning the framework into actionable directives to support the developers on engineering IoT software systems. To that end, we have defined an IoT Roadmap based on acquired evidence. For the definition, we followed an iterative process presented in Figure 16.

The process is composed of four steps. Having the IoT Framework as input, the first step is to **(01) Collect evidence from an IoT Body of Knowledge** to answer the 5W1H questions proposed. The evidence was collected from specialized technical literature through Rapid Reviews performed for each of the seven Facets.

Steps two to four are executed iteratively for each Facet so that every new iteration improves and evolves the previous results. In the **(02) Peer Coding** step, qualitative analysis for all evidence extracted from the technical literature is performed according to GT procedures. In the **(03) Propose Roadmap Items** step**,** based on the codes that emerged in the previous step, we proposed guidelines, activities, and recommendations in the form of items that compose the Roadmap. The proposed items of a prior interaction can be maintained or improved, and new items included. After that, we performed the **(04) Review Roadmap Items**. In this step, the reviewers could agree or disagree with the proposed items in review meetings for discussion until reaching a consensus for every item. The resulting IoT Roadmap comprises the items grouped in categories that emerged from GT for each IoT Facet – contemplating the Roadmap support for IoT multidisciplinarity.

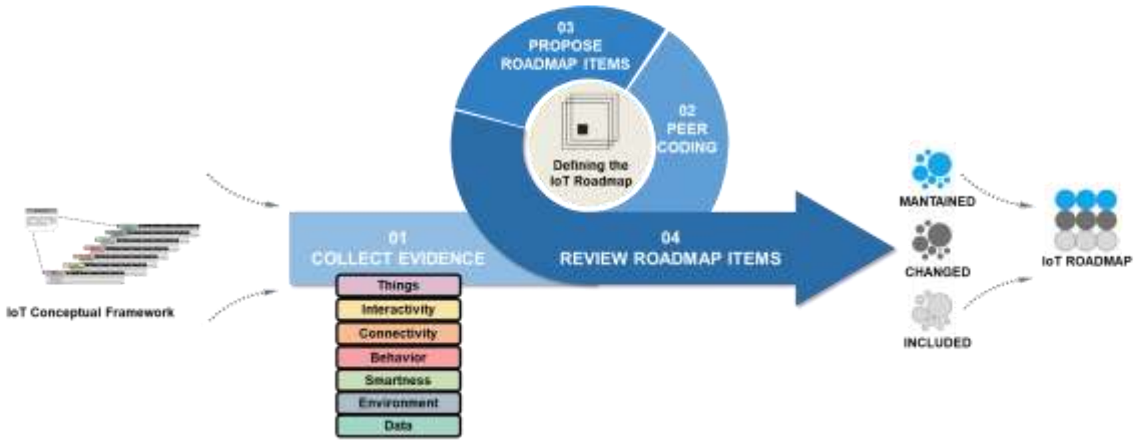


Figure 16. IoT Roadmap Definition: An iterative process.

As we progress in the iterative definition (Figure 16), the Roadmap becomes more robust by confirming existing items and including specific items for each Facet. The initial focus to organize our efforts is on the ***Things*** and **Interactivity** Facets (Motta R. C., 2019), embracing Human-Thing and Thing-Thing interaction from IoT software systems. First, we started the definition of the IoT Roadmap in *Things* Facet, followed by Interactivity Facet. This section presents the result of these two iterations. In the following subsections, we detail the activities performed in each step.

4.2 Collect Evidence from an IoT Body of Knowledge

The research directed the initial conceptual basis for the facets focused on the IoT (Motta, de Oliveira, & Travassos, 2019). Furthermore, the IoT Facets were indicated feasible by the practitioners interviewed (Section 3.3.1). From these inputs and findings in IoT and the progress of the discussions and research, we performed a study to deepen our knowledge of each Facet.

We conducted Rapid Reviews (RR), which are adaptations of systematic literature reviews to fit practitioners' constraints (Tricco *et al.*, 2015). Rapid Reviews have just started to be used in the context of Software Engineering (Cartaxo, Pinto, & Soares, 2018). The procedure to be performed is similar to systematic literature reviews (SLRs) but presents some simplifications to reduce the usual overload of SLRs. For this, we formatted a generic RR meta-protocol that was instantiated for each of the seven Facets (***Things***, **Interactivity, Connectivity**, **Behavior, Environment, Smartness,** and **Data**). The reviews sought to answer if each Facet represented a concern in the engineering of

IoT software systems. This central question was broken into minor 5W1H questions about the Facets, verifying published studies supporting our previous results.

The 5W1H aims to give the observational perspective on a general understanding and characterization of which information is required to the understanding and management of the Facet in a system (*what*); to the software technologies (techniques, technologies, methods, and solutions) defining their operationalization (*how*); the activities location being geographically distributed or something external to the software system (*where*); the roles involved to deal with the facet development (*who*); the effects of time over the facet, describing its transformations and states (*when*); and to translate the motivation, goals, and strategies going to what is implemented in the facet (*why*), in respect of IoT projects, following the structure proposed in the IoT Conceptual Framework.

4.2.1 Planning

The RRs were carried out in the context of a postgraduate discipline of the Systems Engineering and Computer Science Program of the Federal University of Rio de Janeiro in 2018. The discipline was Special Topics in Software Engineering, and the revisions were carried out by six students at the master's level, accompanied by one doctoral student and one professor. Follow-up was carried out weekly, and the discussions and doubts were handled individually. The facets were distributed randomly through a lottery, and each student was responsible for instantiating the protocol for their respective facet. The execution occurred in the second half of 2018. The *Things*, Interactivity and Data Facets were later updated, and we present the latest results covering until 2020.

Each RR is presented in an individual protocol. The main highlights of this study's results are presented in this section. Table 6 presents a summary of the meta-protocol.

Table 6. RR Research Meta-Protocol Summary.

Research questions		RQ1: What is the understanding and management of <<facet>> in IoT projects? RQ2: How do IoT projects deal with software technologies (techniques, technologies, methods, and solutions) and their operationalization regarding <<facet>>? RQ3: Where do IoT projects locate the activities regarding <<facet>>? RQ4: Whom do IoT projects identify to deal with <<facet>>? RQ5: When do the effects of time, transformations, and states of <<facet>> affect IoT projects? RQ6: Why do IoT projects implement <<facet>>?
Search string	**Population**	"ambient intelligence" OR "assisted living" OR "multiagent systems" OR "systems of systems" OR "internet of things" OR "Cyber-Physical Systems" OR "Industry 4" OR "fourth industrial revolution" OR "web of things" OR "Internet of Everything" OR "contemporary software systems" OR "smart manufacturing" OR digitalization OR digitization OR "digital transformation"

		OR "smart cit*" OR "smart building" OR "smart health" OR "smart environment" **AND**
	Intervention *	Defined specifically for each <<facet>> **AND**
	Outcome	**(**understanding OR management OR technique OR “technolog*” OR method OR location OR place OR setting OR actor OR role OR team OR time OR transformation OR state OR reason OR motivation OR aim OR objective) **AND**
	Context	(engineering or development or project or planning OR management OR building OR construction OR maintenance)
Search Strategy	Scopus (https://www.scopus.com/) + Snowballing (backward and forward)	
Inclusion Criteria	The paper must be in the context of software engineering; and The paper must be in the context of IoT; and The paper must report a primary or a secondary study; and The paper must report an evidence-based study grounded in empirical methods; and The paper must provide data to answering at least one of the RR research questions; and The paper must be written in the English language.	
Technical Report	Detailed information about the planning and execution - https://arxiv.org/abs/2101.05869	

The search string was defined using the **PICOC** strategy (Petticrew & Roberts, 2006) based on the 5W1H questions. The **P**opulation was the same for each Facet, setting all words that characterize IoT and similar concepts. The population was proposed based on the researchers' experience and the results from the characterization activity (Motta, Silva, & Travassos, 2019). The **I**ntervention was established and tuned differently for each Facet. Details for each string set are presented in Table 7. We had no **C**omparison since it is the first round of such a secondary study. The **O**utcome is the same for each Facet and is set as all elements to help answer the 5W1H questions. We also considered **C**ontext, defined as the same for each Facet, to delimitate the results better. Inclusion criteria were explicitly defined to ensure that the paper discussed the Facets in the context of IoT. We set as exclusion criteria only documents not representing scientific papers for not losing any relevant work. The intervention was explicitly defined for each Facet with different terms used in the trials.

Table 7. RR Intervention of PICOC for each facet.

Facet	* Intervention
Things	Tag” OR “mobile phone” OR “addressable thing” OR “spime” OR “smart item” OR “virtual thing” OR “identifiable thing” OR “smart object” OR “audio receiver” OR “video receiver”
Interactivity	“Human-thing interaction” OR “Thing-thing interaction” OR “user interaction” OR “Interactivity”
Connectivity	“connectivity” OR “system connection” OR “software connection” OR “things connection” OR “objects connection”
Behavior	“system service” OR “software service” OR “system behavior” OR “software behavior” OR “system function” OR “software function” OR “application service” OR “application function” OR “application behavior” OR “solution behavior” OR “solution service” OR “solution function*” OR “program behavior” OR “program function*” OR “program

	service” OR “product behavior” OR “product function*” OR “product service” OR “emergent behavior”
Smartness	“smartness” OR “intelligence” OR "autonomous reaction" OR "learning capability"
Environment	“use* context” OR “surrounding environment” OR “smart space” OR “smart environment” OR “contextual environment” OR “use* environment” OR “physical environment” OR “system ambient” OR “software ambient” OR “system surrounding” OR “system context” OR “software context” OR “emergent environment” OR “social environment” OR “social context” OR "smart context" OR "smart ambient"
Data	“data capture” OR “data analysis” OR “data processing”

During the RR trials, the terms were selected to balance the recall and precision of the results. The search string’s proposal was made by the three researchers responsible for the study and six collaborating researchers who conducted each RR. The 5W1H questions also structured the Extraction Form, presented in Table 8.

Table 8. RR General Extraction Form

<paper_id>:<paper_reference>	**Extracted information**
Abstract	…
Description	…
Experimental Study type and data	…
RQ1: *WHAT* information is required to understand and manage the <<facet>> in IoT	…
RQ2: *HOW* are software technologies used and their operationalization	…
RQ3: *WHERE* are the activities locations related to <<facet>>	…
RQ4: *WHO* is involved with the <<facet>> in IoT	…
RQ5: *WHEN* the effects of time affect <<facet>> in IoT	…
RQ6: *WHY* motivation, goals, and strategies regarding <<facet>> in IoT	…

4.2.2 Execution

We used Scopus[11] as the search engine to index several peer-reviewed databases and balance coverage and relevance (Motta, de Oliveira, & Travassos, 2019). We incremented the search with snowballing procedures (backward and forward) (Wohlin, 2014) as a strategy to increase coverage. The selection process (see Table 9) began by removing articles that did not fit the inclusion criteria (reading the title, abstract, and full-text reading). After that, snowballing was performed. This procedure was defined to eliminate articles that do not explicitly answer the questions. The execution and more detail on this procedure are available (Motta, Oliveira, & Travassos, 2021).

[11] https://www.scopus.com/

Table 9. RR Selection process.

Review Steps / Facets	Selection in SCOPUS	Removed (duplicated, proceedings and non-English)	Title Selection	Abstract Selection	Full reading Selection	Snowballing Selection	Included Articles
Things	830	728	160	33	21	9	30
Interactivity	2050	2025	538	109	31	8	39
Connectivity	781	752	119	31	11	2	13
Behavior	592	563	103	28	17	2	19
Smartness	2070	2035	353	91	17	7	24
Environment	925	847	170	59	17	5	22
Data	1884	1751	129	46	20	3	23
Total	**9132**	**8701**	**1572**	**397**	**134**	**36**	**170**

As presented in Table 9, we started from 9132 papers (sum of the initial set of papers for each Facet), and we concluded with 170 papers for analysis. We extracted valuable information from these papers, detailed in (Motta, Oliveira, & Travassos, 2021), organizing them in a comprehensive IoT body of knowledge. We recovered relevant information for the selected Facets, presenting a baseline of concepts related to IoT projects. From it, we could provide high-level answers to the 5W1H questions and define an initial understanding of what needs to be developed, giving us a direction to be taken in IoT projects.

4.2.3 Analysis

The reviewers agreed upon a set of final papers, considering the selection criteria established. After the selection, the reviewer retrieved valuable information from the final papers based on the extraction form. In this step, based on the results, we performed a qualitative analysis based on GT coding procedures (Strauss & Corbin, 1990) in the findings.

The packing step was performed through all the review processes to document every decision in each activity and the information collected and analyzed. Here is presented a general mapping of the results for all the RRs together.

Figure 17 shows the number of articles by year, indicating interest in the IoT area over the years.

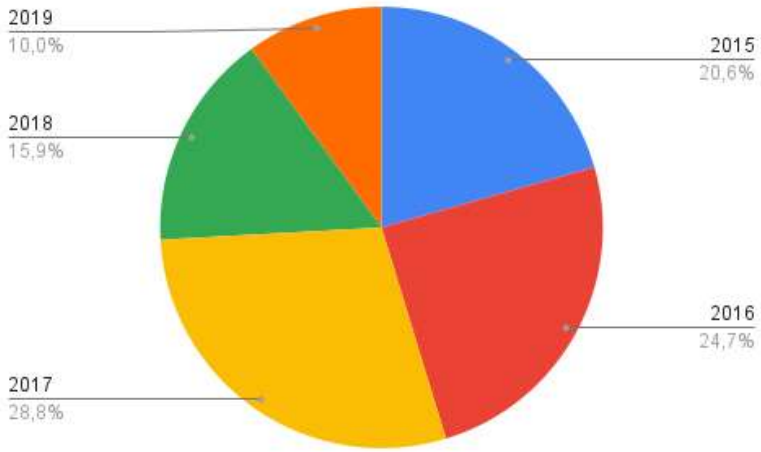


Figure 17. RR Summary of Articles by Year.

Figure 18 presents the number of articles by source. Again, most of the articles (88%) selected come from conferences and journals, with 82 and 69 articles, respectively.

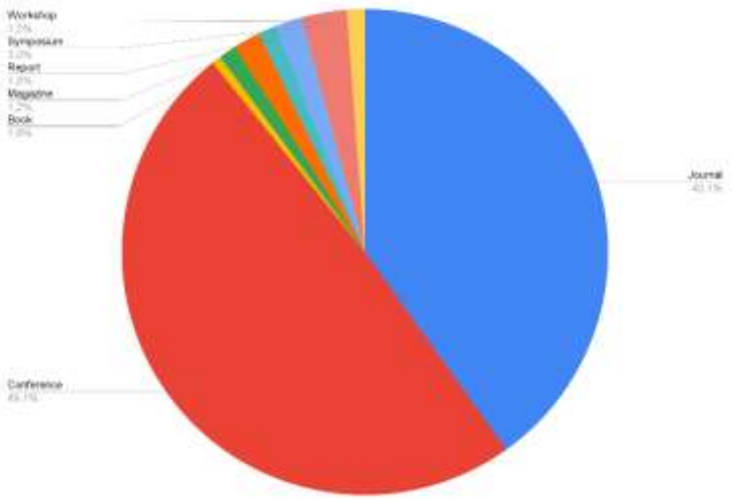


Figure 18. RR Summary of Articles by Source.

Figure 19 shows how many articles we have for each Facet, having Things (30) and Interactivity (39) as the majority of primary sources. This outcome is in line with the understanding of the potential of IoT. IoT allows composing software systems from uniquely addressable objects, extending their capabilities through software, therefore the importance of objects, devices, and the *things* themselves in the *Things* Facet.

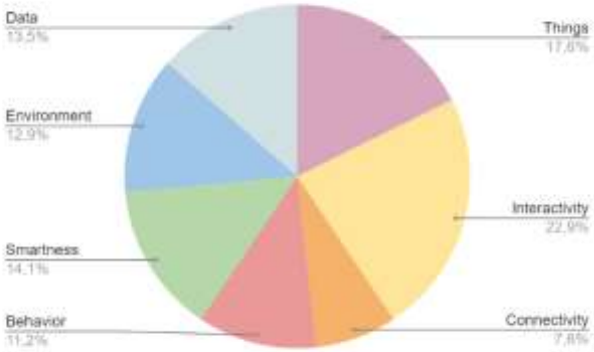


Figure 19. RR Summary of Articles by Facet.

With IoT, it is possible to create a large network of interconnected objects, bringing more capabilities to the interaction between humans and devices that communicate and cooperate to reach a goal, highlighting the importance of Interactivity Facet. Figure 20 presents the number of IoT solutions presented in the primary sources.

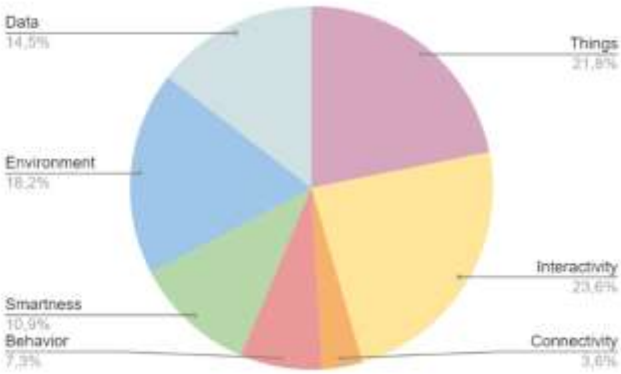


Figure 20. RR Summary of IoT Implementations by Facet.

The solutions are primary studies in our analysis and vary between proof of concepts, user evaluations, and case studies. This content proved valuable for our analysis because it brought a more concrete feature to the concepts proposed in the articles. With that, we identified 55 cases implementing IoT at some level, strengthening the evidence of primary studies and enriching our analysis. See Appendix A – IoT Cases from Rapid Reviews – for further details. A case is a description of the development of an IoT software application for a real problem. For example, the MiniOrb combines a sensor platform with an interaction device to reflect the environmental output of office environments, particularly temperature, lighting, and noise (Rittenbruch & Donovan, 2019).

4.2.4 Results

With the research so far, we claim that multidisciplinarity in IoT is a fact. The Facets represent this vision and must be developed together, one that aims to achieve the solution. A summary of the findings is also presented in the format of Evidence Briefings (Cartaxo, Pinto, Vieira, & Soares, 2016). Appendix B – Examples of Evidence Briefings from Rapid Reviews – presents evidence briefings for each Facet. The technical report details the complete discussion (Motta, Oliveira, & Travassos, 2021). For the sake of organization, here we briefly present a summary of the answers to the research questions.

1. *Things*

The search resulted in 830 articles, with 728 remaining after removing duplicates and proceedings. Later we applied Title and Abstract selection with 33 remaining for a full reading. We also applied backward and forward snowballing procedures. After the final selection, the data set selected in this review comprises 30 papers, focusing on objects and devices, inserted mainly in IoT, Smart Cities, Smart Buildings, Smart Agriculture, Water Management, and Health Care. Table 10 presents the main results for the 5W1H for the *Things* Facet.

IoT employs smart devices (things) to sense, actuate, and interact with users or even the embedded environment. Building *things* is not limited to hardware but involves intertwining different areas that need to work together to deliver quality and security solutions, as supported by evidence on different demands and concerns.

Table 10. Main results of the Rapid Review for *Things* Facet.

Research Questions	Summary of the Answers
What	• *Things* in the context of IoT systems are every device that can sense, actuate or interact with the user or environment. • In other words, these devices are all hardware that can traditionally replace the computer, expanding the connectivity reach. • Tags, home controller devices, mobile phones, wearables, vehicles, and transports like buses, cars and trucks, health devices, farm devices, indoor environment devices, water devices, indoor location solutions, and tracking devices are examples of things. • From the 30 articles in the final set, 30 present some input to characterize ***what***.
How	• Regarding technologies, many solutions were combined to build devices like sensors, actuators, smartphones, microcontrollers, interactable, cameras, communication and network enablers, and others. • Some systems treat *Things* giving a virtual representation of these devices enabling remote access and control of them. • To achieve this is necessary to connect the device with the internet. Some technologies were applied to provide communications services to these devices like WSN, Wi-Fi APs (Access Point), ZigBee, 4G Network, Bluetooth, Bluetooth Low Energy (BLE), Wi-Fi, SMS Gateway, GSM/GPRS, Cellular IoT, and iBeacons; • From the 30 articles in the final set, 28 present some input to characterize ***how***.
Where	There is no general response to this question. The activities' location is the own environment and depends on the domain that is employed. Based on the literature found,

	the authors built systems in places like houses, shopping places, transport, smart cities, factory, roads/streets, military, industry, farms, lignite coal mines, hospitals, offices, water, airport, and buildings. Some solutions were generics like outdoor and indoor locations. • From the 30 articles in the final set, 17 present some input to characterize ***where***.
Who	• In software engineering, there is no evidence about who correctly deals with these devices. As a result, some solutions presented their own user construct and program the *Thing* in a "do it yourself" approach. • From the 30 articles in the final set, 4 present some input to characterize ***who***.
When	The primary sources did not make explicit information regarding this question.
Why	• Things with part of solutions in IoT systems provide a series of benefits for users: comfort, reduced costs, security, increased quality-of-life efficiency, decreased energy consumption, support in the decision-making process, automate a manual process, remote control, and monitoring, and indoor environmental quality. • From the 30 articles in the final set, 30 present some input to characterize ***why***.

2. Interactivity

The search resulted in 2050 articles, with 2025 remaining after removing duplicates and proceedings. Later we applied Title and Abstract selection with 109 remaining for a full reading. We also applied backward and forward snowballing procedures. After the final selection, the data set selected in this review is composed of 39 papers focusing on communication technologies, inserted mainly in the domains of IoT, SoS, Cyber-Physical Systems, and Health Care. Table 11 presents the main results for the 5W1H for the Interactivity Facet.

The evidence showed that, although it has well-defined characteristics that help understand the IoT scenarios, there are many open questions and specific solutions according to the domains. This review has evolved and applied in a more extensive context than this thesis, having some results submitted for publication (Maia, Motta, de Oliveira, and Travassos – "Exploring Interactivity concerns on the Internet of Things Software Systems" submitted to Journal of Software: Evolution and Process 2021 – *under review*)

Table 11. Main results of the Rapid Review for Interactivity Facet.

Research Questions	Summary of the Answers
What	• In IoT projects, interactivity is characterized by the interaction involving *things*, systems, and humans, where interaction is characterized by the ability to communicate, exchange information, and control actions. • Data must be collected (sensing the environment), processed (generally in some cloud), stored (using databases), and transmitted. To transmit and receive information and interact with humans, they utilize networks as a medium of communication. • From the 21 articles in the final set, 21 present some input to characterize ***what***.
How	• To guarantee connectivity: Zig-Bee, Bluetooth, Radio Frequency, RFID, 6LowPAN, WSN, WiFi, IPv6, and others. • To guarantee communication: HTTP, XMPP, TCP, UDP, CoAP, MQTT, and others. • To guarantee to understand: JSON, XML, OWL, SSN Ontology, COCI, and others. • Also, real-world objects are virtualized and represented as Web Resources and accessed through Web Interfaces based on REST principles and Producer and Consumers methods.

	• From the 21 articles in the final set, 21 present some input to characterize ***how***.
Where	The primary sources did not make explicit information regarding this question.
Who	• Designers, architects, developers, managers, and engineers deal with interactivity in different phases of IoT projects. • Changing the scenario: "Engineering is no more a set of vertical activities developed by different engineers but a collaborative process in which people and technology are completely involved in the engineering process." • From the 21 articles in the final set, 6 present some input to characterize ***who***.
When	The primary sources did not make explicit information regarding this question.
Why	• To bridge the gap between the massive heterogeneity in IoT, create an interoperable system that can overcome different standards, protocols, and technologies to perform more efficiently than isolated ones. • Interactivity is one of the main characteristics of IoT projects, making new types of applications possible (such as smart environments), facilitating everyday life, enhancing products competitiveness and sustainability. • From the 21 articles in the final set, 15 present some input to characterize ***why***.

3. Connectivity

The search resulted in 781 articles, with 752 remaining after removing duplicates and proceedings. Later we applied Title and Abstract selection with 31 remaining for a full reading. We also applied backward and forward snowballing procedures. After the final selection, the data set selected in this review comprises 13 papers focusing on communication technologies, inserted mainly in the domains of IoT, Smart Cities, Cyber-Physical Systems, and Health Care. Table 12 presents the main results for the 5W1H for the Connectivity Facet.

Although it has well-defined characteristics that help understand the IoT scenarios, the findings evidenced many open questions and specific solutions according to the domains.

Table 12. Main results of the Rapid Review for Connectivity Facet.

Research Questions	Summary of the Answers
What	Some information and requirements need to be understood to understand and manage connectivity: • IoT is a highly scalable, highly available, robust system with many devices geographically distributed through an extended area. • It requires a seamless connection and network traffic control and management, providing low latency even with limited bandwidth available. • It is deeply influenced by devices limitations and domain requirements, such as low power and high mobility devices. • Deal with limited resources (low memory capacity and low processing power), thus, require efficient operations. • From the 13 articles in the final set, 13 present some input to characterize ***what***.
How	• It uses specific solutions according to the application domain. • It tries to re-use legacy cellular infrastructure and invest in novel communication solutions. • It is mainly based on wireless communication technologies divided into Short-Range, Long-Range, and Cellular-based.

	• From the 13 articles in the final set, 13 present some input to characterize ***how***.
Where	• Through the Network Architecture and the Network layers. • From the 13 articles in the final set, nine present some input to characterize ***where***.
Who	The primary sources did not make explicit information regarding this question.
When	The primary sources did not make explicit information regarding this question.
Why	• Some reasons to implement connectivity are to provide communication among the devices to enable many applications. • From the 13 articles in the final set, four present some input to characterize ***why***.

4. Behavior

The search resulted in 592 articles, with 563 remaining after removing duplicates and proceedings. Later we applied Title and Abstract selection with 28 remaining for a full reading. We also applied backward and forward snowballing procedures. After the final selection, the data set selected in this review is composed of 19 papers, focusing mainly on emergent behaviors, inserted mainly in the domains of Cyber-Physical Systems, Systems of Systems, IoT, and Ultra-Large-Scale Systems. Table 13 presents the main results for the 5W1H for the Behavior Facet.

The behavior of a system is its central point, and therefore, it needs to have a good understanding. Moreover, all the actions of IoT are triggered by some event, which can be a stimulus or a reaction to another event. Furthermore, it has a very delicate emergency feature, making it possible to emerge at unexpected moments. Therefore, it is often difficult to predict how correctly the system behaves in advance for IoT systems. However, there must be specific assurances about the system's behavior for practically all practical applications since it would not be safe to implement otherwise.

Table 13. Main results of the Rapid Review for Behavior Facet.

Research Questions	Summary of the Answers
What	• All behavior exerted by the IoT software system is triggered by some event. Therefore, it is necessary to know when this event will happen and what this event will be. • The behavior of the whole IoT is more than the sum of the behaviors of its constituent systems. Therefore, it is necessary to know how this greater behavior is generated and when it will arise. • From the 19 articles in the final set, 18 present some input to characterize ***what***.
How	• The first and most common way to treat behavior is in stages, where the smaller ones constitute the greater behaviors. With this, it is possible to reduce the complexity of taking care of the behaviors. • Another way to manage behavior is through a state machine (Jackson 2015; Giammarco 2017). • SosADL and Monterey Phoenix are behavioral modeling frameworks for SoS architecture which describes these systems regarding abstract specifications of

	possible constituent systems, mediators, and behaviors (Giammarco *et al.* 2017; Oquendo 2017). • From the 19 articles in the final set, 13 present some input to characterize ***how***.
Where	The primary sources did not make explicit information regarding this question.
Who	• The leading roles for managing the IoT were software engineers, programmers, software architects, and systems architects. The other roles encountered were the system users, the people involved, and each object within a system. • From the 19 articles in the final set, ten present some input to characterize ***who***.
When	• Frequent updates are expected on projects involving IoT over the lifetime of the project. • The main phases of the life cycle identified were initialization, development, validation, implementation, and change verification. • The primary emphasis is assigned to the initial phase of requirements engineering to understand the behaviors of a system. • From the 19 articles in the final set, ten present some input to characterize ***when***.
Why	• The system's behavior is the central object of software development and is proposed as the core object of software development. Early and precise identification of behaviors contributes to a reduction of cost schedule risk. • From the 19 articles in the final set, 15 present some input to characterize ***why***.

5. Smartness

The search resulted in 2070 articles, with 2035 remaining after removing duplicates and proceedings. Later we applied Title and Abstract selection with 91 remaining for a full reading. We also applied backward and forward snowballing procedures. After the final selection, the data set selected in this review comprises 24 papers, focusing on communication technologies, inserted mainly in IoT, Smart Environments in general, Resource Management, Ambient Intelligence, Context-Aware Systems, and Health Care. One of the reasons for this smartness concern in IoT may be the lack of standardization or understanding of a "smart system." Table 14 presents the main results for the 5W1H for the Smartness Facet.

According to the research, to attend to smartness, the system should have some level of autonomy and a set of operations such as sensing, data collection, data processing, decision-making, actuation, and orchestration in the environment that it is immersed. However, to be "smart," it is not necessary to have all these capabilities. Therefore, this review has evolved and applied in a context more extensive than this thesis, with some published results (de Souza, Motta, & Travassos, 2019).

Table 14. Main results of the Rapid Review for Smartness Facet.

Research Questions	Summary of the Answers
What	• The system should have some level of autonomy and is a set of operations such as sensing, data collection, data processing, decision-making, and acting to orchestrate things in the environment immersed and understand the smartness in IoT.

	• In the scenario of IoT projects, smartness deals with data collected, data analyses, treatment, and transmission of data to manage and make a decision. In addition, all these data collected from the ambient help the IoT be aware of what is occurring in the environment. • From the 24 articles in the final set, 21 present some input to characterize ***what***.
How	• IoT projects use technologies such as sensors or wearables to collect data from the environment: • It uses actuators, maker decisions, and acting according to the data collected and treated to perform some environmental activity autonomously. • It uses artificial intelligence, machine learning, neural networking, fuzzy logic to deal with the data. Hence make a decision and act. • From the 24 articles in the final set, 22 present some input to characterize ***how***.
Where	• Smartness is handled in software architecture, such as Client-server architecture, representation transfer (REST), and service-oriented architecture (SOA). It is also treated in the process of system implementation or system design. • From the 24 articles in the final set, 21 present some input to characterize ***where***.
Who	The primary sources did not make explicit information regarding this question.
When	• When IoT needs to decide according to the data collected in real-time, IoT project needs to deal with real-time information. In real-time monitoring and visualization to manage the data obtained. • From the 24 articles in the final set, five present some input to characterize ***when***.
Why	• To make the system more autonomous without user interaction. • To improve the quality of life of end-users. • Management of ambient, such as: save energy, sustainable building, healthcare, and others. • From the 24 articles in the final set, 20 present some input to characterize ***why***.

6. Environment

The search resulted in 925 articles, with 847 remaining after removing duplicates and proceedings. Later we applied Title and Abstract selection with 59 remaining for a full reading. We also applied backward and forward snowballing procedures. After the final selection, the data set selected in this review is composed of 22 papers, focusing on the requirements for such environments, inserted mainly in the domains of IoT, Ambient Assisted Living, Smart Cities, Cyber-Physical Systems, Industry 4.0, Smart House, Smart Campus, and Health Care. Table 15 presents the main results for the 5W1H for the Environment Facet.

The environment can involve many devices composed of sensors, actuators, and other objects generating significant data, leading to connectivity and interoperability, data processing and storage, to be efficient and reliable. This high complex ambient requires system integration, and there is a necessity for trustful and legal regulation. Also, sustainability is a crucial concept for these environments.

Table 15. Main results of the Rapid Review for Environment Facet.

Research Questions	Summary of the Answers
What	• The environment is the place where *things* are, actions happen, events occur, and people are. Smart Environments (SE) or Smart Spaces provide intelligent services by acquiring knowledge about itself and its inhabitants to adapt to users' needs and behavior considering the context (context-awareness). IoT systems apply various technological solutions to attend to specific requirements that differ according to the project. • From the 22 articles in the final set, 21 present some input to characterize ***what***.
How	• In general, the environments are composed of sensors and actuators to sense and change the ambient state. Therefore, technologies like IoT, cloud, smart objects, middleware's, Wireless Sensor Networks, Vehicular Ad-hoc Networks, edge computing, artificial intelligence, machine learning, data mining can be employed on these systems. • Techniques for designing smart software systems using Use Cases and Smart Environment Metamodels can be applied. User interaction, autonomy, and easy management are essential requirements on Smart Environment. • From the 22 articles in the final set, 19 present some input to characterize ***how***.
Where	• The activities' location is the own environment and depends on the domain that is employed. Based on the literature, the environment can be places like city, home, ambient assisted living, campus, office, industry, building, transportation, street, road, bike station, parking space, and others • From the 22 articles in the final set, 22 present some input to characterize ***where***.
Who	• In software engineering, the phases that allocate environment activities allocate developers, system designers, domain experts, technical professionals, end-users, and stakeholders to build an ambient solution. • From the 22 articles in the final set, 22 present some input to characterize ***who***.
When	• Concerning the solutions presented, most deal with software activities related to analysis, design, and implementation phases on system architecture definition, software design, requirement specification, and software implementation. • From the 22 articles in the final set, seven present some input to characterize ***when***.
Why	• Adapt ambient to users' needs and behavior. • Provides comfort, quality of life, and benefits daily lives, accessibility, high productivity, reduces costs and effort, saves time, uses resources efficiently, and gives users autonomy. • Benefit users on their activities by using cutting-edge technologies. • Helps on: health diseases, pollution management, traffic efficiency, deterioration and management of infrastructure, criminality, climate change, cyber-security, and economic development. • Provides natural and sustainable user-centric quality services. • From the 22 articles in the final set, 22 present some input to characterize ***why***.

7. Data

The search resulted in 1884 articles, with 1751 remaining after removing duplicates and proceedings. Later we applied Title and Abstract selection with 46 remaining for a full reading. We also applied backward and forward snowballing procedures. After the final selection, the data set selected in this review is composed of 23 papers. Table 16 presents the main results for the 5W1H for the Data Facet.

IoT generates new prospects for increasing income, lowering expenses, and improving efficiencies. However, simply collecting a large volume of data is insufficient. Therefore, IoT solutions should include elements that allow them to gather, handle, and analyze a large volume of generated data in a scalable and cost-effective manner to reap IoT benefits.

Table 16. Main results of the Rapid Review for Data Facet.

Research Questions	Summary of the Answers
What	• Data can be anything stored (time series, streaming, sequence, graph, spatial, and multimedia). It is a consensus that data is produced in vast quantities in both unstructured and structured formats at all times. Furthermore, the data generated was derived from many data sources, with various formats, and so on. This newly collected data is frequently integrated with historical data that has been stored. This accumulating data provides the foundation for future IoT applications. • The challenges related to what data is used in IoT relate to Volume, Variety, Velocity, Variability, Veracity, and Value. • From the 23 articles in the final set, 16 present some input to characterize ***what***.
How	• Most of the solutions to deal with data in IoT provide a layered architecture with Computing Infrastructure, Storage Infrastructure, Data Analytics, and Data Visualization. • The Data Analytics should cover data collection, perform analytics over data using data mining and analytical algorithms, tools, and existing methods (Descriptive, Diagnostic, Predictive, and Prescriptive). Finally, using solutions such as Spark and Hadoop alongside visualization tools and an interactive interface provide insights into the collected data. • Some of the analytical techniques listed are hidden Markov models, parallel tree learning, sequence alignment algorithms, collaborative filtering, spatial autoregressive model, and statistical models. • From the 23 articles in the final set, 21 present some input to characterize ***how***.
Where	• Most data solutions are processed in Cloud, Edge, or Fog models to enable the suggested architectures.
Who	• Despite not explicitly detailing a role, the need for access control and data protection over different users and profiles is widely represented.
When	• Not so many articles are concerned if the effects of time in the data. However, we understand the importance of the Data Management Life Cycle. The data management cycle has identified stages Data Collection, Data Process, Store and Secure, Data usage, Data share, Data Communication, Archive, reuse/repurpose and destroy, and encompass the activities for each stage. • From the 23 articles in the final set, two present some input to characterize when.
Why	• The value of the Internet of Things and the real-time insights gained from big data is worthwhile. When the IoT and big data waves collide, their value increases favorably. • Governments and authorities can use IoT data to provide a variety of services. They can then take action in an emergency, appropriately manage resources, and improve the quality of life. • From the 22 articles in the final set, nine present some input to characterize why.

4.2.5 Threats to Validity

Some of the validity threats presented for **literature review** and **qualitative analysis** (Section 3.1.4) presented in the previous chapter can be applied at this point.

RRs were used as the research method, with the extracted data analyzed for each facet. We highlight the lack of a structured summarizing method counting on the limited and subjective reviewers' interpretations. Furthermore, the papers included do not cover all the 5W1H questions for each facet. Therefore, defining any approach from this data is limited to the evidence found.

In the RRs, we followed a research protocol and reviews guidelines. However, the entire review procedure was conducted by graduate students accompanied by more experienced researchers to reduce the selection bias. However, this can be considered a threat to our research, and we decided to accept it. Finally, we did not conduct a quality assessment since it is not required for Rapid Reviews (Tricco, Langlois, Straus, 2017).

4.3 First Iteration: The Things Facet

4.3.1 Peer Coding

The coding step is based on qualitative analysis with a textual coding process and provides a more in-depth investigation of RRs findings. The coding process, which is based on the coding of GT methodology (Strauss & Corbin, 1990), designates codes giving meaning to concepts based on a portion of data (excerpts). One researcher accompanied by another executed all the matching from text to code in the coding; therefore, we are naming it "peer-coding."

As previously described, the first iterations focused on the *Things* Facet and then Interactivity Facet. For the *Things* Facet, this step considered the 30 papers selected from the RRs, and they provided a considerable amount of data to be analyzed.

The original texts (excerpts) identified the concepts, comparing similarities and differences by assigning **codes** from excerpts of data identified in the text, marking the relevant excerpts. Keeping in mind what is relevant to the concept under observation, excerpts can be a word, a phrase, or a paragraph. After analyzing the excerpts, the codes are defined together with their descriptions. The descriptions detail the interpretation of data, including a brief understanding and explanation of the codes, and describe its relation to the life cycle phases. When finding some excerpt that is like a previously defined concept, that is when categories emerge. These codes should be grouped in the same **category** - following the constant comparative analysis recommendation. Abstraction is essential to this activity since a category should represent all the grouped codes. After that, all the excerpts should be consistent with the associated code and category – when applicable. The peer-coding involved the researchers reviewing each extraction and the respective code and category until they had a complete agreement. The resulting codes confirmed IoT applications' multidisciplinary nature from this coding analysis since they covered all the IoT Facets at some level.

We used the QDA Miner Lite tool (Figure 21) to support the coding process. It is a free version of qualitative analysis software for coding, making notes, recovering, and analyzing data from text and images extracted from the RRs selected articles. In addition, this tool allows associating each code to the original excerpt to where it is grounded, easing recovering the codes and examining their relations.

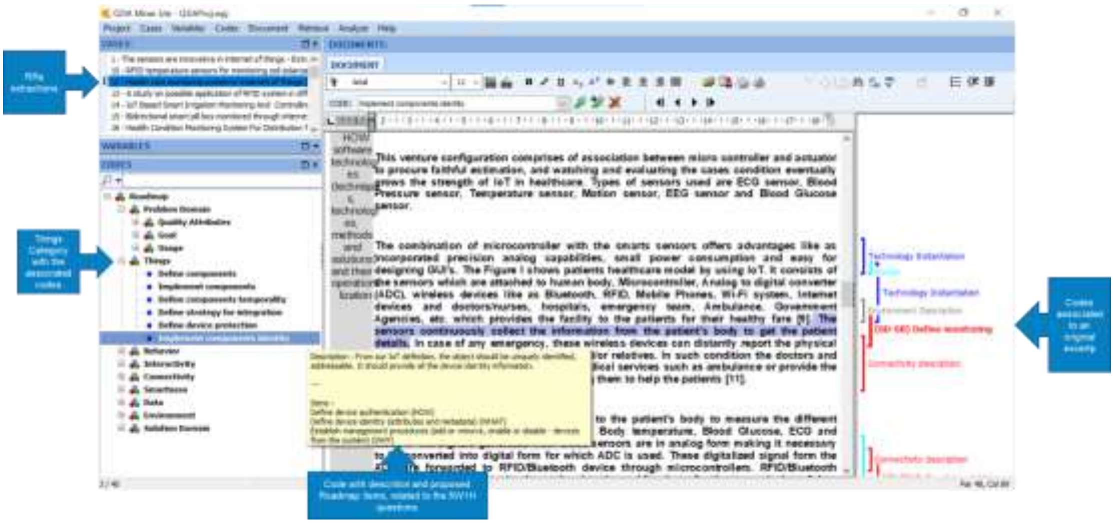


Figure 21. QDA Miner Tool.

Table 17 presents some examples of the excerpts and codes for the *Things* Facet. We coded 969 excerpts into 55 codes for it.

Table 17. Coding example for Things.

Excerpts	Defined Code
"This high demand of beds is caused by the patients who are not necessarily in danger but have to be under observation with physiological monitors. This project aims to help relieve congestion in hospitals and (…) help people who are not able to attend a medical center (Huertas & Mendez, 2016)."	**Motivation**
"Thus, objectives of research in solarization management may relay in the integration of IT solution for real-time monitoring of temperature, evaluation of commercial sensors for application in soils or development of novel one due to signal attenuation, as well as a definition of a theoretical model for data management via software (Luvisi, Panattoni, & Materazzi, 2016)."	
"At the bus stops schedule of buses is not available, so people wait for long hours for a bus, so there is overcrowding at the public bus stops. Sometimes people cannot get the bus on time and, in an overcrowded bus after a long wait, which causes wastage of time. The solution for all problems can get through Intelligent Transportation Systems (ITSs), which are recently under research and development for making transportation more efficient and safer (Kamble & Vatti, 2018)."	
"The RFID reader subsystem is responsible for detecting the presence of birds in the nest and identifying them appropriately, as well as determining the arrival and departure of the bird from the nest, by generating a timestamp for each record (Luvisi, Panattoni, & Materazzi, 2016)."	**Component's temporality**
"Whenever the GPRS-enabled board receives a measurement message, it stamps it with the current timestamp, provided by the on-board RTC (Real Time Clock) (Sales, Remedios, & Arsenio, 2015)."	
"There are four medication sensing sub-circuits, namely, morning, noon, night, and bedtime (before sleeping). Each is sensed via three sets of infrared sensors (IRLED and photodetectors) (Tsai, Tseng, Wang, & Juang, 2017)."	
"Also, there is LCD at the Remote Terminal Unit side to show date, time, temperature, Oil level, Humidity, Vibrations, and current. The RTU design consists of two parts: hardware design and software design (Pawar & Deosarkar, 2017)."	**Data Exhibition**

"The mobile phone is in charge of centralizing the data and visualize the information in a convenient way (Huertas & Mendez, 2016)."	
"The second one includes the GUI where the information stored in the database is displayed to end-users and administrators, as well as allowing the collecting of their inputs (Álvarez López *et al*., 2018)."	

4.3.2 Propose Roadmap Items

The codes defined in the previous step are the basis for proposing the IoT Roadmap Items. Here, the idea is to shape the codes proposed in a roadmap with directions and recommendations of what should be defined and issues to be considered for each Facet in the different development phases.

The originally extracted excerpts led to several codes with their description, according to the GT recommendations. In their turn, the codes supported the definition of IoT Roadmap Items by interpreting them into directives and actionable items that should address the 5W1H questions previously defined. To this end, we analyzed each code and its associated excerpts. Table 18 presents some examples of the proposed items and codes for the *Things* Facet. The researchers interpreted the 55 codes with their excerpts into 115 items for all the IoT Facets, following the GT procedures. The idea is to turn codes into directives, statements, and recommendations that can be followed in IoT projects. The categories that emerged from GT are maintained to organize the items. Therefore, codes can lead to one or more Roadmap items grouped in categories for each IoT Facet.

Table 18. Examples of the codes and proposed items for the *Things* iteration.

Defined Code	Proposed Roadmap Items
Motivation **Description:** IoT developed for a particular goal based on a real problem and motivation. From the data we observed, the motivation behind the solution could affect how the problem is addressed. **Phase: CD | Belongs to Problem Domain**	Define problem domain. (*WHAT*)
	Establish problem motivation. (*WHY*)
	Describe system goal. (*HOW*)
Component's temporality **Description:** Independently integrated components and heterogenic systems, uncertainties, and issues related to temporality across the components should be addressed to reduce risks. **Phase: SD and SR | Belongs to Things Facet**	Describe and indicate strategy for real-time operation. (*HOW* and *WHEN*)
	Describe and indicate a strategy for unifying system time across different components. (*HOW* and *WHEN*)
	Define and describe a strategy for time-related quality attributes. (*WHAT* and *HOW*)
Data exhibition **Description:** Elements that consume data for exhibition purposes. It means devices that enable data visualization.	Define data to be exhibited and locate its origin. (*WHAT* and *WHERE*)
	Describe data manipulation rules and indicate temporality. (*HOW* and *WHEN*)

Phase: SD and SR | Belongs to Things Facet	Identify exhibition device. (*WHO*)

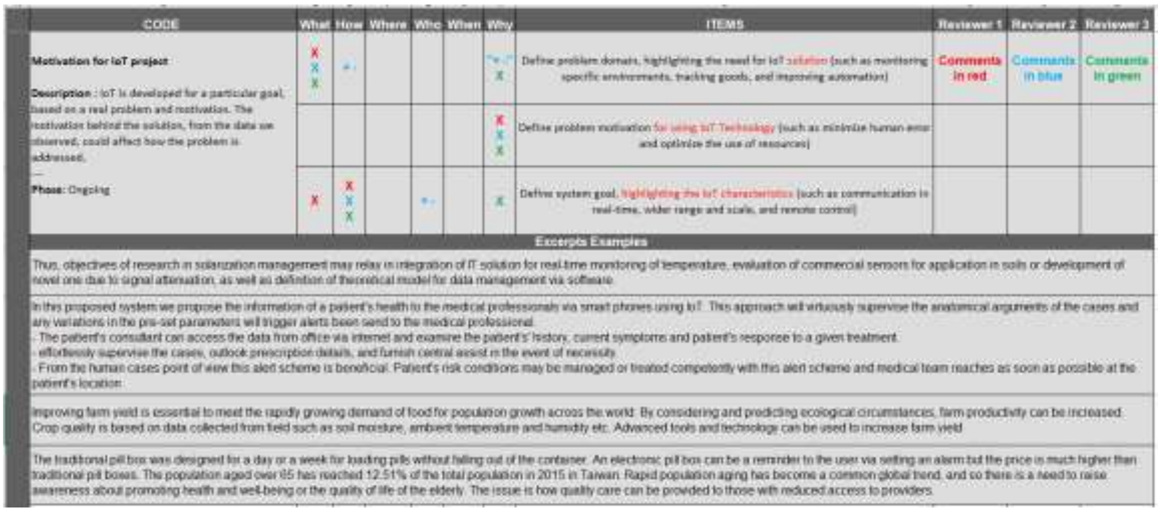
4.3.3 Review IoT Roadmap Items

This step was supported by a spreadsheet to ease the communication among the three reviewers. The organization of items followed the categories established in the peer-coding step. The categories belong to each IoT Facet, giving the Roadmap`s structure with items and categories (emerged from GT) and the IoT Facets. The items were moved to the spreadsheet with their relative excerpts. Then, all researchers revised the item proposed by associating it with the 5W1H perspectives (each marked with X in Figure 22).

The review procedure for the proposed items was (a) to read the code and description, (b) read the proposed items related to the code; (c) then observe whether the proposed item covered the associated excerpts below; (d) lastly, check which item covered the 5W1H questions. Each researcher reviewed the spreadsheet separately, considering the items in the order they appeared. In the end, all the items were reviewed, and we could identify where there was an agreement, partial agreement, or disagreement. The goal was to reach a consensus on the items and categories proposed, considering the excerpts they are grounded in, discussing the definitions and content and their utility in the IoT Roadmap`s context of use. For this, several meetings were held to reach a consensus among the researchers.

The proposed items provide specific items to support the project team to discuss and determine the essential aspects of specifying, designing, and implementing them on IoT software systems. The original 55 codes led to the final 86 items included in the IoT Roadmap after revision.

As the revision cycle (Figure 16) evolves, the items are revisited. In addition, the other Facets can include new items (see, for instance, the second iteration presented in the next section). As a result, from the RR and the qualitative analysis, the first version of the IoT Roadmap has 86 items, organized in 21 categories, that can serve as recommendations to guide the development team.



CODE	What	How	Where	Who	When	Why	ITEMS	Reviewer 1	Reviewer 2	Reviewer 3
Motivation for IoT project **Description** : IoT is developed for a particular goal, based on a real problem and motivation. The motivation behind the solution, from the data we observed, could affect how the problem is addressed. — **Phase**: Ongoing	X X X					X	Define problem domain, highlighting the need for IoT solution (such as monitoring specific environments, tracking goods, and improving automation)	Comments in red	Comments in blue	Comments in green
						X X X	Define problem motivation for using IoT Technology (such as minimize human error and optimize the use of resources)			
	X	X X X				X	Define system goal, highlighting the IoT characteristics (such as communication in real-time, wider range and scale, and remote control)			

Excerpts Examples

Thus, objectives of research in solarization management may relay in integration of IT solution for real-time monitoring of temperature, evaluation of commercial sensors for application in soils or development of novel one due to signal attenuation, as well as definition of theoretical model for data management via software.

In this proposed system we propose the information of a patient's health to the medical professionals via smart phones using IoT. This approach will virtuously supervise the anatomical arguments of the cases and any variations in the pre-set parameters will trigger alerts been send to the medical professional.
- The patient's consultant can access the data from office via internet and examine the patient's' history, current symptoms and patient's response to a given treatment.
- effortlessly supervise the cases, outlook prescription details, and furnish central assist in the event of necessity.
- From the human cases point of view this alert scheme is beneficial. Patient's risk conditions may be managed or treated competently with this alert scheme and medical team reaches as soon as possible at the patient's location.

Improving farm yield is essential to meet the rapidly growing demand of food for population growth across the world. By considering and predicting ecological circumstances, farm productivity can be increased. Crop quality is based on data collected from field such as soil moisture, ambient temperature and humidity etc. Advanced tools and technology can be used to increase farm yield.

The traditional pill box was designed for a day or a week for loading pills without falling out of the container. An electronic pill box can be a reminder to the user via setting an alarm but the price is much higher than traditional pill boxes. The population aged over 65 has reached 12.51% of the total population in 2015 in Taiwan. Rapid population aging has become a common global trend, and so there is a need to raise awareness about promoting health and well-being or the quality of life of the elderly. The issue is how quality care can be provided to those with reduced access to providers.

Figure 22. Example of *Things* items in the revision spreadsheet.

The first version of the IoT Roadmap is available online[12] as evaluated in the Feasibility Study presented in Section 5.1. The *Things* part of the Roadmap focuses on the components - constituent parts of the software system. The *Thing* is a piece of equipment or a mechanism designed to serve a particular purpose or perform a special function. This part combines with other parts to form something more significant. It is related to different components such as hardware, electronic, functional, external to the software system. An example concerning what should be done regarding *Things* Facet is presented in Table 19 with the category **Define Components**, which has six items. The items are organized concerning the 5W1H questions defined in the research to keep consistency and indicate what the team can answer.

Table 19. Example of one category of IoT Roadmap for *Things* Facet.

1. DEFINE COMPONENTS Considering the goals established from the problem domain can extract the components required to achieve such a goal. After the components are identified, they all need to be defined with more accurate descriptions. Following the recommendations, it is possible to answer *What, How, Where, Who, When*, and *Why* concerning components definition.		
Phase: CD (Concept Definition)**, SD** (System Definition)		
1.1	Establish criteria for component selection (such as costs and restrictions).	CD, SD
1.2	Define components' attributes (such as power, size, and memory).	CD, SD
1.3	Identify external partners (not internal to the system but are required for the solution).	CD, SD
1.4	Describe the component's behavior (such as actuation, identification, monitoring, and sensing).	CD, SD
1.5	Establish component aims (such as reducing human intervention, tracking vehicles, connected to the problem domain).	CD, SD
1.6	Identify components for data exhibition (such as dashboard solutions and applications running in the user smartphone).	CD, SD

12 https://bit.ly/3ijhrLW

4.4 Second iteration: The Interactivity Facet

4.4.1 Peer Coding

The same procedure as in the first iteration was followed for peer-coding, performed by the same researchers. In this step, for the Interactivity Facet, 39 papers selected from the RRs were considered for the peer-coding analysis. We noticed that some codes confirmed the items previously defined in the *Things* iteration, strengthened their evidence, and maintained it in this second iteration. Other texts brought a new vision to an existing code, updated, and changed to fit a more extensive concept. Also, other codes were completely new, including new items to cover the theme of interaction different from the theme of things seen previously.

One example of what has changed is presented in Table 20. The first iteration focused on *things*, and most of the interaction was represented in the traditional Graphical User Interface (GUI). For this reason, the original item was related to the "Data exhibition." However, when we added evidence for Interactivity Facet, several different interaction methods were presented. Thus, we have Gesture and Gaze, Voice and Audio, Touch and Tactile, and Multimodal interaction methods alongside GUI. It complies with the IoT proposal to have *things* and humans communicate and cooperate to reach a goal, and the Roadmap can support this new range of interaction options. There is also an example of a new included code for Digital Environments.

In contrast with the traditional physical environment, often covered by sensors in IoT, the Interactivity view aggregates the concept of a Digital Environment. A Digital Environment integrates communications, devices, and interactions in digital form to communicate and manage the content and activities. Augmented Reality, Immersion, and Simulation are some examples of the digital environments enhanced with IoT.

The extractions confirmed our understanding of Interactivity, covering examples of Human-*Thing* and *Thing-Thing* interaction. We coded 624 excerpts into 59 codes (to maintain or change existing ones or include new ones). Table 20 presents a coding example for Interactivity.

Table 20. Coding example for Interactivity.

Excerpts	Defined Code
"The reasons for this are the seamless integration of the infrastructure into the background and the missing or invisible user interfaces. To overcome these challenges, new interaction models are required. How can one interact with tiny devices that do not provide their own user interfaces? Or how to find and access devices in an environment that are invisible to the user? (Nazari Shirehjini & Semsar, 2017)."	**Motivation** **(maintained)**
"Technology has become a necessity in our everyday lives and essential for completing activities we typically take for granted; technologies can assist us by completing set tasks or achieving desired goals with optimal affect and in the most efficient way, thereby improving our interactive experiences (Rosales *et al*., 2018)."	
"Depending on a purpose of a specific Enhanced Living Environment (ELE) system user model is adapted and, since ELE is addressing target group whose requirements change in time, this adaptation usually happens continuously (Grguric, Gil, Huljenic, Car, & Podobnik, 2016)."	**Component's temporality** **(maintained)**
"The things may be out of sync with other things. In GREat-Room, the time it takes to synchrony the things cannot be long because the application can show different information for different users that are in the same context (Andrade, Carvalho, de Araújo, Oliveira, & Maia, 2017)."	
"Employing screen and touch interactions, this version of the interface enables users to access the same information as the tangible device, but with different degrees of input precision and ambient interaction (Rittenbruch & Donovan, 2019)."	**Interaction Method** **(changed from "Data exhibition")**
"In this study, we compare three types of modalities: a tangible, a tangible-gestural, and a screen-based graphical user interface, to investigate how the benefits of the different modalities apply to lighting interaction (van de Werff, Niemantsverdriet, van Essen, & Eggen, 2017)."	
"The speech interface is designed to produce short, simple, command-oriented dialogues with the user. In the case of services that require complex or extended user input (such as creating a shopping list or entering an appointment for a reminder), the Speech User Interface (SUI) directs the user to use the Graphic User Interface (GUI) for input and hands the interaction over to the GUI (Di Nuovo *et al*., 2016)."	
"Fundamental aspects of the holographic interface: The interface is given by a human figure taken from a human original; The interface is visualized at ultra-high-definition resolution levels; An event management system supports the execution of changes in the state of the interface, in response to its interaction with the user; Events can be triggered by sensors deployed in the area of interest, responsible for detecting visitors movements and visitors reactions to the system actions (e.g., a hologram appearing in the room and giving useful information to users) (Marulli & Vallifuoco, 2017)."	**Digital Environment** **(included)**
"Public displays have the potential to reach a broad group of stakeholders and stimulate learning, particularly when they are interactive. Therefore, we investigated how people interact with 3D objects shown on public displays in the context of an urban planning scenario (Du, Degbelo, Kray, & Painho, 2018)."	
"The 3D visualization and 3D UI, acting as the central feature of the system, create a logical link between physical devices and their virtual representation on the end user's mobile devices. By so doing, the user can easily identify a device within the environment based on its position, orientation, and form and access the identified devices through the 3D interface for direct manipulation within the scene. This overcomes the problem of manual device selection. In addition, the 3D visualization provides a system image for the IoT-SE, which supports users in understanding the ambiance and things going on in it(Nazari Shirehjini & Semsar, 2017)."	

4.4.2 Propose IoT Roadmap Items

A similar first iteration procedure was followed in this step, performed by the same researcher. We once again tried to fit the codes into the existing items. If necessary, change and create new items in the IoT Roadmap. Like the codes, some items were maintained as defined in the first version; others were updated and changed. It was necessary to **include** new items enriching the interaction topic (Table 21).

Table 21. Examples of the codes and proposed items for the Interactivity iteration.

Defined Code	Proposed Roadmap Items
Motivation	Maintained
Component's temporality	Maintained
Interaction Method **Description:** IoT innovates the interactions perspectives the things can engage in Human-*Thing* and *Thing-Thing* interactions. **Interaction object (related to things):** Input devices include any component acting as a bridge for interaction between the actor and the system. Output devices: referring to the environment "devices" that act as actuators and provide results and information. **Requirements:** Grammar: a set of know rules to enable interaction. Recognition: the component to identify and process the interaction. **Phase: SD and SR | Belongs to Interactivity Facet**	Identify interaction object and method. (*WHO* and *HOW*) Define and implement an interaction method. (*WHAT* and *HOW*) Define and establish interaction grammar. (*WHAT* and *WHY*) Describe and establish interaction recognition. (*HOW* and *WHY*) Identify interaction sequence and establish expected results. (*WHO* and *WHY*)
Digital Environment **Description:** IoT innovates the interactions perspectives the *things* can engage in Human-*Thing* and *Thing-Thing* interactions. **Phase: SD and SR | Belongs to Environment Facet**	Define and establish the digital environment. (*HOW* and *WHY*)

4.4.3 Review Roadmap Items

The same three researchers performed the items revision step as the first iteration to reach a consensus on the proposed items. Again, the same spreadsheet was used to support the revision. As a result of this iteration, for the IoT Roadmap, ten items were modified, four were removed, 35 included, and the others maintained. This second version has 117 items, organized in 29 categories, that can serve as recommendations to guide the development team, as presented in Table 22. This version of the IoT Roadmap is available online[13] , and it was evaluated through an Observational Study (see Section 5.1.4.).

Two challenges presented in Section 3.2.4, Data and Things, are widely covered as they are presented as facets in the IoT Roadmap. This version of the IoT Roadmap covers part of the challenges (Architecture, Interoperability, Management, Network, Quality, Requirements, Scale, Security) throughout different facets, categories, and items. From what we recovered, the Test should be further explored and remains a challenge for IoT systems, not being covered in the current version of the IoT Roadmap. Besides, IoT can impact several aspects of modern life; the remaining challenges (Professional, Regulation, Social and Testing) require a deeper investigation from other

[13] https://bit.ly/36AjLa8

domains on societal ans technical aspects that can be included in future versions of the IoT Roadmap.

Table 22. Categories and Items for the Second Version of the IoT Roadmap.

IoT Roadmap	Categories	Items
Problem Domain	6	18
Things	5	22
Behavior	5	23
Interactivity	2	10
Connectivity	1	4
Smartness	1	5
Environment	4	11
Data	5	24
TOTAL	**29**	**117**

The example presented in Figure 23 shows the review for the Interactivity Facet and its proposed items with related excerpts. In this figure, we can see the Interactivity definition in red in the upper right. Interactivity is composed of two categories:

1. *Define involved actors* with five items. Items 1.1, 1.2, and 1.4 were proposed in the first iteration and maintained. Item 1.2 had a new reference as evidence confirming the proposition. The blue reviewer edited items 1.3 and 1.5 and confirmed all other reviewers (red and green). It was also proposed to remove the item regarding the actor's control over the system since the category of Interaction Methods covered it.
2. *Interaction methods*, with five items. It originally had only two items removed by the green reviewer since it had better coverage with the new five items. In addition, all the reviewers had edited items 2.1, 2.2, 2.3, and 2.4 to be more descriptive.

The reviewers would then read the item recommendation (for example, 2.1 Define and Implement interaction Method) and, based on the excerpts for each item on the right, assign which question it addressed (in this example, "how" and "who"). Therefore, in this example, the result should be the definition and implementation of one of the interaction methods (Gesture and Gaze, Voice and Audio, Touch and Tactile, GUI or Multimodal).

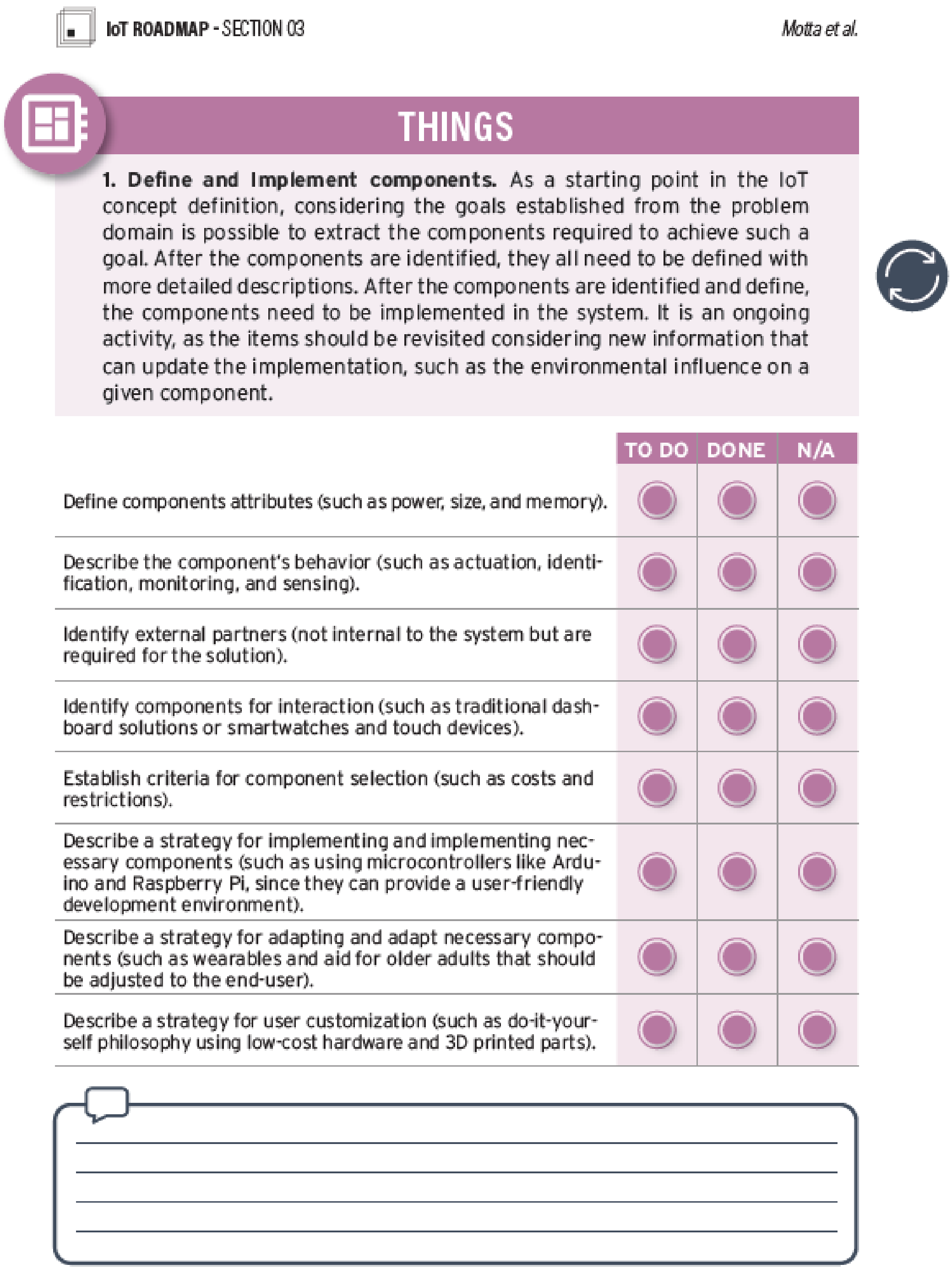
INTERACTIVITY It refers to the involvement of actors in the interaction to exchange information with things. The actors engaged with IoT applications are not limited to humans. Therefore, beyond the sociotechnical human-thing interaction, it should consider non-human actors and the thing-thing interaction.	ITEMS	What	How	Where	Who	When	Why	Interesting excerpts enriched by Interactivity RR
1. Define involved actors **Description:** Identify any human, object or thing that engages in a interaction with the system, including other systems. ---- **Phase:** CD	1.1 Define system admin and responsabilities							Maintain
	1.2 Define the users, roles and responsabilities (Consider user, business, legal, regulatory and functional issues: for example, requirements for special needs)							Automated systems for supporting accessibility usually include functions for adapting the UI to the context of use as well as to specific user characteristics stored in user profiles [2]
	1.3 Describe and Establish user control of configurations, rules and generated data (What, how, why)		X X X				X X X	For example, users can stop or postpone system triggered automatic actions, if they don't like or want them. Users also can remove a rule forever. By so doing, users can delete smart behaviors of their IoT-SE. This helps to overcome the automation challenges [13]
	1.4 Define safety procedures for human users							Maintain
	1.5 Describe and Establish the data personalization per user/role (For example, access control solutions for both the users and components where certain actions can only be associated with a specific role) (What, how, why)		X X X				X X X	Information from the robot or the ambient environment is also made available to the user via notications and warnings. The interface is complementary to speech control of the robot. [12]
	~~1.3 Define actors control over the system~~							.
2. Interaction Methods **Description:** IoT innovate the interactions perspectives the things can engage in Human-Thing (HTI) and Thing-Thing interaction (TTI). HTI is related to human users, and the things, any object that the user will interact with and that has enhanced behaviors through software. TTI refers to the interactivity and interoperability between the things themselves, in varying forms Interaction object (related to things): Input devices: including any type of component acting as bridge for interaction between actor and the system. Output devices: referring to the environment "devices" that act as actuators and provide results and information. ---- **Phase: SD-SR**	**2.1 Define and implement interaction method**		X X X		X X			(see interaction methods below)
	2.2 Define and Establish interaction grammar	X X	X X				X X	
	2.3 Identify interaction object and method (input / output) Review order				X X X			
	2.4 Define and Establish interaction recognition	X	X X				X X	
	2.5 Identify interaction sequency and expected result (such as the action sequency between user and system to gather sensor information) (who e why) there is no how		X		X X	X	X	The keywords used to identify each service are specied in the grammars and may be uttered alone or as part of a longer natural language phrase. During a service request interaction, the user may request any service. The following interaction will be determined by which service was selected. After the user has called the robot, the dialogue proceeds in a system-initiative manner. [12]
	~~2.3 Define and implement the actors interaction interfaces~~							
	~~2.4 Define controls and commands (Voice, gesture, actions...)~~							

Gesture and Gaze	Voice and Audio	Touch and Tactile	Traditional GUI	Multimodal:
Requirements: - Grammar - a set of know gestures and moviments supported by the system (ex.: Primitive gesture vocabulary: Up, Down, Left, Right, Forward, Backward, Clockwise Circle, Counterclockwise circle, Spiral to the left, Spiral to the right [1]). - Recognition - the component to identify and process what gesture or moviment the user is doing (related to smartness) (ex.: Dynamic Time Warping algorithm [1]) - Input / output - (ex.: Movements are acquired from camera streams by using computer vision techniques and coded into Labanotation movement representation models. Hence, the engine aims at providing detailed descriptions on performed movements for further documentation, analysis and processing. [3]	Requirements: - Grammar - a set of know keywords or dialog supported by the system (ex.: The control method is based on a "subject-verb" grammar, in which the subject is the object that triggers the action and the verb corresponds to the action itself (e.g. TV – switch on) [1]) - Recognition - the component to identify what command or dialog the user performing (ex.: The speech recognition is done out-of-the-box, i.e. there was no training session. Users begin verbal interaction with the robot by calling the robot by name using their wearable microphone. The robot's name is dened as a wake-up word which must be recognised before a service request interaction is initiated by the speech interface. [12]) - Input / Output - (ex.: Acoustic: Through their integrated microphones, mobile devices can be used to add acoustic input, such as audio communication, to the target objects. Using speech and audio recognition, context sensing and voice commands could also be supported. [22])	Types: Kinesthetic devices display forces or motions through interfaces. Tactile haptic devices stimulate the skin in order to simulate objects' texture. Requirements: - Grammar - a set of know actions by the system (ex.: NumPad The NumPad gesture family simulates the layout of a number pad, which provides 10 distinct tap locations on the back of the hand and one tap location to the left side of the watch. The other is to undo the last gesture, such that the user can revise their input. [20]) - Recognition - the component to identify what action the user performing (ex.: To classify a gesture, we need to first classify the user's motion state (using something like Google's Activity Recognition service) and choose the appropriate classifier for that motion state [20]) - Input / Output - (ex.: By extending the input outward to the skin, the user can view the screen while interacting, similar to the indirect interaction provided by a trackpad on a laptop. [20])		Combination of different methods
12 papers	7 papers	6 papers	7 papes	11 papers

Figure 23. Example of Interactivity items in the revision spreadsheet.

4.5 The IoT Roadmap

Figure 24 and Figure 25 present an extract of the IoT Roadmap for *Things* and Interactivity Facets, respectively.



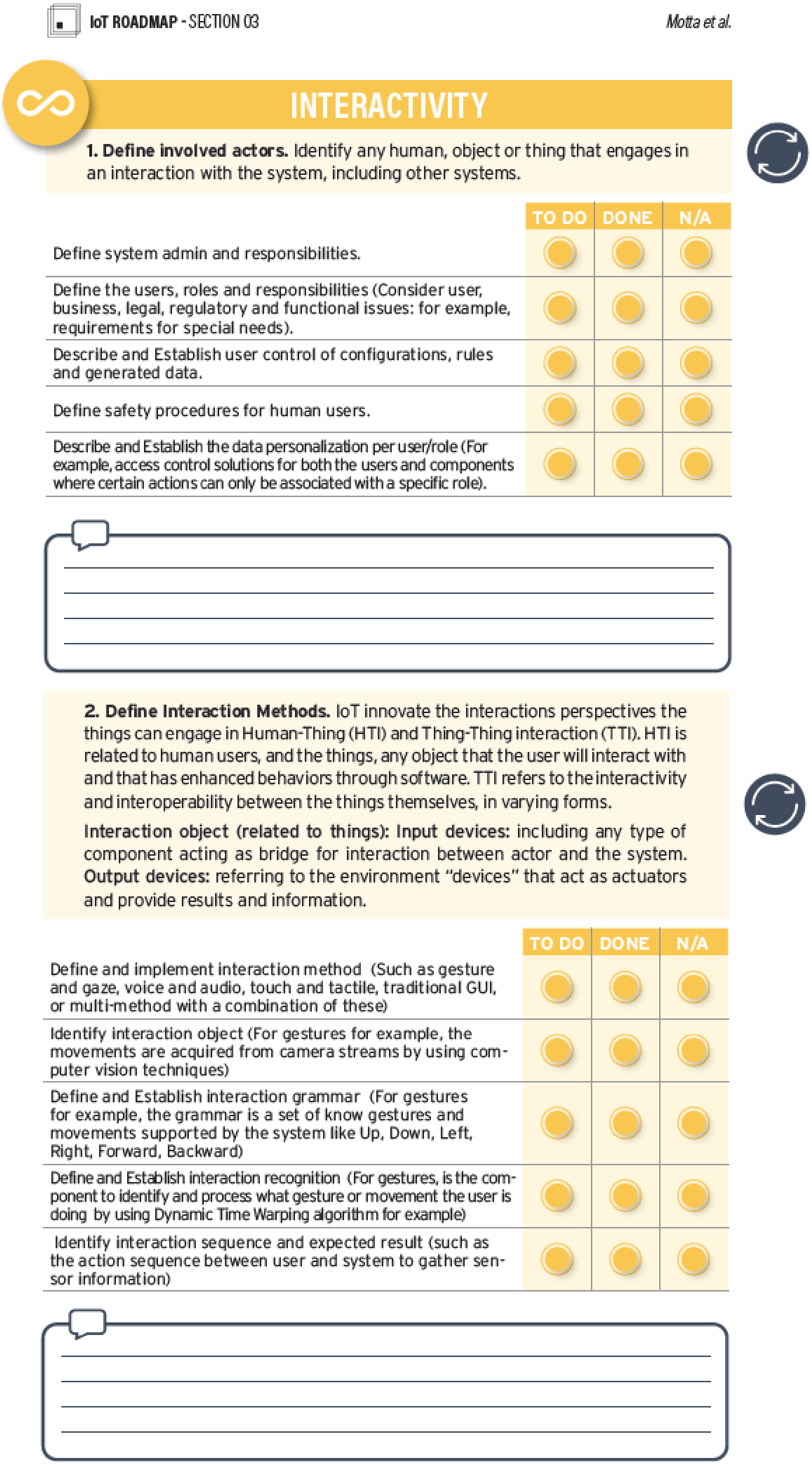
IoT ROADMAP - SECTION 03 — Motta et al.

THINGS

1. Define and Implement components. As a starting point in the IoT concept definition, considering the goals established from the problem domain is possible to extract the components required to achieve such a goal. After the components are identified, they all need to be defined with more detailed descriptions. After the components are identified and define, the components need to be implemented in the system. It is an ongoing activity, as the items should be revisited considering new information that can update the implementation, such as the environmental influence on a given component.

	TO DO	DONE	N/A
Define components attributes (such as power, size, and memory).	○	○	○
Describe the component's behavior (such as actuation, identification, monitoring, and sensing).	○	○	○
Identify external partners (not internal to the system but are required for the solution).	○	○	○
Identify components for interaction (such as traditional dashboard solutions or smartwatches and touch devices).	○	○	○
Establish criteria for component selection (such as costs and restrictions).	○	○	○
Describe a strategy for implementing and implementing necessary components (such as using microcontrollers like Arduino and Raspberry Pi, since they can provide a user-friendly development environment).	○	○	○
Describe a strategy for adapting and adapt necessary components (such as wearables and aid for older adults that should be adjusted to the end-user).	○	○	○
Describe a strategy for user customization (such as do-it-yourself philosophy using low-cost hardware and 3D printed parts).	○	○	○

Figure 24. Part of the IoT Roadmap for *Things* Facet.



IoT ROADMAP - SECTION 03 Motta et al.

INTERACTIVITY

1. Define involved actors. Identify any human, object or thing that engages in an interaction with the system, including other systems.

	TO DO	DONE	N/A
Define system admin and responsibilities.			
Define the users, roles and responsibilities (Consider user, business, legal, regulatory and functional issues: for example, requirements for special needs).			
Describe and Establish user control of configurations, rules and generated data.			
Define safety procedures for human users.			
Describe and Establish the data personalization per user/role (For example, access control solutions for both the users and components where certain actions can only be associated with a specific role).			

2. Define Interaction Methods. IoT innovate the interactions perspectives the things can engage in Human-Thing (HTI) and Thing-Thing interaction (TTI). HTI is related to human users, and the things, any object that the user will interact with and that has enhanced behaviors through software. TTI refers to the interactivity and interoperability between the things themselves, in varying forms.

Interaction object (related to things): Input devices: including any type of component acting as bridge for interaction between actor and the system. **Output devices:** referring to the environment "devices" that act as actuators and provide results and information.

	TO DO	DONE	N/A
Define and implement interaction method (Such as gesture and gaze, voice and audio, touch and tactile, traditional GUI, or multi-method with a combination of these)			
Identify interaction object (For gestures for example, the movements are acquired from camera streams by using computer vision techniques)			
Define and Establish interaction grammar (For gestures for example, the grammar is a set of know gestures and movements supported by the system like Up, Down, Left, Right, Forward, Backward)			
Define and Establish interaction recognition (For gestures, is the component to identify and process what gesture or movement the user is doing by using Dynamic Time Warping algorithm for example)			
Identify interaction sequence and expected result (such as the action sequence between user and system to gather sensor information)			

Figure 25. Part of the IoT Roadmap for Interactivity Facet.

We note that all Facets are presented with a color scheme to help with their identification. The categories are highlighted at the top with the definitions, and below are the composing items with the recommendations. Each item can be marked with "To Do," "Done," or "N/A," depending on the project definition and current phase. The icon represents cross-cutting items that can evolve and change throughout the project. Therefore, they can be revisited if necessary. Finally, at the end of each category is a text field to add comments, doubts, and directions, keeping track of the items' progress and tracing the decisions. The icon represents this function.

Figure 26 presents the process of using the IoT Roadmap. The team should **(1) read** the items recommendations to encourage discussions of the details related to each Facet. This way, the understanding of the items is aligned among all the team members. Then, they should **(2) consider** the relevant recommendations for the project context. The team can **(3) combine** the IoT Roadmap with the existing methods and technologies already in use. In turn, we hope to address the IoT particularities since they present additional characteristics and challenges for development. Finally, the team will **(4) perform** the recommendations and establish their strategy for the project. The IoT Roadmap does not aim to replace everyday activities in the development or the original methods in more traditional software projects but to recall potential elements that should be considered. Thus, the goal is to minimize the project uncertainty, supported by applying this evidence-based IoT Roadmap. All stakeholders can use it as a guide to support discussions and decision-making for directions to develop an action plan.

A PDF instrument[14] materializes the IoT Roadmap. The phases organize the engineering life cycle through time, going from the need for an IoT product (concept definition) to the product's construction (system realization). The IoT Facets are intertwined to achieve such a solution. Therefore, the phases are multi-faceted to address the IoT requirements in a multidisciplinary fashion with the **Facets**. Each Facet comprises various **items** representing activities, definitions, and recommendations for the project team to achieve the desired solution. Each item can be marked as **Done** - if it is already completed, **To Do** - if it is an activity for the subsequent phases, and **Not Applicable** (N/A) - if it is not in the project plan.

[14] https://bit.ly/36AjLa8

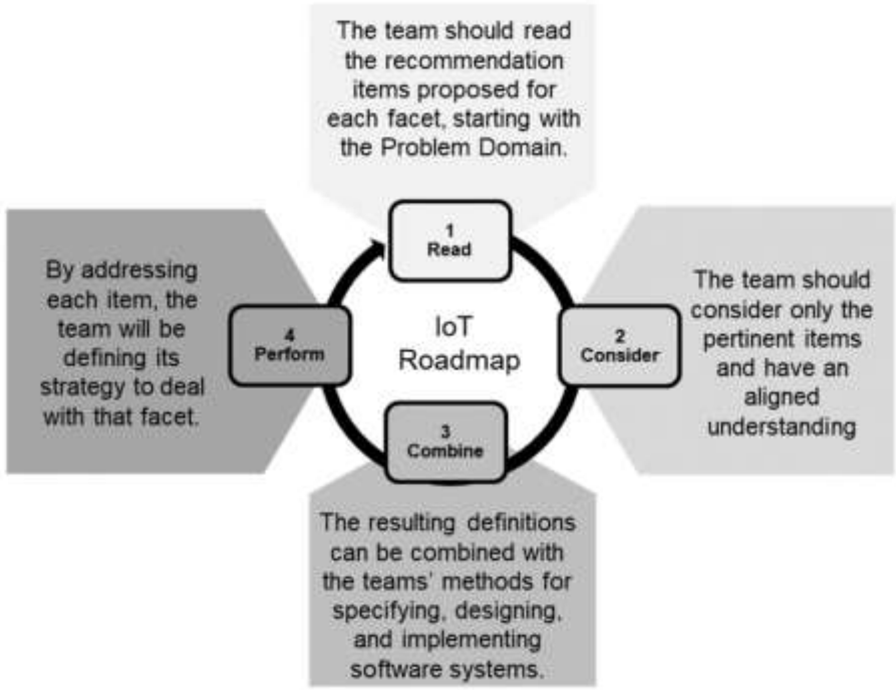


Figure 26. Using the IoT Roadmap.

4.6 Chapter Considerations

In this chapter, we presented the core of this research with an evidence-based Roadmap to support the engineering of IoT software systems. Based on the concepts previously discussed of IoT Facets, System Engineering Life Cycle, and the customization of the Zachman Framework in the IoT Conceptual Framework.

The main contribution of this work addresses the multidisciplinarity and the understanding of the IoT paradigm through a set of 117 items, organized into 29 categories considering IoT characteristics, challenges, involved areas, and technologies for the seven IoT Facets. This complete version of the Roadmap is available online (Motta, Oliveira, & Travassos, 2021). With the characteristics mentioned in the introduction, more experimental studies should be carried out to evidence them, but we consider that the IoT Roadmap is:

- Generic enough: The items are presented in a higher level of abstraction, considering relevant aspects of the IoT paradigm but not specific to a domain or problem.
- Flexible enough: With the protocols proposed and process proposed, new facets can be added and the iterative development can lead to maintain,

change or include items in the IoT Roadmap. This way it can be extended and evolved so that it continues to represent IoT contemporaneity.

- Adaptable enough: The IoT Roadmap has been evaluated regarding its feasibility and applicability indicating that it can be instantiated concretely in different applications in the IoT paradigm.

As a recap of all the IoT Roadmap features, we describe it considering the 14 criteria used for IoT Methods established by (Görkem *et al*., 2017), as exemplified in the Related Work (Section 2.3):

- **Method artifacts:** *What are the method artifacts in the overall process?* The IoT Roadmap is available in a single artifact, presented as an actionable PDF document that the project team can print or use digitally as a support instrument.
- **Process steps:** *What are the process steps?* The team should read the IoT Roadmap and define the recommendations applicable for the project context. Then, the team should follow the recommendations until they are *done* and evidenced in the final IoT product. This straightforward high-level process enables the IoT Roadmap to be inserted at any of the engineering phases.
- **Support for life cycle activities:** *Which life cycle activities are supported by the method?* Based on the Systems Engineering Life Cycle, the IoT Roadmap can be used in the Concept Definition, System Definition, and System Realization Phases.
- **Coverage of IoT system elements**: *Is the process related to all the IoT system elements?* It is one of the most outstanding features of the IoT Roadmap. One of the major concerns in IoT is the multidisciplinarity that we addressed in the IoT Roadmap for Problem Domain and the IoT Facets, named Things, Interactivity, Connectivity, Behavior, Smartness, Environment, and Data.
- **Design viewpoints:** *Does the method include different design viewpoints?* The IoT Roadmap is based on the IoT Conceptual framework that considers the perspectives of Business, Executive, Architect, Engineer, and User who support the definition of the problem domain in the Concept and System definition phases, as the Architect, Engineer, Technician, and User perspectives specialize in solving the problem, representing, therefore, the System Realization phase.

- **Stakeholder concern coverage:** *Does the method support the required stakeholder concerns?* The IoT Roadmap carefully addresses the Problem Domain, covering the motivation, benefits, risks, and expectations of such an IoT project.
- **Metrics:** *Does the method provide any metrics?* No formal metric was established for the IoT Roadmap. However, in the observational study, we easily applied a measure of agreement among users to projects using the IoT Roadmap.
- **Addressed discipline:** *What is the addressed engineering discipline?* It is focused on IoT Software Systems Engineering.
- **Scope:** *What is the scope of the method?* The IoT Roadmap has a general-purpose usage and can be applied and specialized for any specific domain.
- **Process paradigm:** *What is the adopted process paradigm?* The IoT Roadmap is a support method. Therefore, it is compatible with both plan-driven and agile paradigms.
- **Rigidity of the method:** *Is the method extensible?* Yes, with the research methodology proposed, it is possible to add new items and generate new versions of the IoT Roadmap.
- **Maturity of the method:** *Has the method been validated?* Yes, the IoT Roadmap is an evidence-based instrument proposed from the results of mixed experimental methods. The IoT Facets proposition has been evaluated with Practitioners Interviews. The first version of the IoT Roadmap has been evaluated in a Feasibility Study. The second version was evaluated in an Observational Study.
- **Documentation of the method:** *How well is the method documented?* All the research steps towards the IoT Roadmap are documented in this Thesis and its supporting documents and publications.
- **Tool support:** *Does the method have tool support?* Currently, the IoT Roadmap is presented in a PDF format, but computational support infrastructure is foreseen as future work.

We used the 14 criteria (Görkem *et al.*, 2017) as a self-assessment and description for the IoT Roadmap. As a result, we believe that our proposed IoT Roadmap fills some of the research gaps listed before and covers these important external aspects

With the use of the IoT Roadmap, we hope the teams can have support in understanding the project by having a list of items specified and adapted to the project context. The IoT Roadmap also supports project planning, with direction for activities in the life cycle phases. A better project understanding and planning can lead to better general results, as an indicator of how technology can contribute, as an answer to the Methodology's proposed Development Phase.

5 Evaluation Phase

This chapter describes the feasibility and observational studies according to the proposed methodology that guided the IoT Roadmap evaluation.

Disclaimer

On March 11, 2020, the World Health Organization declared COVID-19 a global pandemic. The pandemic has had an unexpected and profound impact on our daily lives, including research activities. Our efforts were directed to adapt to the changes as we tried to continue to work. In this statement, we outline the effects that COVID-19 had on the research undertaken towards the doctoral degree. This statement aims to facilitate the reader's awareness, both now and in the future, considering the public nature of the thesis and the longevity of such that the pandemic influenced the scope, direction, and presentation of the research, especially in this final phase of Evaluation. These are the activities impacted by the pandemic and the strategies used to mitigate them:

- The original feasibility study plans considered returning to the three French companies where we conducted the Structured Interviews, presented in Section 3.3.1. However, the inability to conduct face-to-face research, travel restrictions, and changes in the team of the enterprises led us to change this study for an Online Survey.
- The original observational study plan considered a case study in an IoT company in Brazil to triangulate the results from France. However, the contact company shifted their research from IoT to digital transformation due to the pandemic. This change had us perform the study in the COVID-19 university software projects instead.
- The pandemic has also let a disruption in access to labs, meeting with advisors and colleagues, presentations in seminars and events. It was mitigated by remote collaboration.

We did our best to keep with high academic standards and research quality, to provide original research with intellectual rigor.

5.1 Feasibility Study

According to the methodology followed in the thesis, the feasibility study is the first study to be carried out to evaluate a newly created technology and verify its feasibility according to the proposed objective.

The IoT Roadmap, the object of this research, was initially assessed in a Feasibility Study through an online survey, whose participants had a different level of experience and knowledge concerning Software Engineering and IoT software systems. Participants were openly invited, as this was an initial study to verify whether the use of the IoT Roadmap would be feasible.

5.1.1 Planning

In this step, the study design and protocol were prepared with all artifacts organized by the researchers. In addition, a Term of Consent was built, a form to characterize the participants, in addition to the feasibility questionnaire. The object of study is the IoT Roadmap, an evidence-based artifact to support specifying, designing, and implementing IoT software systems.

The Goal-Question-Metric paradigm (Basili, Caldeira, & Rombach, 1994) was used to organize the study and align the research question with the objectives used in the research. Therefore, the goal is

to analyze the IoT Roadmap,

with the purpose of characterizing it,

in relation to its feasibility observed through usefulness and ease of use,

from the point of view of software engineers,

in the context of IoT software system projects in the industry.

The study package[15] is available with the instruments used and the study results. The procedure was online, to be performed independently and without researchers monitoring. The feedback questionnaire was formulated using *Google Forms*. There is a Term of Consent that the participants had to agree on before proceeding. The

[15] https://bit.ly/3ijhrLW

questionnaire was divided between a section for characterizing the participant and evaluating the IoT Roadmap with 14 questions.

The feasibility was observed through usefulness and ease of use, with the questions proposed following the TAM - Technology Acceptance Model - (Wixom & Todd, 2005). This strategy relies on the participant's perception, where the **perceived usefulness** is the degree to which a person believes that using the IoT Roadmap would enhance an IoT project. Likewise, the **perceived ease of use** is how people believe using the IoT Roadmap would reduce an IoT project's effort. Table 23 presents a summary of the evaluation questionnaire.

Table 23. Summary of Feasibility Study Questionnaire.

Based on the information of all IoT Facets contained in the Roadmap and considering your most recent completed IoT project, order from most relevant (1) to least relevant (8) facet:	
For the most relevant facet, Were the proposed items applicable to the project?	Yes, no - why
For the most relevant facet, Have the proposed items been applied to the project?	
For the least relevant facet, Were the proposed items applicable to the project?	
For the least relevant facet, Have the proposed items been applied to the project?	
Regarding your perception of the ease of use of the IoT Roadmap, how do you feel about the statements below:	
It was easy to learn how to use the Roadmap.	8 points Likert-scale: Strongly Disagree to Agree Strongly
The interaction with the Roadmap was clear and understandable.	
It would be easy to gain skills in using the Roadmap.	
I find the Roadmap easy to use.	
Regarding your perception of the usefulness of the IoT Roadmap, how do you feel about the statements below:	
Using the Roadmap would improve the conception of IoT projects.	8 points Likert-scale: Strongly Disagree to Agree Strongly
Using the Roadmap would facilitate the following activities in IoT projects.	
Using the Roadmap would improve the productivity of the following activities in IoT projects.	
I find the Roadmap useful for the following activities in IoT projects.	
General Feedback	
If you wish, leave any comments or suggestions.	Open Question

5.1.2 Execution

The initial invitation was sent by email, selecting the researchers interested in IoT conveniently from the authors' contacts. Later, the invitation was extended to researchers present in local IoT workshops and events that the authors had participated in. Then the authors from the selected RRs were invited, and the call for the study was open in the authors' *LinkedIn*. The participants were oriented by e-mail on how to perform the study. First, they should use the IoT Roadmap, considering the conception phase of an IoT software system that they had worked on. Second, they consider the content concerning the latest IoT projects and use the IoT Roadmap as seen fit. Finally, the participants were invited to complete the online questionnaire to collect user feedback with the perception about their experience. The questionnaire was available from December 2020 until April 2021 and collected 15 answers. The link for the questionnaire was shared online through invitations.

5.1.3 Results

Participant's characterization. Most of the participants (ten) hold a doctoral degree, others three have a master's degree, one has undergraduate, and one has a specialization. Regarding the reported experience with Software Development, the most experienced participant reported working on more than 50 projects. The least experienced participant worked in three, being 12 projects the mean of software development experience. Regarding the reported experience with IoT development, the most experienced participant worked on more than 20 IoT projects. As the least experienced, four participants worked in only one IoT project; the mean of IoT development experience is five projects. The participants reported playing different roles in their projects, being the most common software engineer (five), researcher (four), and analyst (three), with hardware engineer, tester, and architect with one each. An overview of their background helped us understand the achieved results. More details on the participants' characterization are presented in Figure 27.

Quantitative Results. The first part of the evaluation questionnaire was about the relevance of the Facets` information and their respective items in the IoT Roadmap. With this question, we wanted to observe the pertinence of our proposal to have clear decisive relevance to IoT development.

Considering their most recent IoT project, most participants signalized that *Things*, Connectivity, and Behavior are the most relevant. Therefore, the proposed IoT Roadmap items were applicable and applied to the respective project for these facets. On the other hand, considering their most recent IoT project, Environment was the least relevant Facet on the opposite side. Therefore, the proposed IoT Roadmap items for the Environment Facets were not fully applied, and some of the justifications are "IoT project too informal and simple" (participant 5), "Time restriction" (participant 7), and "the IoT was only partly implemented" (participant 9).

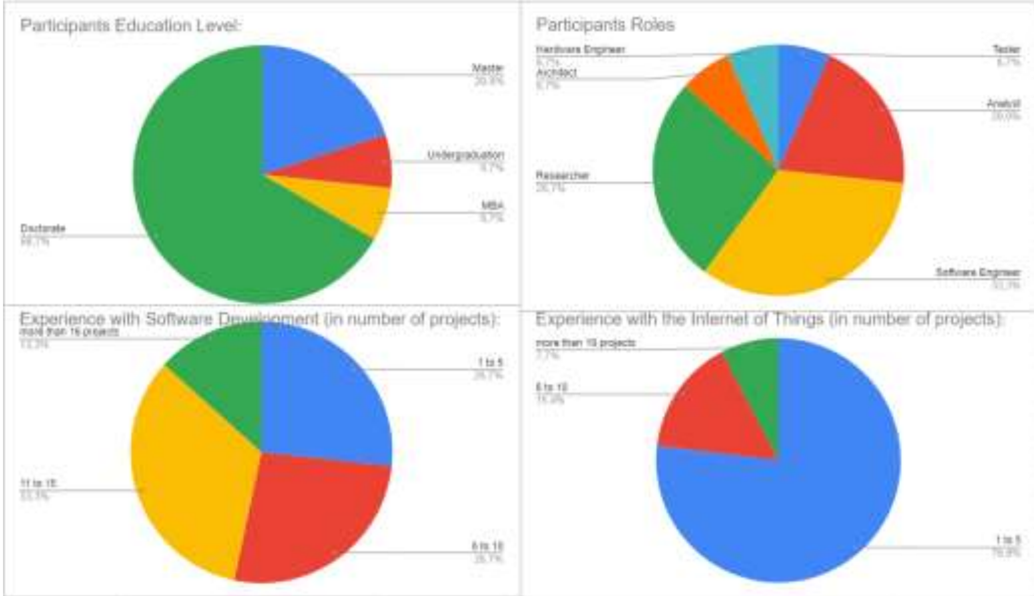


Figure 27. Participants Characterization.

The second part was about the IoT Roadmap **feasibility**, observed through ease of use and usefulness. These two factors were adapted from TAM (Wixom & Todd, 2005), considering the participants' perception of the Roadmap's contribution to an IoT project.

Regarding **ease of use,** all the participants agreed that it was easy to learn how to use the IoT Roadmap, and most (14) agreed that the interaction with it was clear and understandable. Most of them (14) signalized that it would be easy to use the IoT Roadmap because they found it easy.

Regarding **usefulness**, most of the participants (14) agree that the IoT Roadmap would improve the conception of IoT projects. When asked whether using the IoT Roadmap would facilitate the activities in IoT projects, six participants strongly agreed that it would help in the Specification activity. Six participants agree that the IoT Roadmap would help in the Design activity, and four participants partially agree that it would help in the Implementation activity. When asked if using the IoT Roadmap would improve productivity in IoT projects, five participants strongly agreed that it would improve productivity in specification activities. Six participants agree that the IoT Roadmap would improve productivity in the design activities, and three participants strongly agree that it would improve productivity in the implementation activities. The last question was about the utility of the IoT Roadmap in the activities in IoT projects. Seven participants strongly agree that it is useful in the specification activities. Five participants partially agree that the IoT Roadmap is useful in the design activities, and three strongly agree that the IoT Roadmap is useful in the implementation activities. More details for the participant's perception of the IoT Roadmap's usefulness are presented in Figure 28.

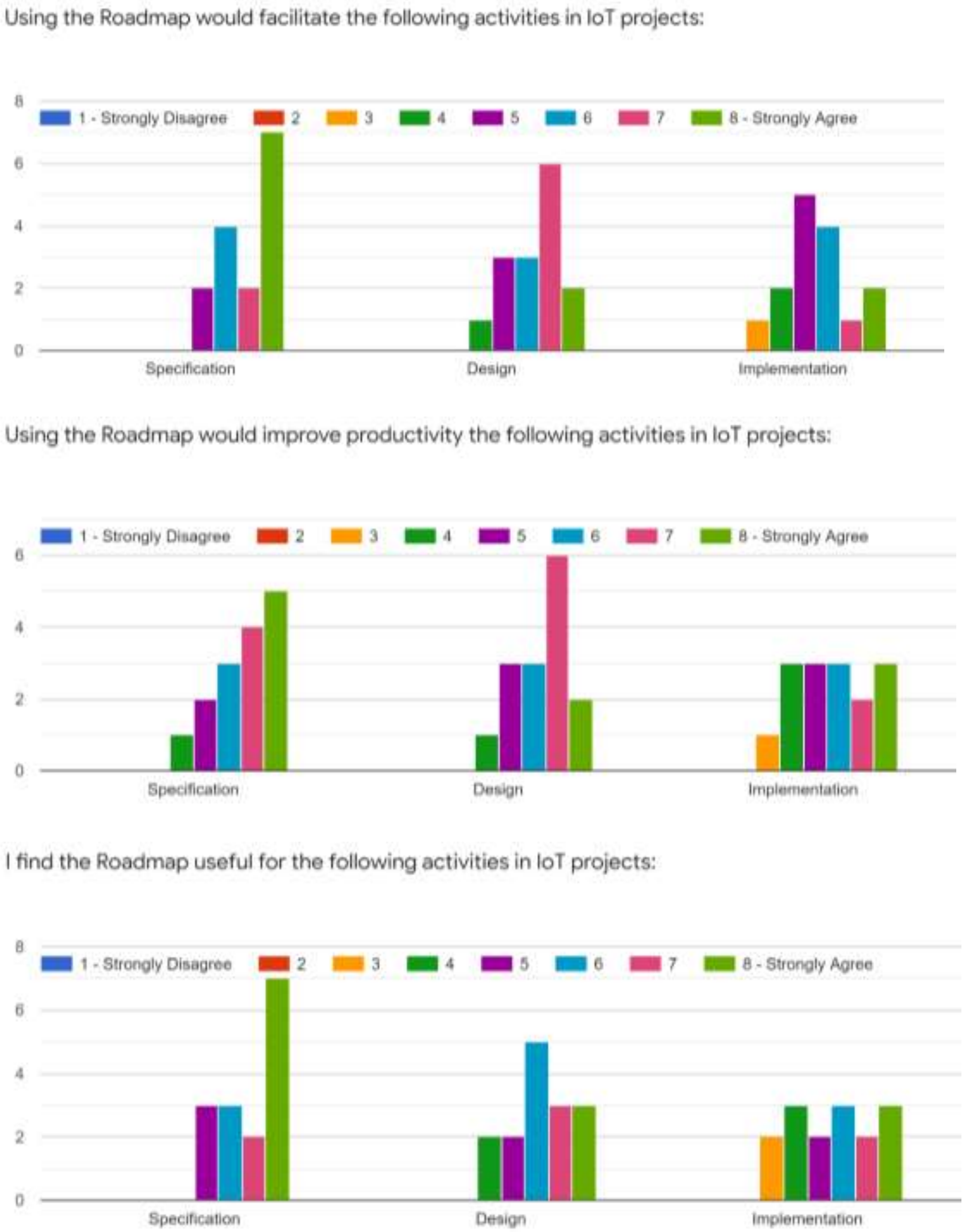


Figure 28. Participants' perception of Roadmap Usefulness.

Qualitative Results. The last part of the questionnaire was an open question, leaving the participants to add their comments and impressions freely. Five participants left comments that were considered for improving the IoT Roadmap in the subsequent iterations. The five comments are fully presented in Table 24.

Table 24. Feasibility Study Comments.

Participant	Comment
Participant 1	I found the role roadmap interesting and useful. It made me consider things that I would not have considered previously. I think it could help a lot during the development of IoT projects. But I missed an image to be used as a reference. Something that helps me to realize where I was (considering the facets and the items) and where I should go next. Perhaps something like this could make it more intuitive to follow. Even if the facets and items can be used in multiple ways, it could suggest how they should be used.
Participant 4	"The roadmap is easy to use and follow. A suggestion, perhaps, would be to put an example in all items. Another suggestion would be to divide the roadmap into specification, design, and implementation categories and place the items according to each category. Despite the roadmap being iterative, some things are specific to each category. For example, would behavior and smartness not be a subcategory of the other? Perhaps, as future work, propose/adapt a verification technique to evaluate the artifact produced by the roadmap.
Participant 6	It would be interesting to have more options for answering the questions: "Were the proposed items applicable to the project?" and "Have the proposed items been applied to the project?". It may be that not all items have been applied or correspond to the project.
Participant 8	It is difficult to answer all the questions without using them in an example. We need to use it to evaluate it correctly. In the facets, some aspects are missing regarding my needs, the smartness of the interactivity, and the management of the authority, which is different from responsibility.
Participant 15	Though I did not understand the logic of done/to do/NA, the provided roadmap is truly useful. The survey questions are a bit general.

The feedback from participants was considered for improvements in the second iteration, reported in Section 4.4, which led to the second version of the IoT Roadmap. The main contributions directly linked to participants' feedback were reviewing the examples presented in each IoT Roadmap item and including a text field to add team discussions and keep track of decisions presented at the end of each category in the IoT Roadmap.

5.1.4 Threats to Validity

Regarding the participant's invitation: Despite our efforts to enlarge the population, the small number of participants is a natural limitation of this study. A possible explanation regards the number of software engineering surveys observed in the same period. Study invitations are bombarding researchers since many studies rely on this strategy to overcome presential studies. In turn, this is leading to survey saturation with decreasing response rates and leading to unrepresentative feedback. Also, the topic requiring knowledge on IoT software engineering, the material's complexity, and the number of tasks to be performed are possible reasons for a limited audience.

The combination of empirical strategies and procedures leads to natural threats (Wohlin *et al.*, 2012), from which we present some highlights.

Internal validity: Concerning the questionnaire, one of the threats is the coverage of the questions and answers. We try to provide, whenever possible, alternative answers to the participants. However, we are aware that we do not list all questions for each Facet, even not to bring exhaustion to the participants. Therefore, it may have limited the results we obtained.

External validity: The results are limited to a small sample of participants. Therefore, it is impossible to generalize the results, so it is necessary to elaborate on new studies to expand external validity.

Construct validity: There was no control of the evaluation execution since the participants performed it independently online. Therefore, there was no mitigation for this threat considering the context of the study execution.

Conclusion validity: The purpose of the study is to observe the IoT Roadmap feasibility. Statistical testing is limited as there is only one group, and the results should be treated only as preliminary indications of feasibility. Thus, the conclusion validity is linked to the study replication in other contexts. However, the study results suggest that the IoT Roadmap can support engineering activities in IoT software systems.

5.2 Observational Study

According to the methodology followed in the thesis, the observational study is the second study to be carried out. Therefore, it improves the proposed IoT Roadmap and understands its application and usefulness in a more practical IoT scenario.

Understanding the problem domain, business rules, and translating needs into a software solution is one of the main challenges in development. It is at this early design stage that decisions and directions affect the overall solution. Therefore, the activities in this phase are essential for any solution, including the new software systems present in the IoT paradigm. In this context, the study aims to assess whether the IoT Roadmap can guide the evolution of artifacts generated in developing IoT software systems, with two development teams working in different IoT projects as participants. The IoT software projects integrate a research and development project portfolio approved by CAPES - Coordination for the Improvement of Higher Education Personnel. Public call 09/2020 - Prevention and Combat of Outbreaks, Endemics, Epidemics, and Pandemics. Proc. nº 223038.014313/2020-19, Project "Digital Technologies for Monitoring, Mapping, and Controlling Outbreaks, Endemics, Epidemics, and Pandemics. " The projects' artifacts provided all the information to describe their features.

5.2.1 Planning

In this step, the study design and protocol were prepared with all artifacts prepared by the researchers. We reused the Term of Consent of the Feasibility Study and the evolved (second version) of the IoT Roadmap.

The Goal-Question-Metric paradigm (Basili, Caldeira, & Rombach, 1994) was used to organize the study and align the research question with the objectives used in the research. Therefore, the goal is

to analyze the use of the IoT Roadmap

with the purpose of understanding

in relation to its applicability

from the point of view of junior software engineers

in the context of IoT software systems projects for COVID-19 developed at the Federal University of Rio de Janeiro.

The study package[16] is available with the instruments used and the study results. The procedure was online, performed in undergraduate classes, with the researchers available for doubts. All the participants signed the Term of Consent before proceeding. Since the study was performed with Brazilian students, part of the instruments used was originally in Portuguese.

5.2.2 Execution

Project 1 Characterization: SAFE-UFRJ. Amid the COVID-19 pandemic, the Federal University of Rio de Janeiro (UFRJ) was unable to maintain its in-person activities in all its facilities, which brought problems for the university's students and the professors and outsourced professors workers who worked there. Therefore, as part of the plan for taking on-site activities at UFRJ, this software project aims to support the monitoring of the conditions of use of UFRJ facilities given the risk levels and

[16] https://bit.ly/36AjLa8

environmental conditions (temperature, CO_2 level, and amount of people per facility) as defined in the UFRJ Biosafety Guide. In this context, the SAFE-UFRJ project aims to:

- Apply Biosafety Guide rules to UFRJ's physical facilities for safe occupation against COVID-19.
- Ensure monitoring of the risks attributed to the conditions of use and occupation of the facilities.
- Ensure preventive technical and managerial action and mitigation of risks associated with monitored conditions.

Figure 29 presents an overview of the modules and the project canvas with more details regarding the available system features.

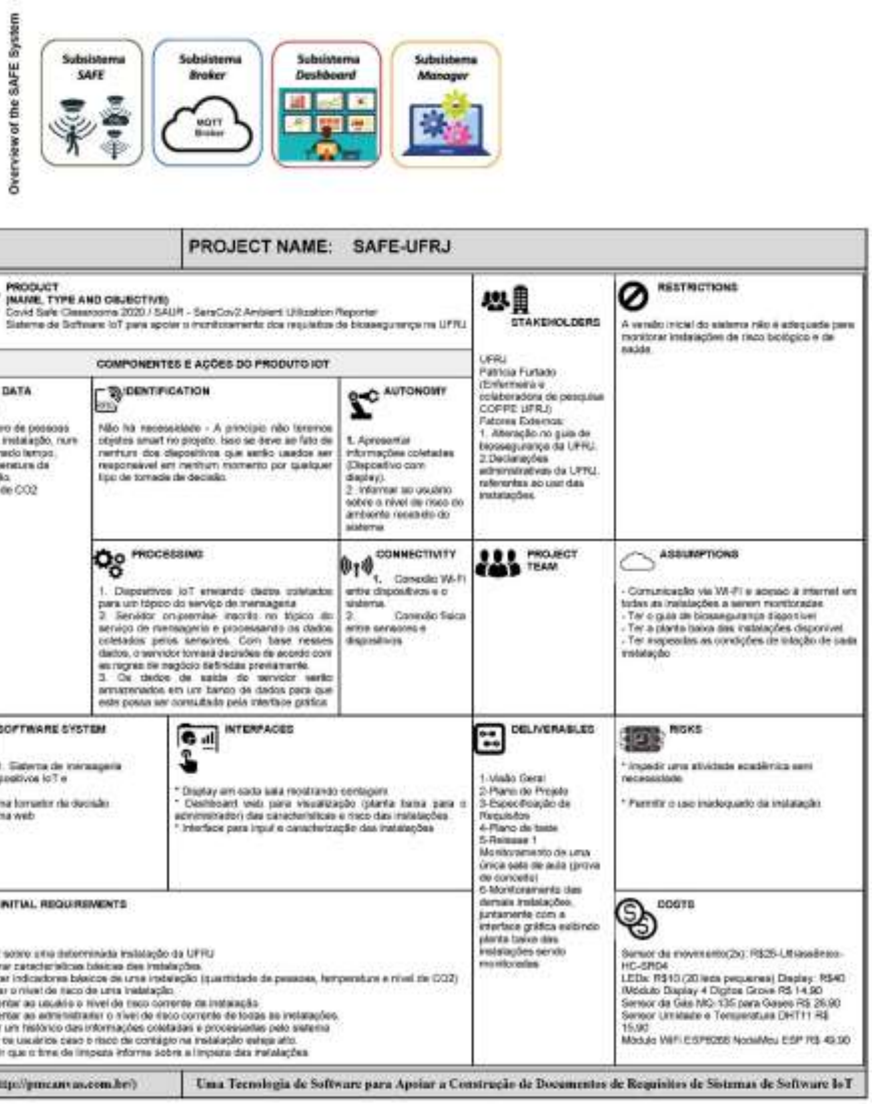


Figure 29. SAFE-UFRJ Modules Overview and Project Canvas.

The SAFE is composed of the following main modules:

- SAFE – IoT device for collecting and sending data from facilities.
- Broker – responsible for communication between the SAFE and Dashboard subsystems. This system uses the MQTT communication protocol between it and SAFE and the Dashboard.
- Dashboard – responsible for displaying data collected by the installation's SAFE subsystem. The dashboard subsystem does not have direct communication with the SAFE subsystem. For that, an intermediary is needed, in this case, the Broker subsystem, to collect data according to device configurations defined in the Manager subsystem.
- Manager – responsible for configuring and managing users and SAFE devices in each installation (room, laboratory, auditorium, secretariat, among others).

Project 2 Characterization: Oxímetro-IoT. We are currently experiencing and experiencing a pandemic that threatens the lives of everyone in society. The current threat is a virus of the SARS-CoV-2 family, known by Coronavirus (also by the acronym COVID-19). The virus has characteristics like the flu virus (influenza), with a clinical picture ranging from asymptomatic infections to severe respiratory conditions (pneumonia).

The most serious manifestation that the COVID-19 has in the victim's body is the severe respiratory condition. In general, patients affected in this way are taken to the ICU and need the help of respirators, in addition to having to be monitored 24 hours using specialized equipment. Patients with less severe symptoms stay inwards to be observed for a certain period. These patients are monitored using equipment such as oximeters and thermometers.

Given the above, this project aims to devise a solution of low-cost software systems for monitoring (percentage of oxygenation, temperature, heart rate) at home and in a ward where patients with low COVID-19 levels are monitored. For this, an adapted oximeter will be developed using the paradigm of IoT software systems. The purpose of the system is to facilitate the monitoring of people who live alone (in the case of at home) or who need to stay in a wardroom without direct supervision from a specialist.

Figure 30 presents an overview of the modules and the project canvas with more details regarding the available system features.

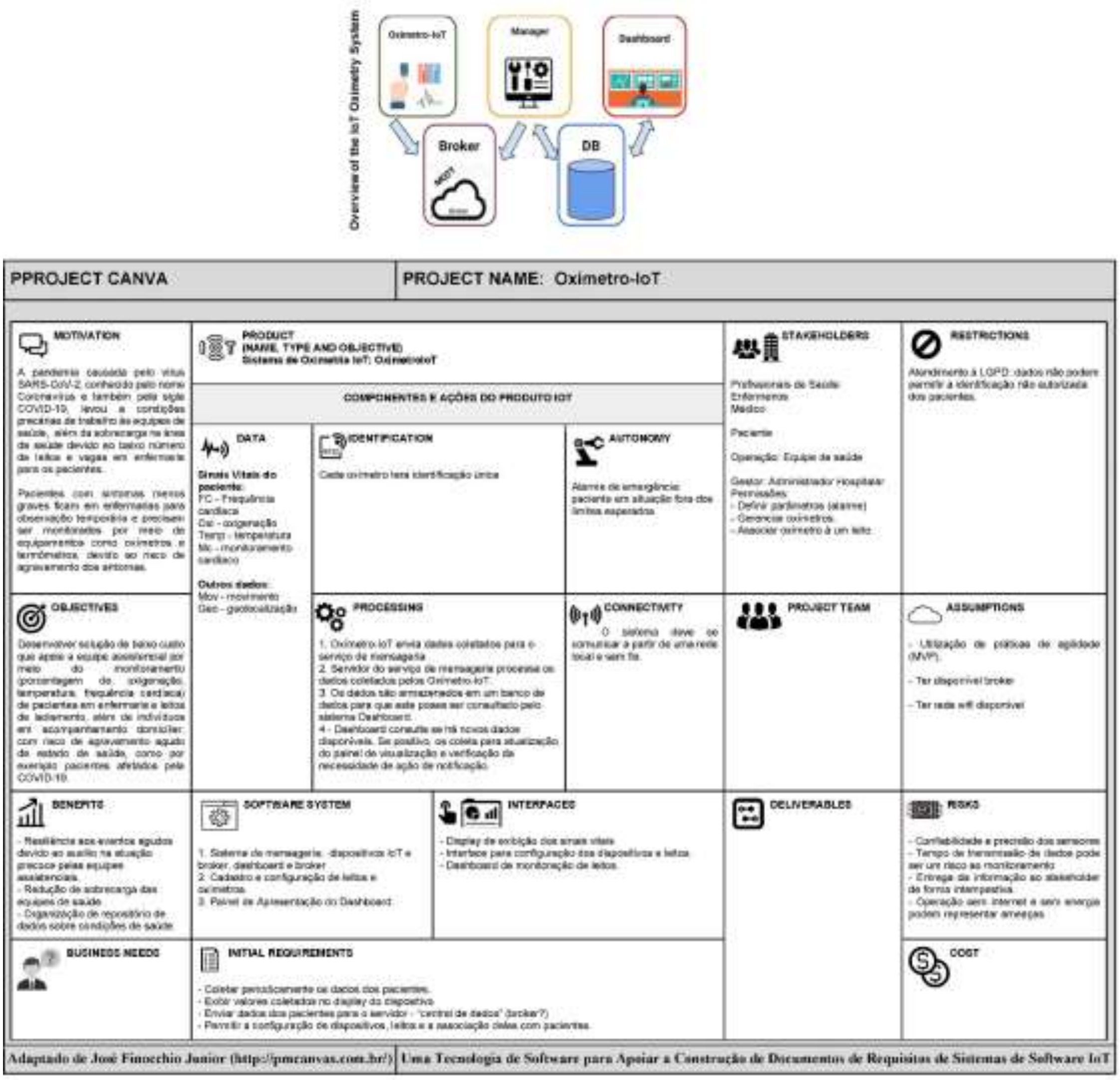


Figure 30. Oxímetro-IoT Modules Overview and Project Canvas.

Regarding the system features made available, the IoT Oximetry Software System consists of the following main modules:

- Oximeter-IoT - IoT device for collecting and sending patient data.
- Broker – responsible for communication between Oximeter and Manager subsystems. This system uses the MQTT communication protocol.
- Manager – responsible for managing Oximeter devices, for the association between such devices and patients being monitored in each context (infirmary or home), and for the persistence of data collected in a database.
- Dashboard – responsible for displaying data collected by Oximeter devices. For this, the Dashboard obtains the data stored in the database according to related settings (e.g., update frequency) defined in the Manager subsystem.

Participant’s characterization. The participants in this study were undergraduate students enrolled in the Federal University of Rio de Janeiro in Computing and Information Engineering and Electronic and Computing Engineering. The study was performed as part of the tasks of the class of Software Development of 2021/1. Although these activities took place in the classroom, both are real and ongoing projects counting with other professionals and specialists not accounted for in the study.

The participants were characterized as IoT Experience, Domain Knowledge, and Software Project Experience with Low (L), Medium (M), or High (H) experiences provided by the class professor and by the Brazilian GPA, recovered from the academic system. The class professor had contact with the students in previous classes. Therefore, he assigned the students experiences based on this background. IoT Experience means a previous contact with the IoT domain, Domain Knowledge means a previous contact with the projects observed, and Software Project means a previous contact with any software development project. Details of the characterization are presented in Table 25.

The allocation was based on the students' personal preferences and balanced by the professor among the teams. The previous class set the initial requirements and provided a proof of concept. The current group used in this study aimed to evolve existing artifacts and move towards a more mature development of the two expected solutions. Four students participated in the previous class and returned to continue the project, using the subject as an elective discipline. They have been distributed in two for each team and can be identified as having the highest experience (H) in the problem domain. We believe that the participation of these students contributes to an adequate evolution of the projects and serves as a parameter for the use of the IoT Roadmap observed in the study.

Table 25. Participants Characterization in the Observational Study.

Participant ID	Project	Course	Brazilian GPA*	IoT Experience	Domain Knowledge Experience	Software Project Experience
O1	OXIMETRO	ECI	5,8	M	H	M
O2	OXIMETRO	ECI	6,9	L	L	M
O3	OXIMETRO	ECI	7,7	L	M	H
O4	OXIMETRO	ECI	4,9	M	M	H
O5	OXIMETRO	ECI	6,4	L	M	M
O6	OXIMETRO	ECI	6,2	L	L	M
O7	OXIMETRO	ECI	6,2	H	H	H
S1	SAFE	ECI	4,8	M	H	M
S2	SAFE	ECI	8,8	M	M	M
S3	SAFE	ECI	5	L	L	M
S4	SAFE	ECI	6,4	L	L	M

S5	SAFE	ECI	6,9	M	M	M
S6	SAFE	EEC	8,4	L	L	L
S7	SAFE	EEC	6,1	H	M	H

Information	Caption		
Performed in the class of Software Development of 2021/1	ECI= Computing and Information Engineering		
All students had previous experience with software projects	EEC= Electronic and Computing Engineering		
The team's allocation was based on students' preferences	L=LOW	M=MEDIUM	H =HIGH
Class Workload: 90 h – 4th-year students			

Results

	GPA Mean	Deviation	%DV
Group Oximeter	6,30	0,87	13,84%
Group Safe	6,63	1,54	23,25%

*The Brazilian GPA represents the accumulated performance coefficient (CR), calculated at the end of each period, represented by the weighted average of the final grades obtained in each subject, weighted by the number of credits the subject confers. It is used to award the Diploma of Academic Dignity in different grades. Students who achieve, throughout the course, an accumulated performance coefficient equal to or greater than 9.5 (nine and a half) are awarded the "Summa Cum Laude" diploma. The "Magna Cum Laude" degree is awarded to students with a cumulative performance coefficient equal to or greater than 9.0 (nine), and the "Cum Laude" degree to students with a CRA equal to or greater than 8.0 (eight). The student's final passing grades in all subjects are considered.

Execution procedure. At the time of the writing of this manuscript, both projects (Oximetro-IoT and SAFE-UFRJ) were still under development. The first round of the project's development was with a team of students in the same discipline in 2020. The previous class was responsible for specifying the projects and generating a prototype. The previous class did not use the IoT Roadmap as support. The current class in 2021 aims to evolve the specification and mature the developed solution. Students from the current class are the participants in this study and were separated into two balanced teams and had the IoT Roadmap as a support tool in the conceptual phase.

The students had classes once a week, every Monday from 1 pm to 5 pm, in 15 classes of four hours each. The classes are held remotely on the Meet platform[17], the course files are shared on the Moodle [18]platform, and project management is carried out on GitHub[19] for code sharing and issues control. Thus, all students and lecturers are experienced with these technologies and have access to all of them. Students were presented with the course proposal in the first class, received project materials through online sharing, and were divided into groups by projects. In the second class, they received a tutorial on IoT development using the IoT Roadmap performed by the author

[17] https://meet.google.com/ - It is a video communication service developed by Google.

[18] https://moodle.cos.ufrj.br/login/index.php - It is the acronym for "Modular Object-Oriented Dynamic Learning Environment", a free software, to support learning, executed in a virtual environment.

[19] https://github.com/ - It is a source code and versioned files hosting platform using Git.

of this thesis. In the third class, the first sprint of the projects began, and from that point on, the students gathered in groups focused on the project. The dynamic of the class was that the first hour was a general meeting to clear up doubts, and the rest of the time, each team met on another link separated by project Assistant professors accompanied each team - post-docs in the software engineering program - acting as project managers. The professor of the discipline - the supervisor of this work and coordinator of the CAPES project - acted as the product owner for both projects. The author of the thesis did not participate in the sprints to reduce the IoT Roadmap use bias.

Goal. In each sprint, the teams should evolve the artifacts and solutions towards a final deliverable IoT product. Both teams followed the class schedule that organized the sprint's expectations. For this study, the students should use the IoT Roadmap to evolve existing artifacts and assess the current state of projects. The IoT Roadmap was used during the project's Conceptual Phase, with the duration of three sprints (three weeks), for this purpose. From the fourth sprint onwards, the teams would go to the Realization Phase (implementation) and rely on the generated artifacts until the end of the course.

5.2.3 Results

The results presented in this section refer to the first sprint of each team, where each student used the IoT Roadmap to independently assess their project considering the existing artifacts and given information. The students analyzed the IoT Roadmap items choosing among *to do*, *done*, and *not applicable* individually. At the sprint meeting, the markings of each one were discussed in a team accompanied by the project managers of each team. Based on what was assigned in the IoT Roadmap, the teams agreed to deal with the items in divergence in the next project steps. We collected the filled IoT Roadmap’s and proceeded to our observational study. As for the teams, they continued in the development of the project.

To calculate the **quantitative results**, we choose ***Fleiss' Kappa*** (Fleiss, 1971) to assess the agreement among the participants about their answer for each IoT Roadmap Facet. The ***Cronbach's Alpha*** (Cronbach, 1951) was used to have a reliability score for the IoT Roadmap.

We decided to calculate *Kappa* since the study involved multiple participants. Besides, it allows strengthening confidence in the IoT Roadmap use by these participants. Furthermore, since there is no right or wrong answers in the Roadmap regarding the item's status for the facets (*to do, done, not applicable*), we wanted to observe the teams' overall vision of the project and the next steps. Therefore, the *Kappa* results could give an overview of the agreements and disagreements among the participants of each team. We used fixed-marginal multi-rater kappa variation (Fleiss, 1971) since we are assessing the agreement between seven participants in each team (this contrasts with other *Kappa* such as *Cohen's Kappa*, which only works with two participants). Also, (Brennan & Prediger, 1981) suggest using fixed-marginal *Kappa* when the participants must assign a particular response to each item. *Fleiss' Kappa* is defined to be:

$$K = \frac{Pr(a) - Pr(e)}{1 - Pr(e)}$$

The *Kappa* results can go from -1.0 to 1.0, where -1.0 indicates total disagreement and 1.0 indicates perfect agreement. Considering the established thresholds from Fleiss's (1981) results from less than 0,40 are "poor," values from 0,40 to 0,75 are "intermediate," and values above that have "excellent" agreement. The *Kappa* was calculated for each facet for both projects as the percentage of agreement can vary depending on the number of items.

Another measure used for quantitative results was ***Cronbach's Alpha***. *Cronbach's alpha* coefficient, described by Cronbach (1951), is a widespread statistical tool in research involving test construction and application. This *Alpha* is commonly used as a reliability measure of the internal consistency of a scale for a set of two or more construct indicators (Bland & Altman, 1997). *Alpha* is estimated considering X as a matrix of type (n x k), which corresponds to the quantified responses of a questionnaire. Each row of the X matrix represents an individual, while each column represents a question. Quantified responses can be on any scale (for our study *not applicable* was 0, *to do* was 1, and *done* was 2). Thus, Cronbach's Alpha coefficient is measured according to:

$$\alpha = \frac{k}{k-1}\left[\frac{\sigma_t^2 - \sum_{i=1}^{k} \sigma_i^2}{\sigma_t^2}\right]$$

The reliability of *Cronbach's Alpha* coefficient usually varies between 0 and 1, where an acceptable value for alpha is 0,70. Calculating the coefficient requires administering only one test to provide a single confidence estimate of the entire study. Thus, we used this measure to analyze the degree of reliability of the IoT Roadmap in use.

In summary, ***Fleiss' Kappa*** gives a measure of the reliability of the participants using the Roadmap considering their agreement as the ***Cronbach's Alpha*** gives a measure of the IoT Roadmap reliability as an instrument.

We used the information that some participants left as comments in the IoT Roadmap for the qualitative results. At the end of each category, the IoT Roadmap provides a space to add any information that can be useful for discussions or evidence of the activities. Figure 31 shows an example of such comments. We extracted this information, when available, and used it to have a deeper understanding of the projects strengthening the quantitative results. Both quantitative and qualitative results are presented divided by project.

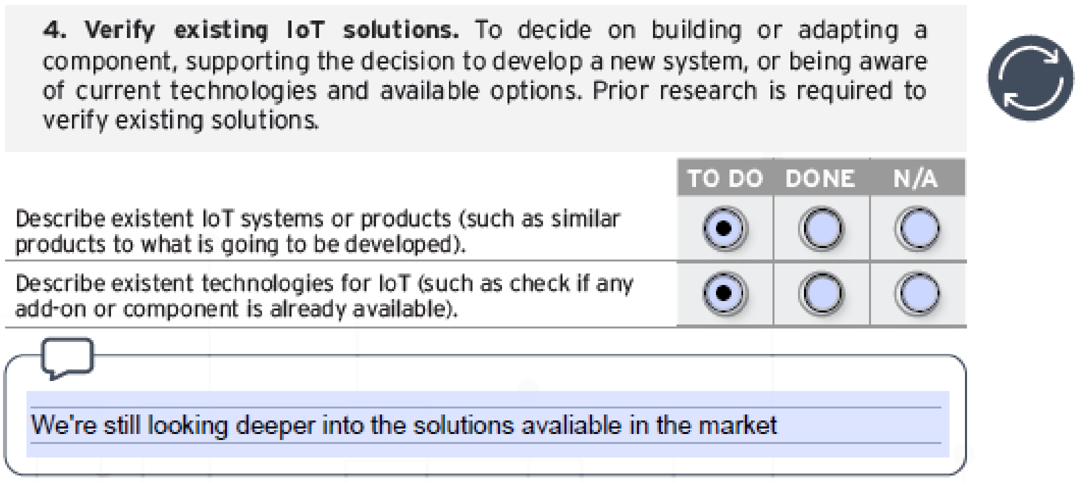


Figure 31. Example of a participants' comments in the IoT Roadmap.

Project 1 Results: SAFE-UFRJ. To calculate *Fleiss' Kappa* (Fleiss, 1971), we collected the seven participants' filled IoT Roadmaps of the SAFE project. Then we tabulated every response (*to do, done, not applicable*) for each Facet. An overview of the results is presented in Figure 32.

Figure 32. SAFE participants agreement.

The *Kappa* for Problem Domain was 0,324, suggesting an overall agreement of 69.31%. The participants agreed that most of the Problem Domain items were *done* since they had defined the Vision and Project Scope documents. However, some disagreement can be observed in the last category that recommends defining a strategy for relevant quality characteristics and attributes. The project's current documentation did not cover the quality part extensively nor offer metrics or measures, and this disagreement indicates this should evolve in the next sprints.

The *Kappa* for *Things* was 0,222, suggesting an overall agreement of 52,81%. However, we could observe a dissent on understanding what is *done* and what is *to do* regarding the components. This dissent is justified because the participants marked *done* indicated they considered those items completed since the current documentation defines the components. On the other hand, the participants that marked *to do* understood that the components are defined but not implemented yet; therefore, they should be developed in future sprints. This disagreement is related to their personal views on the Conceptual Phase and Realization Phase as defined in the IoT Roadmap. It suggests room for improvement on the IoT Roadmap itself.

The *Kappa* for Behavior was 0,588, suggesting an overall agreement of 72,26%. Once again, the Vision and Project Scope documents and other project documentations come at hand since the behaviors for the SAFE have been previously defined, leading to an agreement among the participants.

The *Kappa* for Interactivity was 0,062, suggesting an overall agreement of 42,86%. In this facet, the first category is related to define the involved actors. Many participants agreed that this was already covered in the Project Scope since SAFE will be used by UFRJ staff of public servers, administration, and education professionals. The second category is related to the interaction methods where some participants understand that this definition is not applicable, leading to a disagreement.

The *Kappa* for Connectivity was 0,383, suggesting an overall agreement of 64,29%. For Smartness was 0,489, indicating an overall agreement of 74,29%. Both Connectivity and Smartness Facets have only one category and less than five items, providing a small observation sample. However, it was a general agreement that the architecture and the decision-makers were done and that the project required no artificial intelligence.

The *Kappa* for Data was 0,215, suggesting an overall agreement of 54,17%. The data to be captured and rules are defined in the documentation (Data on temperature, CO_2, and the number of people in a given facility are collected every 2 minutes). This fact led to some participants marking most of the items as *done*. However, some participants reflect that it has not been defined how this Data will be organized; there was no indication of data aggregation mechanisms, procedures for data expiration, or removal. All this leads to disagreement in this facet, related to what is *done* for the Conceptual Phase and what is *to do* for the Realization Phase.

The *Kappa* for Environment Facet was 0,418, suggesting an overall agreement of 62,77%. Much of the disagreement of this facet is related to the category "Define the environmental impact of the solution." Again, the participants relied on the documentation, where the SAFE application environment is well defined (UFRJ's physical facilities). The dissent, in this case, was that some of the participants understood that the SAFE solution would not impact the UFRJ staff, marking the category as *not applicable*. As for the other part of the team, they marked it as *to do* since they still need to investigate and discuss.

Alongside the Kappa calculated individually for the Facets, we have the *Cronbach's Alpha* coefficient resulting in 0,945, indicating high reliability of the IoT Roadmap as an instrument. According to the participants ' views, an overview of the SAFE project status is presented in Figure 33.

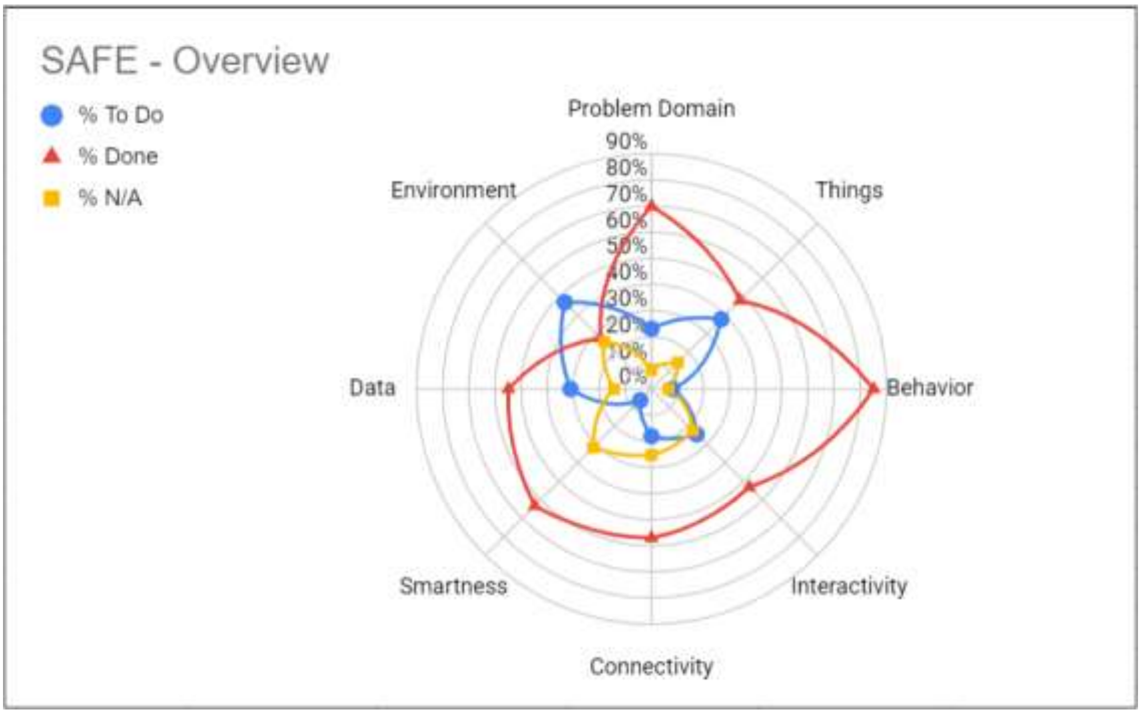


Figure 33. SAFE Project Overview under the perspective of the participants.

As for the qualitative part, combining all the SAFE team comments, we recovered a total of 51 comments on their IoT Roadmaps about the project, from which we present some examples:

“Would it be the case that we put this on an activity diagram?”

“There are no specifications yet on strategies to ensure that data is stored securely, but it is necessary that, at a minimum, the "user" table is protected. Data must be available for access throughout the working hours of the facility. The data must be stored in a MySQL database hosted on a server made available to the project.”

“A requirement that has not yet been listed is the need to have more than one device per room, as it can have more than one input/output. In addition, the security parameters of each room must be configurable, and the devices properly identified by their mac number and the room where it is located.”

“The system must maintain its performance at least 80% of its total processing capacity if there is a high demand of users accessing the system at the same time. It has not been defined how this performance will be obtained.”

“It has not been defined how to perform hardware maintenance, which parts to remove in which order.”

Participants generally commented on the benefit of using the Roadmap to generate discussions and lead to information they would not have previously thought. The IoT Roadmaps considered in the analysis were collected only from the first sprint of the project, and it can be seen from the comments that there are open issues that must be reflected and dealt with by the team. The students were recommended to use the Roadmap items through the next sprints, and that future versions of the solution should consider these changes. Nevertheless, both the comments and the agreements show that the IoT Roadmap accomplishes its goal of leading and assisting the development of an IoT software solution.

Project 2 Results: Oxímetro-IoT. To calculate *Fleiss' Kappa* (Fleiss, 1971, we collected the filled IoT Roadmaps of the Oxímetro-IoT projects’ seven participants. Then we tabulated every response (*to do, done, not applicable*) for each Facet. An overview of the results is presented in Figure 34.

The *Kappa* for Problem Domain was 0,428, suggesting an overall agreement of 76,72%. The participants agreed that most of the Problem Domain items were *done* since they had defined the Vision and Project Scope documents. The difference in understanding was mostly present in the category that recommends verifying existing IoT solutions, where part of the participants marked as *not applicable* as for the other part marked as *to do*.

The *Kappa* for *Things* was 0,207, suggesting an overall agreement of 63,43%. There was a general agreement on item recommendations for the component's attributes and identification; and implementation and customization strategy. However, similar to what was observed for the other project, there was a disagreement on what was *done* and what was *to do* regarding the components. The dissent was also related to their personal views on the Conceptual Phase and Realization Phase.

Figure 34. Oximeter-IoT participants agreement.

The *Kappa* for Behavior was 0,358, suggesting an overall agreement of 75,78%. The participants considered the Requirements List, Project Canva, and Scope documents as directives on the project behavior, leading to a high level of agreement. The differences were related to the category related to actuation. The participants agreed that actuation is not a behavior to be supported in the Oximetry solution. Part of the participants understood that and marked it as *not applicable* – since it should not cover it. The other part of the team marked as *done* – since they should not worry about it. From these differences in understanding, we can improve the IoT Roadmap description regarding the *to do, done*, and *not applicable* status.

The *Kappa* for Interactivity was 0,178, suggesting an overall agreement of 44,76%. The last disagreement can also be seen in this Facet. Part of the team understood that the category related to interaction methods does not apply to the Oximeter-IoT project; for the other part, the methods are already defined and marked as *done.* These differences in understanding lead to an impact on the team's agreement for this Facet.

The *Kappa* for Connectivity was 0,096, suggesting an overall agreement of 55,95%. The participants indicated that the components and requirements had been previously defined, therefore restraining any decision regarding Connectivity. It led to most items being marked as *done*. One participant understood that the Connectivity was yet to be realized, together with the component's implementation. The item with the most disagreement was "Establish Service Discovery mechanisms" and should be aligned in the next sprints.

The *Kappa* for Smartness was 0,549, suggesting an overall agreement of 75,24%. It was a general understanding that the Oximeter-IoT solution would not rely on intelligence or automation. Instead, the team should only consider the strategy for real-time operation – as defined in the documentation.

The *Kappa* for Data was 0,165, suggesting an overall agreement of 50,79%. The team seems to have disagreements on the categories related to data protection, data temporality, and data storage. The marks range from *to do*, *done*, and *not applicable.* The Roadmap indicates that the team should be better define this face for this project and understand better the role that Data has in the Oximetry-IoT solution.

The *Kappa* for Environment was 0,160, suggesting an overall agreement of 44,16%. Therefore, the Oximeter-IoT will be used in the patients' wrists without influence on the Environment. For this reason, most of the items were marked as *not applicable* by most of the participants.

Alongside the *Kappa* calculated individually for the Facets, we have the *Cronbach's Alpha* coefficient resulting in 0,935, indicating high reliability of the IoT Roadmap as an instrument. According to the participants ' views, an overview of the Oximeter-IoT project status is presented in Figure 35.

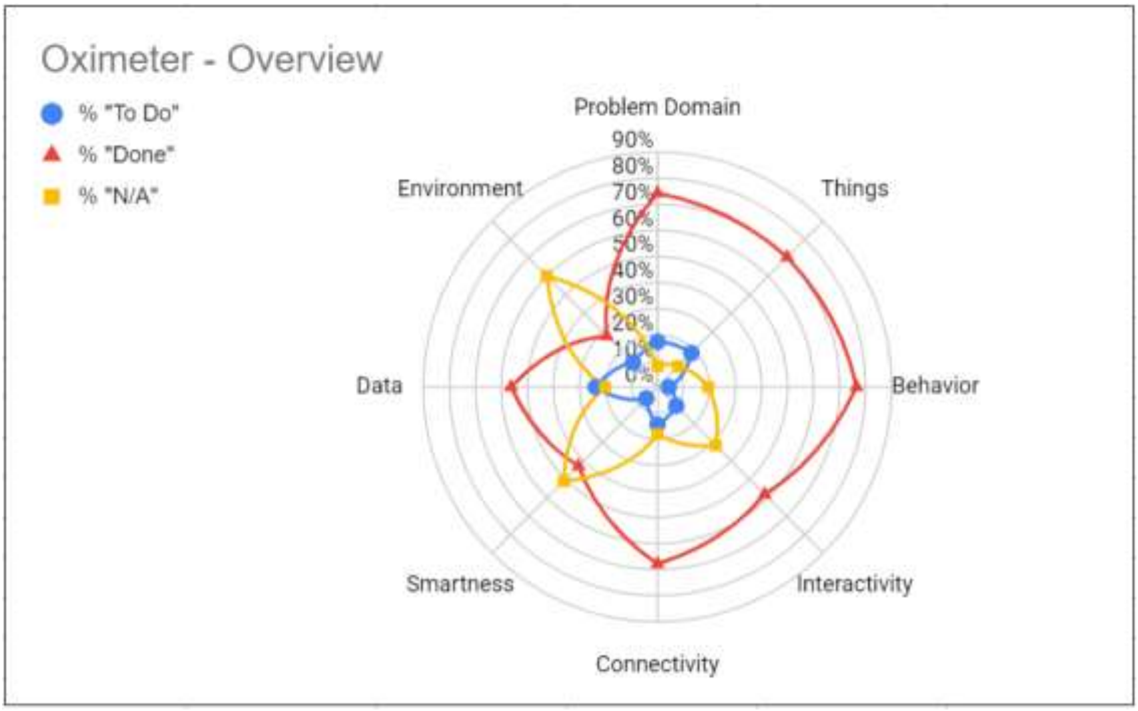


Figure 35. Oximeter-IoT Project Overview under the perspective of the participants.

As for the qualitative part, combining all the Oximeter-IoT team comments, we recovered a total of 54 comments on their IoT Roadmaps about the project, from which we present some examples:

“It is important to describe a strategy to adapt the components to different wrists.”

“We must define a document to mitigate the risks and plan the testing strategies.”

“We do not have a defined threat model.”

“It remains to create the data model.”

“The data lifecycle needs to be defined.”

The IoT Roadmaps utilized in the study were only collected from the project's first sprint, and it is clear from the comments that there are still unresolved items that the team has to reflect on and address. The team participants had also remarked how useful the Roadmap was to spark conversations and lead to details in requirements they had not considered before. Using the Roadmap helped developers create new issues and identify the *to-dos*. They will work on the discovered items in future sprints, and future versions of the solution should consider these improvements. The IoT Roadmap achieves its purpose of leading and aiding the development of an IoT software solution, as evidenced by the comments and agreements.

Lessons Learned. We contacted both project managers to collect their feedback as well. It was performed in an informal meeting. In both project managers' views, the IoT Roadmap should be performed as a starting point for a project. Its previous reading can facilitate the perception of completeness and coverage of artifacts. Furthermore, using the IoT Roadmap as an inspection technique (such as a checklist) becomes feasible and suitable when it has not been previously accessed to start the project. It was also possible to notice a change in the communication behavior between team members, which began to deal with some aspects that had been neglected in the previous versions of the artifacts, that had all been made without the Roadmap).

From the study results and feedback, no improvement needs that impacted the current format of the IoT Roadmap were identified. Therefore, only two adjustments were suggested for a future version of the IoT Roadmap: a) it could have more information on how the items should materialize and b) improve the description between 5W1H directives "Define," "Describe," "Identify," "Indicate," and "Establish" for the recommendation items.

For the first, this adjustment could help the understanding between what is expected as deliverables in Conceptual or Realization Phases; however, it is necessary a dive into the technologies and practices on **how** to materialize such items. Thus, this improvement requires a deeper investigation and can lead to exciting research.

For the second, this adjustment can clarify the item and help its understanding. For the sake of space and to be more concise, the IoT Roadmap presents a condensed version of the research steps carried out and explained in detail in the text of the thesis. In a future version, this tweak can go into the IoT Roadmap "How to Use" section and include our view of the 5W1H represented by the directives (Section 3.4):

- **Define what:**
  - By the Cambridge dictionary - to explain and describe the meaning and exact limits of something.
  - For the IoT Roadmap - to define which information is required for the understanding and management of the Facet. It begins at a high level, and

as it advances in the perspectives, the data description becomes more detailed.

- **Describe how:**
  - The Cambridge dictionary gives a written or spoken report of how something is done or of what someone or something is like.
  - For the IoT Roadmap - to describe how abstract goals are translated in solutions using software technologies (techniques, technologies, methods), defining their operationalization and materialization.
- **Locate where:**
  - By the Cambridge dictionary - to be in a particular place; to find the exact position of something.
  - For the IoT Roadmap, locate the activities related to the geographical distribution, even something external to the software system.
- **Identify who:**
  - By the Cambridge dictionary - to recognize someone or something and say or prove who or what that person or thing is.
  - For the IoT Roadmap - to identify roles involved in the Facet development, including non-human actors.
- **Indicate when:**
  - By the Cambridge dictionary - to show something, point to something, or make something clear.
  - For the IoT Roadmap - to indicate effects of time over the Facet, describing its transformations and sequences of actions.
- **Establish why**
  - The Cambridge dictionary means starting something or creating or setting something in a particular way.
  - For the IoT Roadmap: establish the motivation, goals, and strategies to implement in the Facet.

5.2.4 Threats to Validity

The combination of empirical strategies and procedures leads to natural threats (Wohlin *et al.*, 2012), from which we present some highlights.

Internal validity: The participants received a tutorial on using the IoT Roadmap, and the use was monitored during three sprints for each project. At each team meeting, the participants were asked to deliver the current version of the IoT Roadmap and asked to report their impressions and experience. However, ensuring the validity of the information remains a challenge. It is also important to emphasize that this study was carried out asynchronously, without controlling context variables, considering that the participants used the IoT Roadmap remotely.

External validity: Threats to external validity are conditions that limit our ability to generalize the results of our experiment to industrial practice (Wohlin *et al*., 2012). We can relate to the fact that the developers were undergraduate students. Although undergraduate students may not have extensive experience in industrial applications, they can still have similar skills to beginning software engineers, mitigating this threat (Carver, Jaccheri, Morasca, & Shull, 2004).

Construct validity: There was no control in constructing the project artifacts and teams' meetings during the observational study due to the short time the study was conducted. Therefore, it was impossible to guarantee that the artifacts produced are comparable in their evolution and relation to the IoT Roadmap use. However, it was applied to real IoT projects with managers and developers with knowledge of IoT software systems.

Conclusion validity: The sample size naturally limits the generalization and conclusion of the obtained results. A limitation of the Fleiss Kappa is that the kappa value depends on the marginal distributions used to calculate the level of chance agreement. A limitation of Cronbach's Alpha is that scores with a low number of items associated with them tend to have lower reliability, and sample size can also influence results. Despite the limitations, both indicators are widely used and accepted, adequate for our study's purposes.

5.3 Chapter Considerations

The IoT Roadmap application was analyzed in a more open (feasibility study) environment and controlled (observational study). Therefore, we could identify general and specific issues regarding its applicability for the proposed scenario. The multiplicity of information sources and the qualitative nature of the evaluation approach established for these studies lowered the likelihood of hypothesis testing, but it boosted our observation capacity. Due to different uncontrolled variables, such as remote execution, domain knowledge, and others, we cannot draw a direct conclusion that the IoT Roadmap helped the team to understand the problem and raise important points.

However, we can indicate the usefulness, ease of use, and applicability of the IoT Roadmap in developing IoT software systems. We are aware of potential challenges to the studies' validity. Some of them were depicted and mitigated, while others we cannot even be aware of. However, we recognize that most of these threats apply to various settings in the different experimental approaches. Even so, the results provide evidence that the proposed Roadmap is useful and makes practical sense, as proposed in the Evaluation Phase of the Methodology.

6 Conclusion

This chapter presents the final thesis considerations, highlighting the main contributions as we describe the answers to the research questions. Besides, it outlines the research limitations and possible future works that can arise from the current findings.

6.1 Final Considerations

In this Thesis, we presented the conceptualization, development, and evaluation of an evidence-based artifact named IoT Roadmap to support specifying, designing, and implementing IoT software systems. The IoT Roadmap was organized based on evidence acquired through experimental studies and evolved with the primary studies conducted in its evaluation. The IoT Roadmap encompasses the IoT multidisciplinarity involving *Things*, Interactivity, Connectivity, Behavior, Smartness, Environment, and Data facets with individually designed recommendations for each Facet. Moreover, the recommendations have a temporal composition, covering the generic phases of a system engineering project life cycle (concept definition, system definition, and system realization).

The motivation for such artifact emerged from the growing interest in the IoT and the demand for software technologies that consider this paradigm's particularities and characteristics. Additionally, we observed that the challenges revealed by primary studies and reported in the technical literature reinforce the need for software technologies to support the engineering of IoT software systems. Therefore, the IoT Roadmap can support researchers and practitioners working to ease understanding, planning, and development of IoT software systems.

The recommendations suggested by the IoT Roadmap can contribute to having a clearer direction for the project, providing directives from the problem domain to the materialized IoT solution. Researchers and practitioners can define the Facets and items that are more relevant for a specific project and a specific phase, selecting what may apply to their goals. The IoT Roadmap was organized to give visibility to what has been done with space to add comments and evidence for each item. It can be an alternative to perceive and handle needs, demands, and risks associated with engineering a solution for an IoT software system.

The IoT Roadmap defined in this Thesis provides seven Facets, directed by the problem domain, influencing the conceptualization and realization activities. The knowledge behind the IoT Roadmap shows that such projects should (1) define the problem domain highlighting why IoT is used to reach a goal, (2) consider which components will be used to achieve such goal, (3) define the identification, sensing, actuation and other sets of behaviors to be performed by such components, (4) identify all the actors involved in the solution and their respective interaction methods, (5) establish an adequate medium to have everything connected, (6) define the intelligence, smartness, and automation necessary for such goal, (7) implement the strategies to deal with capturing, analyzing and processing data; and (8) consider the influence on and from the environment the solution is settled in.

The Facets are organized into categories that contribute to the understanding and insights on the IoT paradigm. Additionally, each category is composed of items providing recommendations and actions that software organizations can use to support the engineering of IoT software systems. The current recommendations are straightforward and can be used in sequence or only the desired facets, depending on the project goal and the team skills. This organization enables a reasoning flow from project goals to output and results through discussions and decision-making. Considering the IoT particularities and since it is a recent field, its growth and evolution are expected. However, the research strategy followed can evolve with the field, keeping the IoT Roadmap up to date and relevant.

Two experimental studies were carried out to observe the feasibility and use of the IoT Roadmap. First, a feasibility study was conducted as an online survey, from which participants stated the ease of use and usefulness of the IoT Roadmap. Then, an observational study was carried out to understand how junior software engineers apply the IoT Roadmap in two real IoT software projects. The results indicate the feasibility of the IoT Roadmap since it provided adequate ease of use and usefulness and a positive practical application in two real IoT projects.

Considering the research and results, the main outputs of this Thesis are (1) the body of knowledge of IoT characteristics, challenges, and facets, (2) the set of recommendations to support IoT software systems engineering, and (3) the materialization of the research in an actionable instrument as the IoT Roadmap.

6.2 Contributions

The objective of this Thesis was to propose an evidence-based instrument that can help development teams be aware of what to consider while specifying, designing, and implementing IoT software systems. Furthermore, organizing the knowledge involved in the IoT topic allows a better understanding of the area and identifying appropriate recommendations and the existing challenges.

The problem to be addressed in this Thesis was to support the engineering of IoT software systems considering their multidisciplinarity and characteristics. Therefore, the main research question of this thesis was **What to consider while specifying, designing, and implementing IoT software systems?** We defined the IoT facets, each with its actions and recommendations organized across a set of categories and items. These recommendations should be followed according to what is defined in the problem domain evolving in the different phases of concept definition, system definition, and realization.

Based on the objectives proposed in the Thesis Introduction, the results can be broken down into the following contribution:

- Investigate the characteristics that define IoT software systems and differentiate them from conventional ones.
    - The first step in this research was to characterize IoT regarding its definition, characteristics, and applications, organizing the area and revealing its challenges and research opportunities, focusing on software engineering for the IoT paradigm. A literature review of secondary studies supported answering three research questions: What is the "Internet of Things"? Which characteristics can define an IoT domain? Which are the areas of IoT application? The structured literature review leads to 15 subsequent studies from which we recovered 34 definitions - discussed in the light of the technical evolution - 29 characteristics and several IoT application areas. The result in this investigation sets the direction for our research.
    - Rebeca Campos Motta, Valeria Silva, Guilherme Horta Travassos: **Towards a more in-depth understanding of the IoT Paradigm and its challenges.** J. Softw. Eng. Res. Dev. 7: 3 (2019)
- Investigate the challenges of engineering IoT software systems.

    - The next step counted on identifying 14 challenges of IoT applications, recovered from the technical literature, practitioner's workshops, and a Government Report, which gives an overview of the challenges faced by researchers and practitioners towards the advancement of IoT in practice.
    - Rebeca Campos Motta, Káthia Marçal de Oliveira, Guilherme Horta Travassos: **On challenges in engineering IoT software systems.** In Proceedings of the XXXII Brazilian Symposium on software engineering, pp. 42-51 (2018).
    - Rebeca Campos Motta, Káthia M. de Oliveira, Guilherme H. Travassos: **A conceptual perspective on interoperability in context-aware software systems.** Inf. Softw. Technol. 114: 231-257 (2019)
    - Rebeca Campos Motta, Káthia Marçal de Oliveira, Guilherme Horta Travassos: **On Challenges in Engineering IoT Software Systems.** J. Softw. Eng. Res. Dev. 7: 5 (2019).
- Investigate the disciplines involved in the development of IoT software systems.
    - Having the characteristics and challenges, we wanted to identify the strategies for developing IoT software systems and whether the existing software technologies within the areas (facets) related to engineering such systems are enough to support their development. Therefore, it investigated the IoT multidisciplinarity, integrating different areas to realize successful products according to their purposes. For this, we analyzed the IoT definitions identified in the literature review and organized different areas, topics, and disciplines involved in IoT - named here as IoT Facets. With this part, we promoted some side research focused on IoT requirements and characteristics.
    - Bruno Pedraça de Souza, Rebeca Campos Motta, Daniella de O. Costa, Guilherme H. Travassos: **An IoT-based Scenario Description Inspection Technique.** SBQS 2019: 20-29
    - Bruno Pedraça de Souza, Rebeca Campos Motta, Guilherme Horta Travassos: **Towards the Description and Representation of Smartness in IoT Scenarios Specification.** SBES 2019: 511-516

    - Bruno Pedraça de Souza, Rebeca Campos Motta, Guilherme Horta Travassos: **The first version of SCENARIotCHECK: A Checklist for IoT based Scenarios.** SBES 2019: 219-223
    - Rebeca Campos Motta, Káthia M. de Oliveira, Guilherme H. Travassos: **A conceptual perspective on interoperability in context-aware software systems.** Inf. Softw. Technol. 114: 231-257 (2019)
- Organize a body of knowledge regarding the engineering of IoT software systems.
    - Each facet can bring additional perspectives to the IoT project for planning and management. Therefore, acquiring evidence regarding such facets is important to provide an evidence-based framework to support project conceptualization and realization. With this activity, we answered what takes into account for each IoT Facet. We performed seven *Rapid Reviews* to analyze the Facets and characterize them in the IoT domain regarding what, how, where, when, and why is used in IoT projects. The resulting body of knowledge gives the observational perspective on which information is required to the understanding and management of the facet in a system (what); to the software technologies (techniques, technologies, methods, and solutions) defining their operationalization (how); the activities location being geographically distributed or something external to the software system (where); the roles involved to deal with the facet development (who); the effects of time over the facet, describing its transformations and states (when); and to translate the motivation, goals, and strategies going to what is implemented in the facet (why), in respect of IoT projects.
    - Rebeca Campos Motta, Káthia Marçal de Oliveira, Guilherme Travassos: **Technical Report: Rapid Reviews on Engineering of Internet of Things Software Systems.** CoRR abs/2101.05869 (2021).
    - Rebeca Campos Motta, Káthia M. de Oliveira, Guilherme Travassos: **A Preliminary Study of IoT Multidisciplinary View in the Industry.** INFORSID 2021: 143-148.

    - Evidence Briefings with the research summary for Things, Interactivity, Connectivity, Behavior, Smartness, Data, and Environment – two examples are presented in Appendix B.
- Define an instrument on top of such a body of knowledge to support the engineering of IoT software systems, considering their characteristics, challenges, and involved disciplines.
    - After acquiring all the information from previous activities, we performed qualitative analysis, and we organized the elements in the form of a roadmap to support IoT software systems. All the IoT facets are considered in the Roadmap with items to support the project team to discuss and define the aspects related to specifying, designing, and implementing them on an IoT application. The team should (1) read the recommendations, (2) consider the 5W1H, (3) establish their strategy for the project, and the IoT Roadmap can be (4) combined with the existing methods and technologies already in use. The goal is to minimize the project uncertainty by using the IoT Roadmap. All stakeholders can use it as a guide to support decision-making for directions to an action plan for the development.
    - Rebeca Campos Motta: **Towards a strategy for supporting the engineering of IoT software systems.** EICS 2019: 20:1-20:5
    - Rebeca Campos Motta, Káthia Marçal de Oliveira, Guilherme Horta Travassos: **A framework to support the engineering of internet of things software systems.** EICS 2019: 12:1-12:6
    - Rebeca Campos Motta: **An Evidence-Based Framework for Supporting the Engineering of IoT Software Systems.** ACM SIGSOFT Softw. Eng. Notes 44(3): 22-23 (2019)
    - Rebeca Campos Motta, Káthia Marçal de Oliveira, Guilherme Horta Travassos: **Towards a Roadmap for the Internet of Things Software Systems Engineering.** MEDES 2020: 111-114
    - Motta, de Oliveira, and Travassos: **An Evidence-Based Roadmap for Engineering IoT Software Systems**, submitted to Journal of Systems and Software 2021 – *under review*)
- Evaluate the proposed instrument through experimental studies to assess its feasibility and applicability.

- Two experimental studies were carried out to observe the feasibility and use of the Thesis proposal. The Feasibility study resulted in positive evidence on the ease of use and usefulness of the IoT Roadmap. The Observational study indicates the practical application in two real IoT projects. Both studies strengthened the IoT Roadmap proposal and led to feedback for its improvement in future versions.
- Rebeca Campos Motta, Káthia Marçal de Oliveira, Guilherme Travassos: **IoT Roadmap: Support for Internet of Things Software Systems Engineering.** CoRR abs/2103.04969 (2021)
- Rebeca Campos Motta, Káthia M. de Oliveira, Guilherme Travassos: **A Preliminary Study of IoT Multidisciplinary View in the Industry.** INFORSID 2021: 143-148

For development, the findings presented in this thesis can contribute to the IoT in different ways. First, the body of knowledge can support organizations to understand and characterize their problems and identify how IoT meets their needs. Besides, this information set indicates research and technologies that can help select suitable approaches for IoT projects. Also, the IoT Roadmap has recommendations to support IoT projects while specifying, designing, and implementing IoT software systems in the conceptualization and realization phases. However, to the best of our knowledge, there is no document to guide the development of IoT applications integrating the different perspectives required in this kind of technology, represented by the seven Facets.

For research, this thesis contributes to software engineering as a research area in different ways. The combination of different research methods led to more comprehensive research, resulting in an evidence-based instrument. This combination confirms that mixed methods can be a good research strategy. We used Rapid Reviews to organize a trustworthy body of knowledge. This activity presents relevant insights on how this method achieves relevant results. The thesis also presented how to use Grounded Theory coding procedures to analyze and combine knowledge from industry and academia, reinforcing theoretical results. Additionally, it evidenced research opportunities from the IoT open challenges. For example, the need for *testing* approaches to evaluate the *things* and the influence on and from the *environment* and involved *actors*.

6.3 Limitations

Despite the valuable contributions and interesting outcomes, there are a few limitations that should be mentioned:

- Despite the IoT Roadmap being organized with actions and recommendations, its scope does not cover specifying, designing, and implementing activities. However, we understand that this can lead to research and space for contributions in this direction in the IoT area.
- The IoT Roadmap considers part of the challenges (Architecture, Interoperability, Management, Network, Quality, Requirements, Scale, Security – Section 4.4.3) recovered in the research. Despite our initial effort to observe Interoperability, we did not dive into the challenges individually neither clarify how they should be addressed and evaluated in the different facets. There is much need to overcome these challenges, especially the key ones related to interoperability and security. The Roadmap is flexible enough to include more items for such challenges, but for this Thesis, we did not perform an in-depth investigation for them.
- Geographical constraints, legal regulations, protocol restrictions, and the overall conflict between the know physical world and the virtual software environment are out of the scope of this research. However, these issues come up during the research and seem to be promising areas for investigation.
- The IoT Roadmap only lists the recommendation for each Facet. The body of knowledge lists the current research in the area, providing approaches and technologies that can help address the facets in an IoT project. However, neither discuss details on applying such technologies nor evaluate what is proposed in the primary studies. For that, their original references describe how to perform them and how they were assessed. Furthermore, there is no assessment on dependency problems neither an organization of tradeoff between the IoT Roadmap items. For that, another experimental study should be performed.
- Two versions of the Roadmap have been proposed and evaluated through the research, covering two of the seven Facets (*Things* and Interactivity only). Having only two facets limit the content of the proposed Roadmap to the knowledge present in this spectrum and missing out on content from other

facets. We can achieve a more complete and robust roadmap once all the facets are covered, and more experimental studies are performed. Nevertheless, we consider the IoT Roadmap a robust instrument since the second interaction that we have included the Interactivity Facet, few new items are added even though we got more evidence for the previous ones.

- For each study performed, we listed the validity threats and what was done to mitigate them when possible. However, the threats can be a limitation of this Thesis.

6.4 Future Work

Some questions remain unanswered in the context of this Thesis, and as a result, they are candidates for further investigation. Some of our research topics are based on more assessment studies, while others emerge from knowledge evolution.

- **How general or specific are the proposed items in the IoT Roadmap?** The proposed items are meant to give a broad orientation on relevant aspects to concern while specifying, designing, and implementing IoT solutions without getting into the specifics of how they should be materialized and what roles and stakeholders are involved. It was one of the suggestions in the Observational Studies (Section 5.2.3). We performed studies to observe the feasibility and applicability of the IoT Roadmap. However, perhaps a study focused on the validity of the proposed items can be an excellent direction to answer such a question.
- **How does the IoT Roadmap work through the complete engineering lifecycle?** The IoT Roadmap and its theoretical base, the IoT Conceptual Framework, consider the generic phases of conceptual definition, system definition, and system realization. However, it was only possible to observe the conceptual definition phase in the two real projects on the Observational study performed. Therefore, observing the IoT Roadmap use during the engineering lifecycle can give insights into its operation and provide opportunities for improvement.

We also highlight some activities that can direct the future work of this research:

- **Improvements to the IoT body of knowledge and the IoT Roadmap.** We organized the results based on the literature review with qualitative analysis.

Thus, to improve the overall result, it is possible to update the reviews and expand the IoT Roadmap to cover the other facets not addressed in the last version. In addition, it is important to perform new experimental studies to evaluated the generalizability, flexibility, and adaptability of the IoT Roadmap.

- **Propose a computational support infrastructure for the IoT Roadmap.** It is an alternative to the current PDF format. It was proposed for the qualifying proposal, but it was not addressed in the Thesis because of time constraints. It is possible to include templates of artifacts, methods, and technologies specific to IoT to complement the tool and indicate what must be done to meet each item suggested in the IoT Roadmap. To have such infrastructure could contribute to the applicability and usability of the IoT Roadmap and disseminate this solution.

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Appendix A – IoT Cases from Rapid Reviews

This appendix presents a summary of the IoT implementations presented in the RR articles. The solutions are primary studies in our analysis and vary between proof of concept, user evaluation, and case studies.

Case #	Paper	Description
1	CENTENARO, Marco *et al.* Long-range communications in unlicensed bands: The rising stars in the IoT and smart city scenarios. **IEEE Wireless Communications**, v. 23, n. 5, p. 60-67, 2016.	Experimental setup to assess LoRa coverage in a system that monitors and controls the temperature and humidity of different rooms to reduce the costs related to heating, ventilation, and air conditioning.
2	ROJAS, Rafael A. *et al.* Enabling connectivity of cyber-physical production systems: a conceptual framework. **Procedia Manufacturing**, v. 11, p. 822-829, 2017.	UR3 lightweight robot designed for assembly and workbench tasks using the framework for Industrial Internet System proposed
3	ROJAS, Rafael A. *et al.* Enabling connectivity of cyber-physical production systems: a conceptual framework. **Procedia Manufacturing**, v. 11, p. 822-829, 2017.	Adept Cobra i600, designed for several industrial applications, using the framework for Industrial Internet System proposed
4	ROJAS, Rafael A. *et al.* Enabling connectivity of cyber-physical production systems: a conceptual framework. **Procedia Manufacturing**, v. 11, p. 822-829, 2017.	Adept Quattro, a four-arm Delta robot designed for high-speed industrial applications like packaging, using the framework for Industrial Internet System proposed
5	JIN, Wenquan; HONG, Yong-Geun; KIM, Do-Hyeun. Design and Implementation of a Wireless IoT Healthcare System Based on OCF IoTivity. **INTERNATIONAL JOURNAL OF GRID AND DISTRIBUTED COMPUTING**, v. 11, n. 4, p. 87-96, 2018.	Implemented a wireless IoT healthcare system that collects muscle information, temperature, and blood pressure, using OCF IoTivity for communication between wireless E-health devices and a wireless E-health server.
6	SUTAR, Shiv H.; KOUL, Rohan; SURYAVANSHI, Rajani. Integration of SmartPhone and IoT for development of smart public transportation system. In: **2016 international conference on internet of things and applications (IoTA)**. IEEE, 2016. p. 73-78.	A system using Android and IoT-based approaches efficiently provides dynamic bus tracking information to bus stops and commuters.
7	BIANCHI, Valentina *et al.* MuSA: A smart wearable sensor for active assisted living. In: **Italian Forum of Ambient Assisted Living**. Springer, Cham, 2016. p. 197-208.	The HELICOPTER project considers clinical, environmental, and wearable devices for monitoring patients and helps caregivers. For example, the wearable device MuSA provides personal information about posture, intensity, and duration of physical activity throughout the day. In addition, it enables sensor data tagging with a proximity-based identification mechanism.
8	REDDY, Vishwateja Mudiam *et al.* Internet of Things-enabled smart switch. In: **2016 Thirteenth International Conference on Wireless and Optical Communications Networks (WOCN)**. IEEE, 2016. p. 1-4.	A smart switch using a web App and cloud configuration to control its operation. The Web App provides input to Raspberry Pi, and it then controls the switch. The physical switch is connected to a mono pulse generator and transistor.
9	GAO, Xin; ZHANG, Bo; LI, Shudan. A 220-volts power switch is controlled through WiFi. In: **2016 First IEEE International Conference on Computer**	Using an Android smartphone app, a smart switch can control the switch and the watt level when connected to the WiFi.

	Communication and the Internet (ICCCI). IEEE, 2016. p. 526-529.	
10	TEW, Jonathan Ross; RAY, Lydia. ADDSMART: Address digitization and smart mailbox with RFID technology. In: **2016 IEEE 7th Annual Ubiquitous Computing, Electronics & Mobile Communication Conference (UEMCON)**. IEEE, 2016. p. 1-6.	The ADDSMART component is a smart mailbox that incorporates address digitization technology with an Arduino microcontroller board to control an RFID reader, camera, motion sensor, locking solenoid, and WiFi module. This mailbox's primary functions are notifying the homeowner when new mail arrives, acting as a driveway monitor, and notifying the homeowner.
11	NASR, Elie; KFOURY, Elie; KHOURY, David. An IoT approach to vehicle accident detection, reporting, and navigation. In: **2016 IEEE International Multidisciplinary Conference on Engineering Technology (IMCET)**. IEEE, 2016. p. 231-236.	An IoT solution registers the vehicle and the passengers and automatically notifies the authorities in case of accidents. The solution counts with near-field sensors, GPS, shock sensors, and vehicular connectivity.
12	LUVISI, Andrea; PANATTONI, Alessandra; MATERAZZI, Alberto. RFID temperature sensors for monitoring soil solarization with biodegradable films. **Computers and Electronics in Agriculture**, v. 123, p. 135-141, 2016.	A solution for soil data digitalization of data relative based on RFID with temperature sensors performances applied in sandy, loam, and clay soils with different moisture-holding capacities. The solution aims to help solarization management.
13	CHIEOCHAN, Oran; SAOKAEW, Aukit; BOONCHIENG, Ekkarat. An integrated system of applying the use of internet of things, RFID and cloud computing: A case study of the logistic management of electricity generation authority of Thailand (egat) mae mao lignite coal mining, lampang, Thailand. In: **2017 9th International Conference on Knowledge and Smart Technology (KST)**. IEEE, 2017. p. 156-161.	The research was applied to managing the logistics in a real case scenario in lignite coal mines. RFID technology, Arduino, and Cloud Computing were combined to generate a digital report related to coal transportation.
14	KHAN, Sarfraz Fayaz. Health care monitoring system in the Internet of Things (IoT) by using RFID. In: **2017 6th International Conference on Industrial Technology and Management (ICITM)**. IEEE, 2017. p. 198-204.	Research in the healthcare area, providing an IoT body sensor monitoring information with ECG sensor, Blood Pressure sensor, Temperature sensor, Motion sensor, EEG sensor, and Blood Glucose sensor.
15	SARAF, Shweta B.; GAWALI, Dhanashri H. IoT based smart irrigation monitoring and controlling system. In: **2017 2nd IEEE International Conference on Recent Trends in Electronics, Information & Communication Technology (RTEICT)**. IEEE, 2017. p. 815-819.	The proposed system helps improve the quality and quantity of their farm yield by sensing ambient temperature and humidity values, soil moisture value, and water level of the tank, all presented in a mobile-based application for the user in a smartphone.
16	PAWAR, Rohit R.; DEOSARKAR, S. B. Health condition monitoring system for distribution transformer using Internet of Things (IoT). In: **2017 International Conference on Computing Methodologies and Communication (ICCMC)**. IEEE, 2017. p. 117-122.	A mobile embedded system is a significant component of power systems to monitor and record the parameters of a distribution transformer. The monitoring is based on the current sensor, Temperature sensor, Oil level sensor, Vibration sensor, and humidity sensor. The system is designed to send alert messages whenever the sensed parameters exceed predefined limits.
17	SALAMONE, Francesco *et al.* Design, and development of a nearable wireless system to control indoor air quality and indoor lighting quality. **Sensors**, v. 17, n. 5, p. 1021, 2017.	A smart object can manage and control indoor environmental quality, built with a do-it-yourself approach using a microcontroller, an integrated temperature, and a relative humidity sensor. It allows the indoor thermal comfort quality adjustment by interacting directly with the air conditioner and ventilation.
18	ÁLVAREZ LÓPEZ, Yuri *et al.* RFID Technology for management and tracking: e-health applications. **Sensors**, v. 18, n. 8, p. 2663, 2018.	The proposal describes the use of RFID for e-Health applications, providing a tracking and managing application for hospitals' assets, such as the available beds and use of items.
19	SALES, Nelson; REMÉDIOS, Orlando; ARSENIO, Artur. Wireless sensor and actuator system for smart irrigation on the cloud. In: **2015 IEEE 2nd World Forum on Internet of things (WF-IoT)**. IEEE, 2015. p. 693-698.	It is a solution for precision agriculture related to irrigation. A cloud-based solution connects the wireless sensor network of soil moisture sensors. The system is optimized with external weather information. The actuator nodes receive a message to automatically start irrigation based on analysis of the sensor, the weather, and predefined rules.

20	PUTJAIKA, Narayut, *et al.* A control system in intelligent farming by using Arduino technology. In: **2016 Fifth ICT International Student Project Conference (ICT-ISPC)**. IEEE, 2016. p. 53-56.	The smart farm solution proposed aims to help in quality improvement and product quantity in agriculture. The solution contains a sensor system, including a temperature sensor, humidity sensor, moisture sensor, and light intensity sensor. In addition, the control system has watering and roofing functions activated based on the statistical data collected from the sensor system and the weather information to decide and control the farm environment.
21	RAY, Partha Pratim. Internet of things cloud-enabled MISSENARD index measurement for indoor occupants. **Measurement**, v. 92, p. 157-165, 2016.	The application uses DHT11 sensors connected to Arduino Uno and a connectivity module with Wi|Fi to monitor the MISSENARD Index. In addition, this application can monitor the thermal comfort of the indoor occupants contributing to their wellbeing.
22	KAMBLE, Pravin A.; VATTI, Rambabu A. Bus tracking, and monitoring using RFID. In: **2017 Fourth International Conference on Image Information Processing (ICIIP)**. IEEE, 2017. p. 1-6.	The application implemented is a low-cost Bus tracking system, with IR sensors, RFID, and Arduino board, which helps the commuters know the exact location of the bus and expected arrival time at a particular bus stop and the seat occupancy level on the smartphone.
23	HUANG, Qian; MAO, Chen. Occupancy estimation in smart building using hybrid CO2/light wireless sensor network. **Journal of Applied Sciences and Arts**, v. 1, n. 2, p. 5, 2017.	The system consists of hybrid sensors and a central control computer that measures CO2 and lights transmitted via wireless communication. In addition, the initiative is related to smart building research by providing a building occupancy estimation.
24	MARQUES, Gonçalo; ROQUE FERREIRA, Cristina; PITARMA, Rui. A system based on the internet of things for real-time particle monitoring in buildings. **International journal of environmental research and public health**, v. 15, n. 4, p. 821, 2018.	The system called iDust is addressed to real-time healthcare monitoring for environment data collection of particulate matter, considered the pollutant that affects more people. The user can monitor indoor air quality through a web dashboard for data visualization and remote notifications and plan interventions.
25	LIU, Yu *et al.* Active plant wall for green indoor climate based on cloud and Internet of Things. **IEEE Access**, v. 6, p. 33631-33644, 2018.	It proposes a remote monitoring and management solution for a plant wall system to contribute to indoor climate monitoring and control buildings. First, a set of environmental parameters are monitored to perceive the indoor climate. Then, the data are continuously fetched and sent to the cloud using WiFi. Finally, according to pre-defined settings, a local microprocessor controls the plant wall system's watering, lighting, and ventilation. Other services are available in a web-based user interface to monitor an indoor climate in real-time, check historical data from a database, and update the schedules and settings.
26	BARTOLOZZI, Marco *et al.* A smart decision support system for smart city. In: **2015 IEEE International Conference on Smart City/SocialCom/SustainCom (SmartCity)**. IEEE, 2015. p. 117-122.	A real case applied in smart city services of *Km4City,* solution in use in the Florence metropolitan area. The proposal is a Smart Decision Support System for Smart City, based on the Analytical Hierarchical Process model. The model can integrate social and data processes and gather Smart City-related data to support decision-makers, using properly defined functions and thresholds.
27	GUTIERREZ, Jose M. *et al.* Smart waste collection system based on location intelligence. **Procedia Computer Science**, v. 61, p. 120-127, 2015.	Using Geographic Information Systems (GIS) and sensors, the proposal measures the waste volume in trashcans or containers, capable of transmitting information to the Internet via a wireless link. It aims to optimize the management and strategies of waste collection logistics. The system is simulated in a realistic scenario in Copenhagen and provides a dynamic OnDemand collection based on waste level status.
28	DE PAOLA, Alessandra *et al.* Smart buildings: an AmI system for energy efficiency. In: **2015 Sustainable Internet and ICT for Sustainability (SustainIT)**. IEEE, 2015. p. 1-7.	The system aims to improve buildings' energy efficiency using a pervasive monitoring infrastructure and artificial intelligence techniques related to Smart Buildings. Using a Sensor and Actuator Network gathers information about the environment and the users and acts on the environment to satisfy users' needs. Sensory data is stored at the intermediate level and analyzed by some intelligent modules responsible for modeling the underlying environments and timely reactions if unexpected events occur. The intelligent core of the systems resides at the utmost level, where the actions

		needed to improve the energy efficiency of the whole building are defined.
29	ATABEKOV, Amir *et al.* Internet of Things-based temperature tracking system. In: **2015 IEEE 39th Annual Computer Software and Applications Conference**. IEEE, 2015. p. 493-498.	The temperature tracking system can provide device internal and external information that can help administrators or users diagnose a temperature problem, such as overheating, and remediate it before a device takes drastic measures - such as turning itself off. The device used to sense the temperature is the Raspberry Pi with a temperature sensor.
30	KORZUN, Dmitry G. *et al.* Performance evaluation of Smart-M3 applications: A SmartRoom case study. In: 2016 18th Conference of Open Innovations Association and Seminar on Information Security and Protection of Information Technology (FRUCT-ISPIT). IEEE, 2016. p. 138-144.	The IoT environment is localized in a physical room equipped with various computing (e.g., server machines, computers) and media devices (e.g., projectors, TVs, interactive boards). Devices are connected via wireless and wired local area networks. The software infrastructure of SmartRoom provides means for application operation and ensures the application is operating correctly. In addition, it supports collaborative activities such as conferences and presentations and automates the related content shared over the SmartRoom space.
31	HE, Jing; ATABEKOV, Amir; HADDAD, Hisham M. Internet-of-things based smart resource management system: a case study intelligent chair system. In: **2016 25th International Conference on Computer Communication and Networks (ICCCN)**. IEEE, 2016. p. 1-6.	The Intelligent Chair system connects chairs to the internet, so its information is automatically collected (such as whether the chair is occupied and occupancy duration) by applying sensing technologies. In addition, the identification of the students can be automatically collected using RFID technologies. Data is collected in real-time and is stored in the cloud server. Therefore, educational systems can use it, such as smart environment management, to observe time tracking management, students' attendance, and a dynamic checking system.
32	COSTA, Túlio *et al.* NuSense: A Sensor-Based Framework for Ambient Awareness applied in Game Therapy Monitoring. In: **SEKE**. 2016. p. 434-438.	
33	SAIFUZZAMAN, Mohd; MOON, Nazmun Nessa; NUR, Fernaz Narin. IoT-based street lighting and traffic management system. In: **2017 IEEE region 10 humanitarian technology conference (R10-HTC)**. IEEE, 2017. p. 121-124.	The system can make decisions for traffic control (ON/OFF/DIM) considering the light intensity. Day and night modes are identified by fixing a particular intensity value on the LDR sensor, controlling traffic lights. It has a solar cell for the power supply, and a secondary backup maintains that the system is working. It controls traffic signals automatically without human intervention, monitoring the entire system through the internet and surveillance cameras.
34	CORNO, Fulvio; DE RUSSIS, Luigi; SÁENZ, Juan Pablo. On the design of energy and user-aware study room. In: **2017 IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT-Europe)**. IEEE, 2017. p. 1-6.	A solution that obtains knowledge about its occupants' behaviors and provides them feedback when needed: in this two-way aware smart study room, the users are also aware of the building issues and can provide their feedback by reporting the issues that require assistance. The users' behavior is characterized by the data from their interaction with university services and spaces and their access to the wireless network. The users' awareness of their energy consumption is achieved by developing real-time visualizations displayed on their devices and a large screen located in the study room.
35	CHEN, Min *et al.* Smart home 2.0: Innovative smart home system powered by botanical IoT and emotion detection. **Mobile Networks and Applications**, v. 22, n. 6, p. 1159-1169, 2017.	The proposal of a greenhouse for a Smart Home uses a sensor network to collect data, including ambient temperature, humidity, soil humidity, illumination intensity, CO2, O3, O2, NO2, and others. The system monitors these data and implements automatic control of the greeneries.
36	OLIVEIRA, Edvar da L. *et al.* Smartcom: Smart consumption management architecture provides a user-friendly smart home based on metering and computational intelligence. **Journal of Microwaves, Optoelectronics and**	In the topic of Home Energy Management Systems, the proposal is a Smart Consumption system. It integrates the supervisory system of the power utility with the metering elements available to the consumer. It can also control alternative energy sources and enable the automation of domestic appliances using intelligent devices and the

	Electromagnetic Applications, v. 16, n. 3, p. 736-755, 2017.	message control of consumption based on rules or routine activities.
37	MEDINA, Bruno Eduardo; MANERA, Leandro Tiago. Retrofit of air conditioning systems through a wireless sensor and actuator network: An IoT-based application for smart buildings. In: **2017 IEEE 14th international conference on networking, sensing, and control (ICNSC)**. IEEE, 2017. p. 49-53.	An energy-efficient solution applies to new or old buildings, a control system adaptable to any air conditioner. The proposal learns the commands from the air conditioner remote control and sensors to monitor external temperature and air humidity. These values are used to calculate the heat index and establish an appropriate set-point temperature for the air conditioner. The system can use this information for automatic mode and use a central command unit composed of a calendar and a real-time clock to allow users to program desired working periods.
38	YONG, Binbin *et al.* IoT-based intelligent fitness system. **Journal of Parallel and Distributed Computing**, v. 118, p. 14-21, 2018.	The fitness system is enriched with sensors to monitor the health statuses of exercisers. When exercising, the exercise data is collected by sensors and a fitness band. Subsequently, these data are sent to the system to be analyzed. With the help of artificial intelligence technology, the system can extract useful guidance information for users' bodybuilding.
39	ESPINILLA, Macarena *et al.* The experience of developing the UJAmI Smart lab. **Ieee Access**, v. 6, p. 34631-34642, 2018.	A smart lab where the devices can be worn by the user or embedded in the lab to collect data and obtain a personalized profile of the user's physical and physiological patterns. The initial set of devices can analyze sounds, images, body motion, ambient parameters (light, temperature, humidity, and others), vital signs (blood pressure, body temperature, heart/pulse rate, body/weight/fat, blood oxygenation, ECG, and others), sleep patterns and other health parameters, daily activities, and social interactions.
40	PALACIOS, Pablo; CORDOVA, Andres. Approximation and temperature control system via an actuator and a cloud: an application based on the IoT for smart houses. In: **2018 International Conference on eDemocracy & eGovernment (ICEDEG)**. IEEE, 2018. p. 241-245.	A solution based on the IoT via a mechanical actuator ON/OFF control system within the parameters of temperature and position. The proposed system integrates the Raspberry Pi that works as a configurable computer, a cloud service, a temperature sensor, and a mobile device with a GPS-based application for monitoring and managing the energy control system from anywhere at any time.
41	CICIRELLI, Franco *et al.* Metamodeling of smart environments: from design to implementation. **Advanced Engineering Informatics**, v. 33, p. 274-284, 2017.	It presents a smart office with the functions of room monitoring, desk monitoring, and control. The environmental information is collected in the room through sensors, recovering humidity, temperature, presence, light, and sound. In addition, each desk in the office is monitored for power consumption and has a smart switch for power control. The switch can be controlled by the users or automatically switched off when recognizing energy waste.
42	SHIREHJINI, Ali Asghar Nazari; SEMSAR, Azin. Human interaction with IoT-based smart environments. **Multimedia Tools and Applications**, v. 76, n. 11, p. 13343-13365, 2017.	A 3D user interface enables the visualization of the smart environment and its devices and directly correlates with the physical objects and their 3D representations. The status and states can then be visualized within the interface easing the interaction with the devices.
43	WHITTINGTON, Paul; DOGAN, Huseyin. A SmartDisability Framework: enhancing user interaction. 2016.	An Automated Transport and Retrieval System uses robotics and Light Detection, Ranging, and sensors to create means for a wheelchair user to autonomously dock a powerchair onto a platform lift without needing an assistant. It can be operated by touch, joystick, or head tracking interaction methods, significantly improving the system's usability.
44	VACHER, Michel *et al.* Evaluation of a context-aware voice interface for Ambient Assisted Living: qualitative user study vs. quantitative system evaluation. **ACM Transactions on Accessible Computing (TACCESS)**, v. 7, n. 2, p. 1-36, 2015.	The SWEET-HOME system is composed of an audio analysis system and an Intelligent Controller. It is linked with a home automation network composed of data sensors and actuators for switches, lights, blinds, and multimedia control. It has several microphones per room, so voice command is made possible from anywhere in the house in a hands-free way. Finally, the system

		contains a dedicated communication system that quickly contacts relatives, physicians, or caregivers.
45	OAKLEY, Ian *et al.* Beats: Tapping gestures for smartwatches. In: **Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems**. 2015. p. 1237-1246.	Investigation of wearable devices, such as a smartwatch, enriched with rapid sequences of screen touches and releases made by the index and middle fingers of a user's hand as input available via the touch screens of tiny devices.
46	SHEPPARD, David; FELKER, Nick; SCHMALZEL, John. Development of Voice Commands in Digital Signage for Improved Indoor Navigation Using Google Assistant SDK. In: **2019 IEEE Sensors Applications Symposium (SAS)**. IEEE, 2019. p. 1-5.	A digital sign can vocally interact with the user, allowing the sign to address a user's specific needs. The Smart Sign is a small device running the Android operating system that uses the power of the Google Assistant to handle spoken queries. The device has a touchscreen and uses a small microphone to accept verbal input. It can serve as a navigation aide like traditional signage. For example, the user can ask for directions to a room, and the Smart Sign will provide them with a map of the building with a route plotted on the map leading from their current location to their requested destination.
47	ZABALZA, Jaime *et al.* Smart sensing and adaptive reasoning for enabling industrial robots with interactive human-robot capabilities in dynamic environments—A case study. **Sensors**, v. 19, n. 6, p. 1354, 2019.	An integrated system based on a robotic manipulator is proposed, where the robot can perform operations in real-time under dynamic conditions. Online planning is made to enable a robotic end effector to perform pick-and-place tasks within a given workspace. Such online planning involves moving the robot to a start (pick) position, picking a given object, transporting it to a given goal (place) position, and releasing it.
48	RITTENBRUCH, Markus; DONOVAN, Jared. Direct end-user interaction with and through IoT devices. In: **Social Internet of Things**. Springer, Cham, 2019. p. 143-165.	MiniOrb, a system that combines a sensor platform with an interaction device. It reflects the environmental output with a tangible input approach to allow users to share their subjective perceptions of their office environments' comfort, particularly temperature, lighting, and noise.
49	VAN HOVE, Stephanie *et al.* Human-Computer Interaction to Human-Computer-Context Interaction: Towards a conceptual framework for conducting user studies for shifting interfaces. In: **International Conference of Design, User Experience, and Usability**. Springer, Cham, 2018. p. 277-293.	The smart shopping cart guides the customers through the supermarket based on the position of the shopping cart in the supermarket and the customer's shopping list. In addition, it serves as an inspiration tool with contextual promotions, which results in a more efficient and enjoyable shopping experience.
50	ALANWAR, Amr *et al.* Selecon: Scalable IoT device selection and control using hand gestures. In: **Proceedings of the Second International Conference on Internet-of-Things Design and Implementation**. 2017. p. 47-58.	SeleCon is a gesture-based system that aims to provide a natural selection and control method for users to interact with smart IoT devices. A user using the wearable device can point his arm towards the target device to select it. The SeleCon can identify which IoT device is selected by monitoring the direction of the wrist movement. The user then draws a gesture in the air to give a command to the selected device.
51	VAN DE WERFF, Thomas *et al.* Evaluating interface characteristics for shared lighting systems in the office environment. In: **Proceedings of the 2017 Conference on Designing Interactive Systems**. 2017. p. 209-220.	The Floorplan is a graphical user interface installed on a personal device and provides a space map, indicating the room's layout. To start the interaction, users can select the interfaces' devices and control their functions, such as activating sliders to adjust intensity and temperature within the selected area.
52	CARVALHO, Rainara Maia; DE CASTRO ANDRADE, Rossana Maria; DE OLIVEIRA, Káthia Marçal. AQUArIUM-A suite of software measures for HCI quality evaluation of ubiquitous mobile applications. **Journal of Systems and Software**, v. 136, p. 101-136, 2018.	The GREatPrint is a solution that supports documents by finding the nearest printer to the user. The application works as follows: after selecting a file, the user clicks on the print button of the given document. Then, the application collects Wi-Fi networks closer to the mobile device by scanning the network with higher signal intensity. According to this information, the system checks which printer is in the range of that network. Thus, the application sends the document to be printed and informs the user of the print destination.
53	CARVALHO, Rainara Maia; DE CASTRO ANDRADE, Rossana Maria; DE OLIVEIRA, Káthia Marçal. AQUArIUM-A suite of software measures for HCI quality evaluation of ubiquitous mobile	The GREatMute is a service that runs in the background of the user's mobile phone. It monitors Google Calendar for events during which the user cannot receive a call, e.g., meeting, class, or cinema. The application places the user's mobile device in

	applications. **Journal of Systems and Software**, v. 136, p. 101-136, 2018.	silent mode by locating such events, so the user is not disturbed by these events.
54	CARVALHO, Rainara Maia; DE CASTRO ANDRADE, Rossana Maria; DE OLIVEIRA, Káthia Marçal. AQUArIUM-A suite of software measures for HCI quality evaluation of ubiquitous mobile applications. **Journal of Systems and Software**, v. 136, p. 101-136, 2018.	The GREatTour is a guide for visiting the GREat Lab. It provides information about the environments of the laboratory that the user is visiting. The application works as follows: the user scans the QRCode found on the environment door to request the location information. Then, a map of the lab is displayed, highlighting the environment where the user is. Finally, the user can view media options (texts, photos, and videos) for the selected environment.
55	SHIREHJINI, Ali Asghar Nazari; SEMSAR, Azin. Human interaction with IoT-based smart environments. **Multimedia Tools and Applications**, v. 76, n. 11, p. 13343-13365, 2017.	A personal assistant system for smart environmental control. AmIS integrates the virtual media repository and the user's physical environment into a unified digital personal environment. AmIS uses an automatically created 3D visualization model of the environment. Entering a room, it discovers the infrastructure and available devices and builds the integrated user interface. Changes to the environment, new devices, or re-positioned devices can be identified and update in the UI. Henceforth, the user can access identified devices through the 3D interface and directly manipulate them. Thus, it eases the interaction and provides access to all ubiquitous data distributed among several devices.

Appendix B – Examples of Evidence Briefings from Rapid Reviews

This appendix presents a summary of the Rapid Reviews results in the format of Evidence Briefings.

The information acquired in the Rapid Reviews executed was aggregated and summarized to be presented in the format of evidence briefings (EBs), as discussed by (Cartaxo *et al.* 2016).

EBs are a medium to transfer knowledge from researchers to the industry. They are motivated by software practitioners who tend not to use research papers as a source of new knowledge (Cartaxo *et al.*, 2016). Thus, the idea is to present a more concise instrument, which summarizes a paper's ideas and main findings to a broader audience. Some advantages presented by the authors is that this medium increases the research visibility and is considered an excellent way to share research findings since it promotes "clear and understandable information" (Cartaxo *et al.* 2016), also it has been used by other works in the area (Silva *et al.* 2018).

The original template, available to use under an open-source license (CC-BY) in the link http://cin.ufpe.br/eseg/briefings, was adapted to our context, with the main elements, as described below and represented in Figure 36. The title of the briefing (1), sometimes simplifying the paper title to make the briefing more appealing to the practitioners;

- The logos and identification of the research group and the university (2).
- A summary (3) to present the briefing's objective, motivation, facet definition, and context.
- Informative box (4), separated from the main text, highlights the target audience and the purpose of the briefing and answers the research questions.
- The additional information (5), extracted from the original empirical study.
- The references to the original empirical study (6).

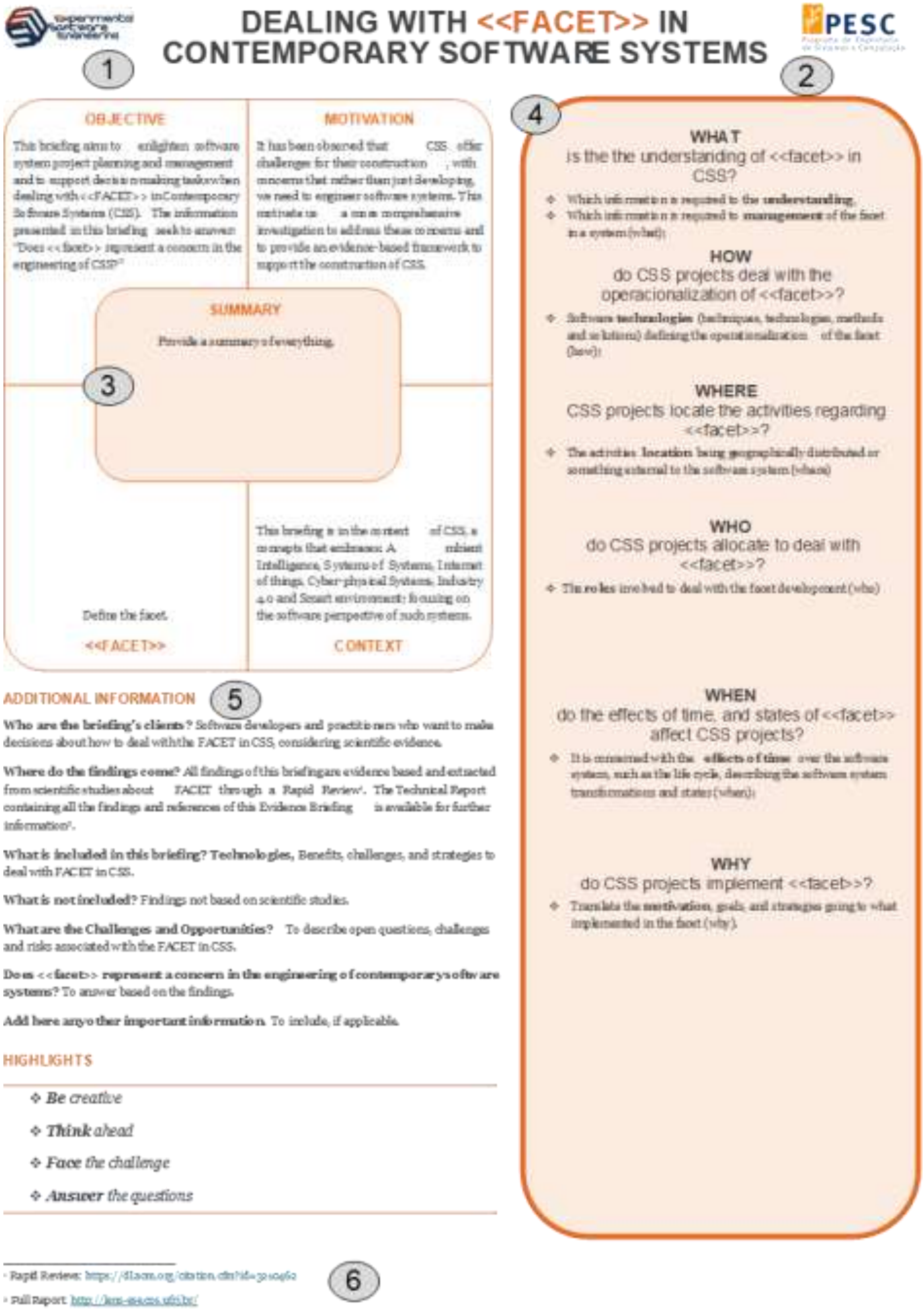

Figure 36. Overview of the elements of the EB template.

As we did on the protocol, this EB is a meta-template instantiated for each facet. Below are the EBs generated for Things and Interactivity Facets.

DEVELOPING IOT SOFTWARE SYSTEMS? TAKE THINGS INTO ACCOUNT

CONTEXT

IoT allows composing systems from *things* equipped with identifying, sensing, or actuation behaviors and processing capabilities that can communicate and cooperate to reach a goal. For so, different facets should be taken into account, such as *things*.

THINGS

It exists in the physical realm, such as sensors, actuators or any objects equipped with identifying, sensing or acting behaviors and processing capabilities that can communicate and cooperate to reach a goal, varying according to the systems requirements.

SUMMARY

Improving quality of life, productivity, reducing costs are some of the advantages provided by IoT. In the core of IoT is the *things*. They make possible to sense, act, identify and interact in new forms with users and environment. Acting as a bridge between the virtual and physical worlds, these smart devices and components should

OBJECTIVE

This briefing aims to enlighten project planning and to provide guidance when dealing with Things in IoT. The information presented in this briefing seeks to answer: "What taken into account when considering *things* for IoT?".

MOTIVATION

IoT offers challenges for their construction, with concerns that rather than just developing, we need to engineer software systems. This motivated us to a more comprehensive investigation to address these concerns and to provide evidence-based support for IoT engineering.

ADDITIONAL INFORMATION

Who are the briefing's clients? Software developers and practitioners who want to make decisions about how to deal with *things* in IoT, considering scientific evidence.

Where do the findings come? All findings of this briefing were extracted from scientific studies about *things* through a Rapid Review[1]. The Technical Report[2] containing all the findings is available for further information.

What is included in this briefing? Technologies, challenges, and strategies to deal with *things* in IoT projects.

What are the Challenges and Opportunities? How to define the requirements, the large amount and the heterogeneity of devices, the necessity to deal with limit resources, interoperability, security and privacy are among the main challenges to deal with *things* in IoT.

Do things represent a concern in the Engineering of Internet of Things Software Systems? Yes. Things are in the core of every IoT solution, constantly evolving in some aspects (such as resources capabilities) but with several open challenges (such as safety and security), it should be carefully addressed in every step of development.

HIGHLIGHTS

❖ *The **combination of technologies** allows developing solutions for several scenarions, previously not possible.*

❖ ***Microcontrollers and sensors** where widely used in most of the solutions.*

WHAT

is the the understanding of things in IoT?

- Everyday devices that enables **identification**, **sensing**, **actuation**, **monitoring**, **interacting** with the user or environment.
- It permits an **evolutionary model of system design and deployment**.

HOW

do IoT projects deal with the operacionalization of things?

- Define the components according to their **behavior**, **limitations** and **events**.
- Provide strategies to **adapt**, **build** or **buy** components.
- Establish procedures for **integration** and **protection** in case of external components and do-it-yourself approaches.
- In terms of technologies there are a lots of solutions that were combined to build the devices like sensors, actuators, smartphones, microcontrollers, tags, interactables, cameras, communication and network enablers, among others.

WHERE

IoT projects locate the activities regarding things?

- The location is basically the own **environment** where the solution is deployed and depends on the problem domain.
- Consider the environment impact on the components and vice-versa.
- The solutions where in places like houses, shopping, transport systems, smart cities, factories, roads, military, farms, mines, hospitals, offices, airport, among others.

WHO

do IoT projects allocate to deal with things?

- **Engineers**, **architects** and **technicians** are responsible for tailor the model, design and implement proposed solution.
- **Users** can actively participate in the process with do-it-yourself approaches and more active roles.
- **Actors** in the system can be other systems and are not limited to humans anymore. Therefore, the interactions, roles and responsibilities should be well defined.

WHEN

do the effects of time, and states of things affect IoT projects?

- The context of use can affect the behavior of the device, have consequences on the system. **Repeatable patterns and rules** should be defined.
- It is important to **unify temporality** across different components as well as procedures in case of **real-time operation**.

WHY

do IoT projects implement things?

- In general, the use of *things* with part of a solutions in IoT provide a **series of benefits** such as comfort, simplify user life, reduce costs, accessibility, reduce the risk of mistakes, efficiency, enhance productivity, decrease energy consumption, support in decision making, automate a manual process, and remote control and monitoring.

[1] More on Rapid Reviews: https://dl.acm.org/citation.cfm?id=[illegible]
[2] Full Report: https://goo.gl/[illegible]

DEVELOPING IOT SOFTWARE SYSTEMS? TAKE INTERACTIVITY INTO ACCOUNT

CONTEXT

IoT allows composing systems from *things* equipped with identifying, sensing, or actuation behaviors and processing capabilities that can communicate and cooperate to reach a goal. For so, different facets should be taken into account, such as smartness.

INTERACTIVITY

It refers to the involvement of actors in the exchange of information with things and the degree to which it happens. Beyond the sociotechnical concerns surrounding the human actors (human-thing interaction), we also have concerns with other actors (thing-thing interaction).

SUMMARY

The most important of them is the fact that there is no more unique system, but an enormous quantity of systems, components, things, and applications, which has to work together. For this reason, understanding, defining and dealing with interactivity is an important for IoT solutions.

OBJECTIVE

This briefing aims to enlighten project planning and to provide guidance when dealing with Interactivity in IoT. The information presented in this briefing seeks to answer: "What taken into account when considering interactivity for IoT?".

MOTIVATION

IoT offers challenges for their construction, with concerns that rather than just developing, we need to engineer software systems. This motivated us to a more comprehensive investigation to address these concerns and to provide evidence-based support for IoT engineering.

ADDITIONAL INFORMATION

Who are the briefing's clients? Software developers and practitioners who want to make decisions about how to deal with *interactivity* in IoT, considering scientific evidence.

Where do the findings come? All findings of this briefing were extracted from scientific studies about *interactivity* through a Rapid Review[1]. The Technical Report[2] containing all the findings is available for further information.

What is included in this briefing? Technologies, challenges, and strategies to deal with *interactivity* in IoT projects.

What are the Challenges and Opportunities? IoT generally involve devices developed and implemented by a diverse range of vendors, using different languages, architectures, and technologies, without a pattern, causing a high level of heterogeneity. The worst case is heterogeneity in data, which affects the semantic (the meaning) and the syntax (the format) and harms interactivity because even if the systems can communicate, they cannot understand each other. Everyone who wants to propose a solution to CSS context must know that if the "conventional" systems are not made homogeneously, the level of heterogeneity increases a lot as well as the level of interaction and autonomy.

Does interactivity represent a concern in the Engineering of Internet of Things Software Systems? Yes, and interactivity challenges should be overcame to achieve interoperable, seamlessly and collaborative solutions.

HIGHLIGHTS

❖ ***Heterogeneity*** *is an intrinsic characteristic of IoT.*

❖ *It can affect the semantic (the meaning) and the syntax (the format) and harms interactivity because even if the systems can communicate, they cannot understand each other. That is a great challenge in Interactivity.*

WHAT
is the the understanding of interactivity in CSS?

- Interactivity is characterized by the interaction involving things, systems, and humans where interaction is characterized by the ability to communicate, exchange information and control actions.
- It is important to **define actors' control and mechanisms** for the interaction methods (Voice, gesture, actions...).

HOW
do CSS projects deal with the operacionalization of interactivity?

- **To guarantee connectivity:** Zig-Bee, Bluetooth, Radio Frequency, RFID, 6LowPAN, WSN, WiFi, IPv6 and others.
- **To guarantee communication:** HTTP, XMPP, TCP, UDP, CoAP, MQTT and others.
- **To guarantee understanding:** JSON, XML, OWL, SSN Ontology, COCI and others.
- Real-world objects are virtualized and represented as Web Resources and accessed through Web Interfaces based on REST principles and Producer and Consumers methods.
- Alternative solutions should also be considering when dealing with human in the loop, to address human-thing interaction – such as voice and gestures commands.

WHERE
CSS projects locate the activities regarding interactivity?

- Most of the times, the activities regarding interactivity are located in a system's architecture, on frameworks, middleware, and platform.

WHO
do CSS projects allocate to deal with interactivity?

- **Designers, architects, developers, managers, and engineers** deal with interactivity in different phases of IoT projects.
- **Changing the scenario:** "Engineering is no more a set of vertical activities developed by different engineers but a collaborative process in which people and technology is completely involved in the engineering process".

WHEN
do the effects of time, and states of interactivity affect CSS projects?

- Activities regarding Interactivity are present all over a system or application **lifecycle**. Especially, they affect the design, development, integration, deployment, and operation phases.
- Interactivity is achieved by the exchange of information among "Things" and the orchestration of these operations occur during **runtime**.

WHY
do CSS projects implement interactivity?

- To **bridge the gap** between the massive heterogeneity present in IoT in order to create an interoperable systems, that can overcome different standards, protocols and technologies to perform more efficiently than isolated ones.
- **Interactivity** is one of the main characteristics of IoT projects, making new types of application possible (such as smart environments), facilitating everyday life, enhancing products competitivity, and sustainability.

[1] More on Rapid Reviews: https://dl.acm.org/citation.cfm?id=3210462
[2] Full Report: https://goo.gl/m7jtR