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Three Phase Methodology: A Contribution to the Teaching and Development of the Internet of Things

Metodologia das Três Fases: Uma Contribuição para o Ensino e Desenvolvimento em Internet das Coisas

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Thesis presented to the School of Electrical and Computer Engineering of the University of Campinas in partial fulĄllment of the requirements for the degree of Doctor in Electrical Engineering, in the area of Telecommunications and Telematics.

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Resumo

A Internet das Coisas (IoT) é uma área em constante desenvolvimento e que tem chamado a atenção de pesquisadores e profissionais nos últimos anos. A IoT é uma área multidisciplinar por natureza, envolvendo vários campos do conhecimento, como computação, telecomunicações, ciência dos dados e eletrônica. Essa integração de conceitos, técnicas e tecnologias torna a IoT uma área heterogênea, onde é necessária a junção de vários componentes conceituais e práticos para o entendimento e desenvolvimento de uma solução IoT. Sendo assim, a tarefa de ensinar IoT é uma atividade complexa. Essa tese apresenta um conjunto de trabalhos que contribuem para a área de ensino de IoT. A principal contribuição é a proposta de uma metodologia inovadora, chamada de Three-Phase Methodology, que usa conceitos de Project Based Learning (PBL) para ensinar IoT. É uma metodologia estruturada e sistemática que define como uma solução IoT é pensada, planejada e desenvolvida. A TpM foi aplicada e aprimorada durante todo o projeto de pesquisa que levou a essa tese. Os resultados apresentados aqui mostram que se trata de uma metodologia promissora, com resultados sólidos para o ensino e desenvolvimento em IoT. Além da aplicação da TpM, várias aplicações baseadas na metodologia foram desenvolvidas e avaliadas, trazendo um arcabouço de ferramentas para o ensino e desenvolvimento de soluções IoT.

Keywords: Internet das Coisas; Metodologias Ativas; Aprendizado Baseado em Projetos; Desenvolvimento de Projetos.

Abstract

The Internet of Things (IoT) is an area in constant development that has attracted the attention of researchers and professionals in recent years. The IoT is a multidisciplinary area, bridging several fields of knowledge, such as computing, telecommunications, data science and electronics. This integration of concepts, techniques and technologies makes the IoT a heterogeneous area, where it is necessary to combine several conceptual and practical components for the understanding and development of solutions. Therefore, the task of teaching IoT is a complex activity. This thesis presents a set of works that contribute to the teaching of IoT. The main contribution is the proposal of an innovative methodology, called the Three-Phase Methodology (TpM), which uses Project Based Learning (PBL) concepts to teach IoT. It is a structured and systematic methodology that defines how an IoT solution is thought, planned, and developed. The TpM was applied and improved throughout this research project. The results presented in this work show that the TpM is a promising methodology for IoT teaching and development. In addition to the application of the TpM, several applications based on the methodology were developed and tested, creating a framework of tools for the teaching and development of IoT solutions.

Keywords: Internet of Things; Active Methodologies; Project Based Learning; Project Development.

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- L. C. B. C. Ferreira, R. Yamaguti, Omar C. Branquinho and P. Cardieri, "A TpM-based collaborative system to teach IoT", in Computer Applications in Engineering Education, vol. 30, pp. 292-303, August 2021. Impact Factor: 2.109
- L. C. B. C. Ferreira, P. R. Chaves, R. M. Assumpção, O. C. Branquinho, F. Fruett and P. Cardieri, "The Three-Phase Methodology for IoT Project Development", in Internet of Things; Engineering Cyber Physical Human Systems, October 2022. Impact Factor: 5.711

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- R. M. Assumpção, P. R. Chaves, L. C. B. C. Ferreira, P. Cardieri, O. C. Branquinho and F. Fruett, "Advancing Engineering Education: Using the Three-Phase Methodology to Teach IoT", in Computer Applications in Engineering Education. Impact Factor: 2.109

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- L. C. B. C. Ferreira, P. R. Chaves, R. M. Assumpção, O. C. Branquinho, F. Fruett and P. Cardieri, "Analysis and Discussion of Recent Initiatives on Teaching Internet of Things Concepts", in XL Simpósio Brasileiro de Telecomunicações e Processamento de Sinais (SBrT2022), 2022.

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1 Introduction

The Internet of Things (IoT) involves several areas of knowledge, such as computing, communications, energy, data analysis, and microelectronics. These areas are already consolidated in the literature and with several commercial applications. However, integrating them to develop IoT applications is not a trivial task. The multitude of existing manufacturers, products, and technologies makes this work even more complex (Uckelmann Dieter 2011).

This variety of products and manufacturers, the lack of standardisation and the multidisciplinary nature are factors that make IoT teaching activities difficult. Consequently, the shortage of trained professionals leads to difficulties in the application and dissemination of IoT technologies (Uckelmann Dieter 2011).

The training of professionals to work in the IoT area has motivated several initiatives in Brazil. For instance, Federal Law No. 9394/1996 established the bases and guidelines for a more flexible and innovative educational model, the National Curriculum Guidelines (DCN) (CNI SESI 2020). Also, the National Workgroup for the Strengthening of Engineering, created in 2016, now dedicated to science, technology, engineering, the arts, and mathematics (STEAM), has contributed to the publication of the new DCN for Undergraduate Engineering Courses, in force since in 2019. These guidelines emphasize competence development, project-based learning, and better communication with society. The DCN proposed that engineering courses should be based on practical and active learning experiences, in a process in which the students are fundamental agents. The DCN also endeavors to modernize the assessment process from a generic evaluation process to a continuous, diversified one, in tune with academic activities, based on competencies. This assessment process should reinforce what has been learned while promoting feedback from teachers (CNI SESI 2020).

Furthermore, the National Internet of Things Plan, from June 2019, encourages the development of programs, methodologies, and tools for the teaching of IoT. The plan is an initiative of the Ministry of Science, Technology, and Innovation and the Brazilian National Development Bank, and aims to improve the quality of life and promote efficiency and productivity gains through IoT. The plan's objective is to implement and develop IoT in the country and integrate it into the international IoT scenario.

The contributions to the teaching of IoT presented in this thesis are aligned with the initiatives mentioned above. The Three-Phase Methodology (TpM) is a manufacturer and technology-independent teaching methodology that embraces Project Based Learning (PBL) and hinges on three well-defined phases: (i) Understanding the Business, (ii)

Requisites Gathering, and (iii) Implementation.

The TpM has as its main characteristic the need for a proper understanding of the business in need of the IoT solution, as an essential part of the teaching process. This feature provides a broader, contextualized view, that does not focus on technology, starting from a project to be elaborated. This characteristic is in line with recent studies, which show that not paying proper attention to the project is one of the main causes of IoT project failure.

According to (Jha 2016), “eight out of ten IoT projects fail even before they are launched” and most new projects of IoT solutions are “in search of a business problem”. The author adds that companies are first developing solutions and then offering them to solve business problems that may not exist yet.

In “Why IoT Projects Fail” report (Woolley 2020), a survey conducted with 637 representatives of 250 companies distributed across 42 countries, showed that one of the barriers to success in the development of IoT projects was the higher level of knowledge in design and architecture needed. This indicated that methodologies and architectures that simplify the development process can play a decisive role. Another important finding of this report was that often the definition of the business, its objectives, and expected returns are not taken into account, seriously contributing to the failure of IoT projects. The report concludes that focusing the solution on technology only is a mistake.

The concern with the business through a more generic approach was also mentioned in (Uckelmann Dieter 2011) as an important requirement for the future development of IoT. While technologies are important, they are not enough to embrace the broad spectrum that an IoT solution covers.

The TpM makes use of the manufacturer-independent, IoT Open Source Reference Model (Déo 2018) to describe IoT applications. It can be used to model any application into six layers, from monitoring the Things in the environment (i.e., sensors) to the end user interface.

The training of professionals to develop IoT solutions will help to disseminate and popularize the technology. Big companies and corporations, generally, can acquire complete solutions from established suppliers, including training on their products. Medium- and small-sized companies however need professionals who have the ability to design low-cost IoT solutions that meet their needs (Deo 2018).

This finding is already perceived in some initiatives, such as the creation of the CrossLab (Saponara 2018) in Italy, a laboratory dedicated to the joint work of researchers from different areas, including IoT, which aims to guarantee small and medium-sized companies in Tuscany access to these technologies.

In (Uckelmann Dieter 2011) this concern with small and medium-sized companies is raised, as the need to define approaches that include market share is explained, not making IoT exclusive to large companies.

Several works address problems related to teaching and training of professionals in IoT. In (Srinivasa e Sowmya 2016) the authors treat IoT teaching using a PBL approach, but discussing theoretical aspects only. They define some steps for the elaboration of an IoT solution, which are: Problem identification; Preparing the computer (loading operating system, etc); Connecting sensors to the computer; Internet transmission; Basic Reading of Data; Cloud Interface; Cloud Computing. The study was only theoretical and had the objective of motivating students to research some IoT topics. The main conclusion of the article was that the PBL approach encourages critical thinking, problem-solving, reporting writing, speaking, and presentation skills.

In (Ali 2015) the authors define four areas for IoT teaching: Embedded Programming, Hardware, Networking and Communication, and Distributed Computing. The PBL approach is not used in this work. The authors use a software/hardware suite to address in a traditional way issues related to the areas mentioned above. What stands out in this work is an attempt to teach IoT in a more thorough way, integrating knowledge. A criticism of this work is the unstructured and non-systematic way of teaching, where the authors themselves mention that weekly assessments are carried out and the course content and methodology are changed from class to class, not having a defined pattern to be followed. In this work, the objective is to define a structured and systematic methodology for teaching, in addition to establishing a logic in relation to the areas for teaching IoT.

The work of (Hormigo e Rodriguez 2018) is an IoT teaching initiative using PBL. The author's idea is to propose an initial project, related to an IoT application in an urban garden. In this work, the authors developed a 15-week course. They provide all software and hardware resources, as well as the necessary documentation for students. Stages are divided into weeks and tasks are given for each stage. At the end of the activities, questionnaires are answered by the students, to evaluate their own work and to evaluate the methodology used. According to the authors, the main difficulties encountered by the students were of technological nature, such as programming and communication technology. These findings were important because the methodology proposed focused only on technology. There is no mechanism to present students the context in which the solution is inserted, or why a certain technology is used. Being a purely technology-driven course, student motivation tends to drop when they encounter technical difficulties. In a multidisciplinary area such as IoT, this difficulty can take away the student's interest in the area. The authors conclude that the use of PBL can be a way to teach IoT, but there is a need to adjust the methodology. They also point out as positive points the greater interest and motivation of students for challenges that involve real-world problems.

In this doctoral work, the methodology is not focused on technology, but on its application as a whole, dividing the application of IoT into three well-defined phases.

With the evaluation of the works in this area and their contributions, it was possible to elaborate a methodology that seeks to use the best characteristics of PBL, adapted to the needs of IoT teaching. It is a proposal that aims to be innovative and address the main difficulties encountered in IoT teaching.

This work presents an adaptable and flexible methodology for teaching and developing IoT solutions. The aim is to prepare professionals to work in any company, be it small, medium or large.

1.1 Document Structure

The thesis is presented as a compilation of the papers published by the author in technical journals and conference proceedings, in accordance with Unicamp legislation and following Information CPG No. 002/2021. The contents presented here are copies of these papers. Permission grants to reproduce the published papers are attached in Appendix C. In addition, this research project has permission from the Unicamp Ethics Committee, under process number 26437819.0.0000.5404. The documentation can be found in Appendix A.

The remainder of the dissertation is structured as follows:

- **Chapter 2 - A PBL-Based Methodology for IoT Teaching:** This chapter presents the article published in the IEEE Communications Magazine, in November 2019 (Ferreira et al. 2019). The paper describes the Three Phase Methodology. The references that supported its creation and the foundations used for the elaboration of the methodology are also discussed. The paper reports the first use of the methodology with a group of students and brings the first observations on the application of the methodology. The results show that the approach is promising and point out ways to use it in future works.
- **Chapter 3 - A TpM-based collaborative system to teach IoT:** This chapter presents the article published in the Computer Applications in Engineering Education Magazine (Ferreira et al. 2021), in September 2021. This article introduces a system developed for the elaboration of IoT projects, following the TpM. The system was developed to facilitate the application of the methodology, is an evolution of the first article and was motivated by the results presented in chapter 2 (Ferreira et al. 2019). The system was tested and validated, the results showed that its use helped the understanding and application of the TpM.
- **Chapter 4 - The Three-Phase Methodology for IoT Project Development:** This chapter presents the article published in Internet Of Things: Engineering Cyber

Physical Human Systems, an Elsevier Magazine. The paper was published in October 2022. In this work, the TpM is presented as a methodology for corporate projects. Based on experiences obtained during the application of the methodology in an academic environment, it was found that the TpM has great potential to be used in corporate environments, as it is an agile methodology developed for IoT. The TpM was tested by a development team, and the results showed that the methodology can be used as a methodology for IoT projects.

- **Chapter 5 - Analysis and Discussion of Recent Initiatives on Teaching Internet of Things Concepts:** This chapter brings an article presented at the Brazilian Symposium on Telecommunications and Signal Processing (SBrT2022) in September 2022. This article analyses and discusses the research group's production in IoT teaching. It presents the results obtained, such as published articles, courses offered, summarised results, and reflections that can be used for the continuation of the research work. This paper is a conclusion of this research work, summarising the challenges and discoveries that happened during the last four years, in addition to proposing new paths and new possibilities for the work.

- **Chapter 6 - Conclusions:** This chapter summarises the contributions of each chapter, making a qualitative analysis and pointing out possible paths new research could follow.

2 A PBL-Based Methodology for IoT Teaching

This chapter is a replica of the paper:

L. C. B. C. Ferreira, O. C. Branquinho, P. R. Chaves, P. Cardieri, F. Fruett and M. D. Yacoub, “A PBL-Based Methodology for IoT Teaching,” in IEEE Communications Magazine, vol. 57, no. 11, pp. 20-26, November 2019. Impact Factor: 9.619

In this article, the Three-phase Methodology is presented. The methodology’s structure and components are introduced, along with a detailed description. In addition, the article presents the first results of application of the methodology.

The references and concepts that were used on its elaboration are cited. Its structure, components and detailed description are also presented. In addition, the first results of its application are disclosed.

Abstract

The Internet of Things has dramatically expanded its scope of applications in the last few years, reaching all areas of human activities, from biology to technology to social sciences. In the same way, IoT applications are becoming a driving force in the economy, playing a central role in many businesses. This scenario presents challenges in the teaching and designing of IoT applications due to its inherent multidisciplinary nature, with areas of knowledge ranging from electrical and computing engineering to those related to the target application to the business itself. In this article, we present a teaching methodology that relies on the project-based learning approach and makes use of a six-layer IoT Open Reference Model that covers all aspects of an IoT solution, from sensors to the end-user interface. The proposed methodology focuses on a complete understanding of the business behind the application and on the end-user needs. Following a top-down approach, from the business to the devices required to collect the necessary information, the approach allows students to have a complete view of all components involved in any IoT application. The proposed methodology has been applied in graduate and extension courses at the University of Campinas and has proven extremely useful.

2.1 Introduction

Internet of Things (IoT) is certainly a reality. Its applications, though, are not as widespread as predicted or even desired, but its growth potential is rather impressive. Reports indicate that billions of objects will be connected in the coming years, exchanging information and interacting with the environment in a smart way. On the other hand, the training of professionals to work with IoT remains a concern, mainly due to the multidisciplinary nature of the system itself. IoT involves diverse fields of knowledge, such as computing, communications, energy, data analysis, microelectronics, and others. Additionally, IoT applications have been used to solve problems in a variety of areas, from biology to technology to human behavior sciences. In this sense, it is imperative to recognize any IoT application as part of a business plan and of a larger system, with its own rules and peculiarities. Accordingly, an appropriate design of IoT solutions requires expertise in a number of different fields rendering limited its widespread use.

The first step towards teaching IoT is to recognize its multidisciplinary nature. On the other hand, educational institutions face an additional challenge as follows. A quick survey of the IoT market shows an incredible number of available technologies from numerous manufacturers, each of which with its own attributes and, most of the times, tailored to a rather particular application. The multitude of products and technologies renders the teaching process intricate, because, if any particular system is adopted in an IoT course, its scope becomes limited. Ideally, training courses should prepare professionals to develop solutions regardless of the technology employed.

This article presents an IoT teaching methodology, using Project Based Learning (PBL) in connection with a three-phase cycle: (i) *Understanding the Business*, (ii) *Requirements Definition*, and (iii) *Implementation*. This teaching methodology, named Three-Phase Methodology (TPM), focuses on the IoT design process and aims at addressing the issues, as pointed out above, concerning the intrinsic complexity of an IoT solution and the need for a manufacturer-independent design approach. As will be discussed in the following sections, a detailed understanding of the business behind the intended IoT solution is an essential part of the design process proposed in the TPM. Also, TPM makes use of an Open Source Reference Model for IoT applications, which is manufacturer-independent and can model any IoT application through six layers, from the things that monitor the environment (i.e., sensors) to the interface to the end user.

The remainder of the paper is organized as follows: Section 2.2 briefly reviews the concepts of PBL and IoT. Section 2.3 presents the structure of TPM and its key concepts. In Sections 2.4, 2.5 and 2.6, the three phases of TPM are thoroughly described. Section 2.7 presents some details on the application of the proposed teaching methodology in graduate courses at the University of Campinas, Brazil. Finally, Section 2.8 concludes the paper.

2.2 Basic Concepts of PBL and IoT

In this section, we review the basic concepts of the PBL methodology and discuss some intrinsic characteristics of the IoT field that motivate the development of the learning process presented in this work.

2.2.1 Project Based Learning

PBL is an active teaching methodology that instigates students to gain knowledge and skills by solving real-world problems (Dias e Brantley-Dias 2017). The principles of the PBL methodology are based on the concept of learning by doing, an idea first outlined by John Dewey in his book *My Pedagogical Creed* (Dewey 2015), published in 1897. Roughly speaking, PBL integrates know-how and practice, with emphasis on the development of critical thinking and problem-solving skills. Accordingly, the learning process is guided by the problems presented to students, who are led to solve problems autonomously. In this sense, the role of the instructor in this process becomes fundamentally that of an advisor (Bell 2010).

PBL works across subjects, involving competences and skills from several areas. This particular characteristic is one of the main reasons for its choice to be employed for teaching IoT.

Another feature of PBL that justifies its choice is the fact that this methodology encourages students to develop self-learning skills. This is a highly desirable craft when working with fast-changing technologies, such as computing, wireless communications, and data processing.

In its standard format, PBL follows seven steps (Dias e Brantley-Dias 2017):

- Nomenclature: Words, expressions, technical terms, and concepts related to the problem with which students are not acquainted must be identified and explained.
- Problem definition: A list of challenges to be addressed while solving the problem must be created.
- Brain storm: A discussion using students' previous knowledge and background is carried out aiming at finding a solution to the problem at hand. .
- Summary: The main takeaways from the previous discussion are listed, recalling the problems and hypotheses identified, the contributions based on previous knowledge, with a list of pros and cons.
- Formulation of learning objectives: Based on students' previous knowledge, a list of obscure points is created, i.e., topics that must be studied in more detail.

- Search for information: The sources of the knowledge needed to solve the problem are found.

- Reporting, discussion, solution: All the pieces of information gathered to solve the problem are integrated.

It should be mentioned that the PBL in IoT teaching as presented in this work makes use of its very basic principles, i.e., not all the steps listed above apply. The primary attribute borrowed from the traditional PBL methodology is the use of the problem definition as the starting point of the project development. In this sense, the seven steps are replaced by three phases. The details of the proposed teaching methodology are presented in Section 2.3.

(Readers interested in more information about teaching experiments based on PBL and active teaching methodologies, in the context of IoT, are referred to (Srinivasa e Sowmya 2016; Hormigo e Rodriguez 2018).)

2.2.2 Internet of Things: Challenges and Issues

IoT technologies allow things or devices to act intelligently and collaboratively (Salman e Jain 2015). In the IoT context, things no longer make decisions individually, but they do actively and ubiquitously communicate and collaborate, in order to carry out critical decisions (Srinivasa e Sowmya 2016). An IoT technology, along with cyber-systems, cloud computing, and machine learning, forms the basis for the so-called “Industry 4.0” (Salman e Jain 2015).

Despite the remarkable advances that have been made in recent years, IoT still faces many challenges to become a widespread technology. One of these challenges relates to the lack of standards for the design and implementation of IoT applications, combined with the multitude of technologies and products from numerous manufacturers. This scenario creates barriers to its widespread dissemination, particularly in the small to the medium-sized enterprise. A typical business in this market does not have the necessary financial resources to acquire the solutions offered by larger IoT manufacturers, and often lack personnel with the specialized knowledge required to create alternative IoT solutions at lower costs.

As already mentioned, another critical issue in this scenario concerns the training of professionals. Several IoT solutions are offered, each one focusing on a particular application and with distinct features. This variety of products hinders the training of professionals since no methodology allows for the use of these solutions within a standardized and systematic context.

This scenario has motivated the development of the teaching methodology proposed in this paper and presented in the following section.

2.3 PBL for IoT Teaching: The Three-Phase Methodology

The teaching of IoT has attracted a great deal of attention in the last few years, due to the peculiarities and the multidisciplinary nature of the systems involved (Ali 2015; Srinivasa e Sowmya 2016; Hormigo e Rodriguez 2018). The Three-Phase Methodology proposed here differs from other methodologies found in the literature. This methodology is based on a technology-independent, Open Source IoT Reference Model. With TPM, students are provoked to question and propose ideas about a given chosen project. Instead of using the classical approach of PBL, TPM follows well-defined steps as a guide to design, specify, and implement IoT solutions in general. These three steps are: (i) *Understanding the Business*, (ii) *Requirements Definition*, and (iii) *Implementation*.

TPM is based on the premise that there is always a well-defined problem to be addressed by an IoT solution. The reasons for a company to seek a solution based on IoT include adding value to a product, improving an existing process, and offering a new service, among others. Therefore, the understanding of the business related to the problem to be solved may provide important guidelines when designing an IoT solution. The process of *Understanding the Business* is the first phase of the TPM methodology and aims to collect the customer needs and expectations. This step must precede any technological choice.

In this sense, the role of the specialist emerges in the process. The specialist is a professional with knowledge of the business and who is responsible for providing the designers with detailed information about the problem to be solved. For instance, if the business is in the area of agriculture, a professional in this field is required to yield theoretical and practical support for the choices to be made in the development of the IoT solution. This specialist may be someone from the company itself or somebody else hired for this purpose.

After the connection between business and things is understood, the requirements for the solution can be defined, based on the objectives established in the previous phase. This process is carried out in the *Requirements Definition phase* when the components of the IoT system are defined as well, though no technology choice is made yet.

The last phase in TPM is the *Implementation phase*, when the technologies that best meet the specifications defined in the previous steps are investigated and the solution is implemented.

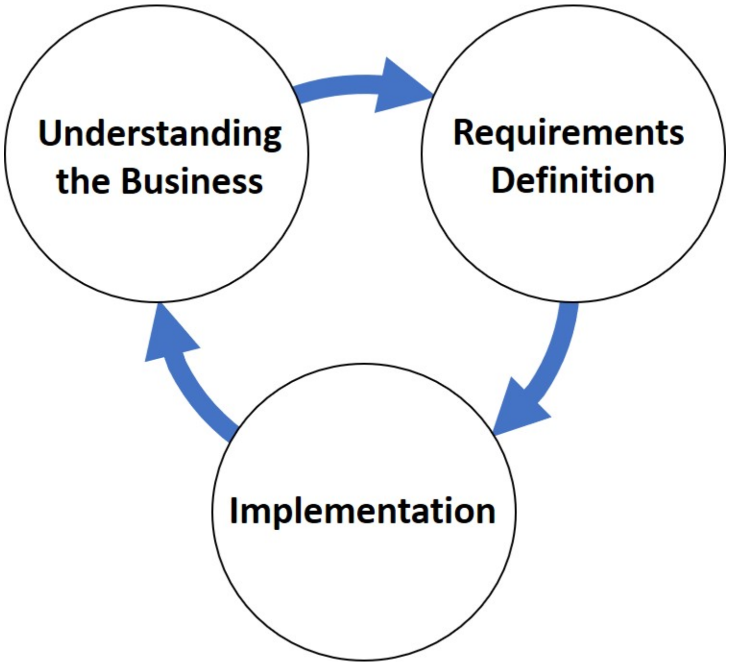

Figure 2.1 – The Three-Phase Methodology.

These three phases are iterative and incremental (see Figure 2.1), such that during the solution lifespan, the three steps can be repeated to meet new business demands or to correct failures. In the following sections, the three phases of TPM are described in the context of the teaching process.

2.4 Understanding the Business - Phase 1

2.4.1 The Business

The purpose of TPM is to connect the business to things through IoT, using business rules and specialized knowledge, as illustrated in Figure 2.2.

As discussed in the previous section, the details of the business associated with the IoT application in mind may provide the guidelines of the project, by identifying priorities, operational conditions, and the type and format of the information to be provided to the customer by the IoT application.

At this stage, students are presented to the problem to be solved, when they are encouraged to raise questions about it and are expected to understand the demands from the IoT application. This stage comprises the main PBL characteristic borrowed by TPM since students are supposed to build knowledge from the problem presentation down to the solution specification.

The type of business behind the IoT application varies from project to project, even when dealing with projects in the same area of activity, as each project may have

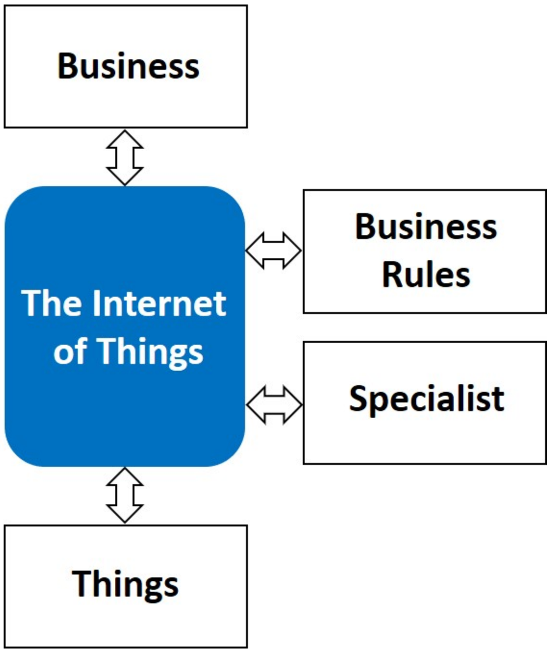

Figure 2.2 – The Business-Thing connections.

its peculiarities. Therefore, the business phase is of paramount importance. If not well delineated, the final solution may not satisfy the end user.

2.4.2 The Things

Things are entities needed to achieve the purposes of the business. These things can be physical entities, such as temperature, humidity, and luminosity, or electronic devices (e.g., relays and cameras). In this step of the methodology, students are supposed to define the type of things to be employed in the IoT solution, and this definition will guide the processes of specification and implementation of the sensors/actuators to be used in the project.

2.4.3 The Specialist

As already mentioned, the proposed teaching methodology requires the involvement of specialized personnel, who will provide information to support the decision-making processes found in different phases of the methodology. This professional can be someone directly connected to the business or explicitly hired for that end.

2.4.4 The Business Rules

The business rules are premises and restrictions applied to the operation of any business. Therefore, these rules should be taken into account throughout the solution development process. The business rules can be determined by analyzing the target scenario in which the IoT solution will be employed. It may also be necessary to study regulatory issues related to the respective activity.

In the process of learning about the business rules, the following issues must be considered:

- The relevance of the IoT solution in the business process and the respective added value.
- The execution flow (inputs, processing, and expected outputs).

The development of an IoT solution begins with a clear understanding of the business rules, which should be consistent with the needs of the company.

2.5 Requirements Definition - Phase 2

During the Requirements Definition phase, students are encouraged to discuss the problem, aiming at defining the requirements of the IoT solution, and document the corresponding specifications of the system to be implemented. TPM deals with the design of solutions that connect the business to the things. It is based on a top-down approach, starting at the business level and flowing down all levels, as far as the one where sensors and actuators (things) are located. This top-down approach is based on a six-level *IoT Open Reference Model* proposed in (Déo 2018), shown in Figure 2.3. Accordingly, the discussion carried out in this phase leads to the definition of the tasks to be performed at each level of the Reference Model. It should be noted that this discussion does not involve any technology choice, but only how the solution in mind should work. The use of a PBL-based methodology motivates students to come up with new ideas and to develop skills to work in a team environment, essential for professionals in any field nowadays.

In the following section, we present a brief description of each level of the IoT Open Reference, shown in Figure 2.3.

2.5.1 Level 6 - Display

The Display level covers the way information is to be depicted to assist the end user in the decision-making process. This information can be presented, e.g., through charts, graphs, and numbers. Emergency and other actions necessary for the business are signaled and dealt with at this level.

2.5.2 Level 5 - Abstraction

At the Abstraction level, the stored data is used to transform information into knowledge. It is at this level that a specialist's expertise is required. Students, with

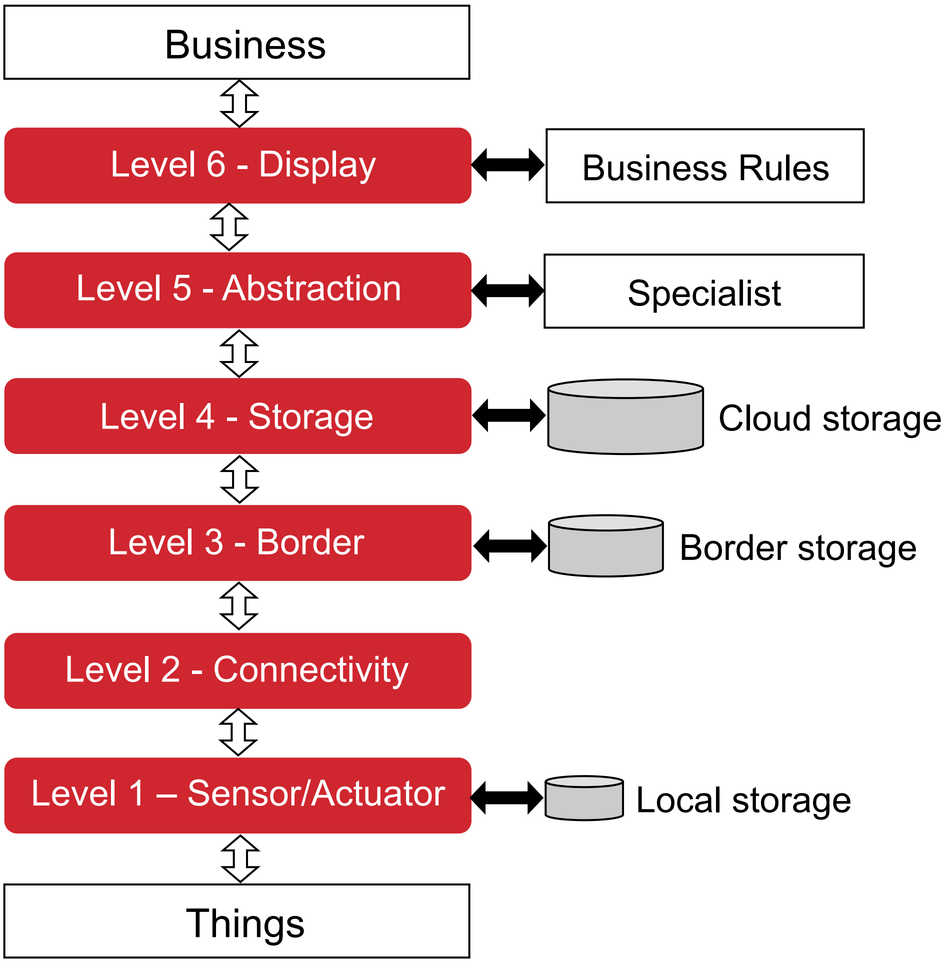

Figure 2.3 – The IoT Open Reference Model.

the assistance of the specialist, analyze the scenario and propose an appropriate way to accomplish the abstraction from the available information. Students can make use of techniques like artificial intelligence, data mining, and machine learning, among others.

2.5.3 Level 4 - Storage

The Storage level defines how the collected data is to be stored. The storage can be in the cloud, in the client's system, or in both. The decision regarding data storage depends on issues such as the required level of availability and security and the amount of data. At this point, students are prompted to discuss issues related to redundancy, data security, and storage location. These issues may require special attention if the IoT application in mind involves a large amount of data.

2.5.4 Level 3 - Border

This Border level defines the characteristics of the element that connects the IoT solution to the Internet, the so-called *border element*. This element operates on both the IoT local network and the Internet, providing the connection between these two worlds.

Therefore, the border element must always be present in the system. Also, this element may be required to perform network functions using more advanced strategies, including Software-Defined Networking and Network Function Virtualization. In this sense, it should be emphasized to students that the Border level embraces items related to the network infrastructure of the IoT solution, which may account for a large portion of the operational cost. Students are expected to specify the border element, taking into account issues such as processing capacity, storage, baud rate, and costs.

2.5.5 Level 2 - Connectivity

This Connectivity level deals with the connection between things and the border element. This connection may be provided through wireless or wired links or by a hybrid solution. Wireless technology is typically employed in the IoT context, mainly when a large number of sensors/actuators are distributed over a large area. However, the decision about the type of technology to be employed must take into account several other issues, including costs, things to be monitored/controlled, operating environment, required capacity and reliability of the transmission system, among others. Students should discuss all these issues in light of the project needs and requirements, in order to define the technology to be adopted.

2.5.6 Level 1 - Sensor Node/Actuator

The Sensor Node/Actuator level concerns the devices responsible for collecting data or acting upon the environment. At this point, students decide upon sensors or actuators to be be used, based on the type of data to be collected or on the action to be taken. Typically, the raw data collected by sensors must be processed to extract useful information or to remove redundancy. Several data processing strategies can be employed, including (i) local processing, to reduce the amount of data transmitted, (ii) cloud computing, for resource intensive applications, and (iii) fog computing, for resource intensive applications with stringent latency requirements. The first strategy is implemented at this Level 1, whereas the last two are typically performed at the border element or beyond. Another important issue to be discussed and decided upon regards the degree of autonomy of the devices. For instance, the devices can be configurable by entities located at other levels, in order to adjust their operation according to decisions made at these levels. Alternatively, devices can operate autonomously, when their operation does not depend on the decisions made at other levels.

The discussion carried out within each level should lead to a document describing the requirements and specifications of all devices and entities of the system, which will guide the implementation phase, as discussed next.

2.6 Implementation - Phase 3

Once the system specification phase is concluded, the technological choices are made and the implementation begins. Students start by assessing the technological options available in the market and choosing the ones that best fit the specification established in the previous phase.

A bottom-up approach is used in the implementation phase, since it is first necessary to define how things are monitored/controlled and how that information reaches the Business, following the specifications defined on the previous phase. Thus, the implementation starts at Level 1 (Sensor/Actuator), through the higher levels, until it reaches the Business. The Implementation phase then follows the opposite direction to the Requirements phase.

In the next sections, we revisit all six levels of the IoT Open Reference Model, now from the perspective of the Implementation phase.

For a better understanding of the Implementation phase, we will illustrate the implementation process using an open source IoT development kit specially designed and built by some of the authors for teaching purposes. This development kit, shown in Figure 2.4 and presented in detail in the next sections, follows the IoT Reference Model discussed in Section 2.5 and has been employed in graduate and extension courses offered at the University of Campinas, Brazil.

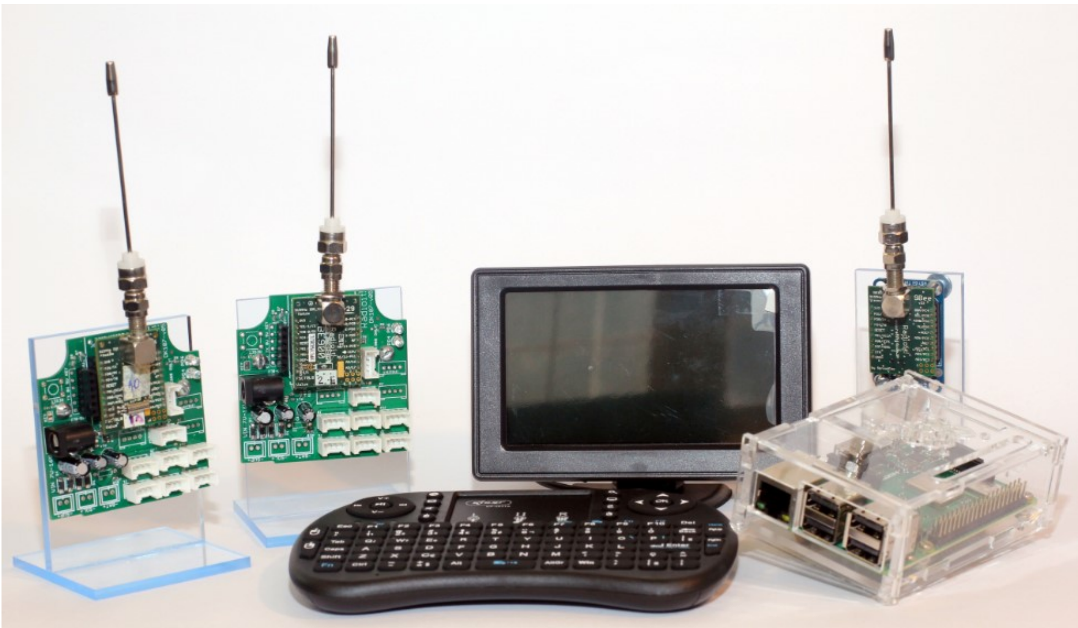

Figure 2.4 – The open source IoT development kit used to illustrate the presentation of the implementation phase.

2.6.1 Level 1 - Sensor Node/Actuator

The development kit contains two local nodes, a sinking node, a mini-computer equipped with screen, mouse, and keyboard.

The local nodes employ the DK107 development board (Radiuino 2015), along with a communication module, denoted BE900, which is implemented using an ATMEL ATmega328 microcontroller and a Texas Instruments CC1101 RF transceiver.

Students are instructed on how to use the development kit, through practical experiments. In addition, they are motivated to survey products available in the market that can be used as local nodes. Arduino is an option that has become attractive, offering, for example, the Arduino IoT Cloud (Arduino 2016), which is a set of tools for creating IoT applications.

Intel has an Arduino-based solution, called Arduino Create (Intel 2016), which enables simplified prototyping of commercial applications based on Intel architecture.

Sigfox has a set of sensors, called the IoT Sensor, which is prepared for transmission to the cloud through the Sigfox network (Sigfox 2016).

By analyzing these products from the point of view of the Reference Model, students can easily identify where and how to use them within an IoT solution.

Many products offer an IoT service, but most of them work only at some levels of the Reference Model, leaving the other levels to be implemented using other technologies. Providing students with skills to evaluate the IoT products found in the market, from the perspective of the Reference Model, is a paramount target of the teaching methodology proposed here, as these skills help them spot the most suitable technology for the project at hand.

2.6.2 Level 2 - Connectivity

The open source IoT development kit uses the CC1101 transceiver with the Radiuino communication protocol (Radiuino 2015).

Students may run several experiments using this transceiver in order to have a better understanding of the mechanisms and techniques involved in wireless communications, such antenna gains, propagation environment, modulation format, and transmission bit rate, and their effects on the system performance. The instructor should guide students through these experiments, and point out the main takeaways of each one of them.

Students should also be introduced to alternative solutions for connectivity in the context of IoT available in the market, such as LoRa, Sigfox, Bluetooth, WiFi, and LTE.

2.6.3 Level 3 - Border

The Open Source IoT Kit employs a Raspberry Pi computer loaded with a Linux-based operating system, with scripts written in Python to automate processes, and Zabbix (Zabbix 2014) for data management and storage. Students are instructed on how this edge element works by running tests and trying different configurations. Students should also discuss the protocols used to connect the IoT network to the Internet, such as MQTT, CoAP, REST and web sockets. These protocols are responsible for communicating with the TCP/IP protocol stack.

Students should survey alternative combinations of hardware and software that can play the role of the edge element. The Arduino platform, for example, has made available the Arduino Pro Gateway for Lora solution, which plays the role of an edge element with transmission support using Lora. The use of Raspberry Pi for this function has been well documented in the literature, as there is a wide range of possibilities for operating systems and communication interfaces.

2.6.4 Level 4 - Storage

At this level, Zabbix is used again, now along with a MySQL database. Students must test different configurations, including local storage, cloud storage, or a hybrid solution. As already mentioned, issues such as cost, data volume, redundancy, and required level of security, must be taken into account when designing the storage system.

There are several options for storage in the cloud, such as Tago (Tago 2014) and ThingSpeak (ThingSpeak 2014), which offer online platforms for managing and storing data. A possible alternative is the use of a storage server with a conventional database management system, such as MySQL and Oracle.

2.6.5 Level 5 - Abstraction

At Level 5, students experiment with data abstraction, by extracting useful information from the raw data collected by sensors. In the open source IoT development kit, Zabbix combined with the Grafana plugin is used for the abstraction. The Tago and ThingSpeak platforms offer this functionality as well. There is also the possibility of using other programming languages for more specialized data processing, such as Phyton, Matlab, R, and Scilab. Students can also try other data treatment strategies, such as artificial intelligence, machine learning, and data mining.

2.6.6 Level 6 - Display

Zabbix is once again used, now to display the information extracted from data, through charts and tables. As mentioned before, different strategies for displaying the information can be used, including alarms and graphs showing the correlation among different data.

2.7 Application of the Methodology

The TPM approach has been applied in graduate (60 hours) and extension (32 hours) courses offered at the School of Electrical and Computer Engineering and the Institute of Computing, both at the University of Campinas, Brazil. Students enrolled in these courses were divided into groups and asked to propose and implement IoT applications, following the TPM strategy. Instructors with expertise in sensors, wireless communications, and network management introduced key topics in their fields and were available during classes to guide the discussions proposed in the strategy. Students were also encouraged to seek assistance from professionals working in the field of the concerned IoT project, who would play the role of the specialist as foreseen in the strategy. A number of projects were proposed in several areas of applications, including environment audible noise monitoring, solar energy monitoring, energy consumption in households, restaurant queue length monitoring, etc. The proposed methodology has then been successfully applied to all projects and all of them were fully functional at the end of the course.

Students were then asked to respond to a questionnaire designed to assess the effectiveness of the TPM approach and to evaluate the students' experience when applying the methodology and the use of the development Kit. The main questions and a summary of the outcomes are presented in Table 2.1.

In Table 2.1, 1 and 5 correspond to lowest and highest scores, respectively. As can be seen in the upper and lower part of the Table, the great majority in the audience had had no contact whatsoever with the IoT subject. The results show that the use of the methodology greatly facilitated the accomplishment of the course target, which was to have the IoT applications fully functional at the end of the course. In fact, this is also attested by the students themselves who nearly unanimously approved of the use of the methodology as well as the use of the proposed development kit. Another important remark extracted from the Table is that the students showed their willingness to use the proposed methodology in their future work.

Even though no formal survey among instructors was carried out, it was a common understanding among them that the TPM strategy offers students a more structured and systematic approach to implement an IoT solution, based on a broader view of the context within which the IoT solution is to be inserted. This broader view

Table 2.1 – Questionnaire applied to students.

Questions	**Yes**	**No**
Did you have any previous experience with IoT?	35%	65%
When proposing the initial project, did you miss a methodology to follow?	70%	30%
Did you already know any methodology for teaching/developing IoT solutions?	0%	100%
Has the course achieved its goal?	97%	3%

Assessment - Please Rank	**1**	**2**	**3**	**4**	**5**
The ease of understanding the methodology	0%	0%	5%	30%	65%
The effectiveness of the methodology in helping design your project	0%	0%	5%	40%	55%
The level of difficulty in applying the methodology	5%	20%	20%	30%	25%
The effectiveness of the methodology in helping understand IoT	0%	0%	5%	35%	60%
Your willingness to use this methodology again in a future work	0%	0%	15%	15%	70%
The usefulness of the teaching resources (practical experiments, IoT development kit)	0%	0%	7%	23%	70%

was shown to be very beneficial during the process of selecting technological solutions. Instructors also noticed that the proposed methodology encouraged students to take part in class discussions, this having a direct impact on the quality of their final reports. The fact that the methodology splits the project design into three distinct phases directly leads to this full and thorough class engagement since each phase demands its considerations and discussions.

As a follow up to the courses, the students have been motivated to proceed with a view at entrepreneurship having their projects as a flagship product.

2.8 Conclusion

This paper presented a PBL-Based methodology for IoT teaching following a Three-Phase Methodology for IoT design. This design methodology relies on three well-established phases, namely Understanding the Business, Requirements Definition, and Implementation. The IoT Open Source Reference Model was used to guide the proposal.

The proposed methodology has been applied in graduate and extension courses at the University of Campinas and a survey carried out among attendees showed the effectiveness of the methodology. We do recognize that this is just a preliminary assessment but that hints this to be a promising methodology. Of course, only a thorough and further application of it and by different players will attest the effectiveness of the proposed methodology.

In order to support the application of the proposed teaching methodology, an Open Source IoT development kit was created, which has also been tested in those courses.

The proposal is promising as it employs non-proprietary solutions that meet the various levels of the Reference Model and can be a standard for the teaching of IoT.

Future work will focus on the development of a software framework to be used together with the IoT Kit to assist in the development of TPM.

2.9 Considerations about this paper

The publication of this paper was an important milestone on the development of this work. From this point it was possible to advance in areas that had been little or not explored.

One evident aspect was the lack of tools to operationalize the application of the methodology, which is shown in Table 2.1. The statement "The level of difficulty in applying the methodology" received the worst evaluation. Therefore, this feature received special attention in the continuation of the work.

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3 A TpM-based collaborative system to teach IoT

This chapter is a replica of the paper:

L. C. B. C. Ferreira, R. Yamaguti, Omar C. Branquinho and P. Cardieri, "A TpM-based collaborative system to teach IoT," in Computer Applications in Engineering Education, vol. 30, pp. 292-303, August 2021. Impact Factor: 2.109

This article presents a tool for the application of the TpM. As noted in Chapter 2, the methodology was first presented in its conceptual form, with no tool proposed for its application.

As previously mentioned, in Chapter 2, the lack of concern with the operationalization of the methodology influenced the result regarding its applicability. These results motivated the creation of a tool for this purpose. The system presented in this paper was developed to solve this issue.

Abstract

The Internet of Things (IoT) is a multidisciplinary field involving different areas of knowledge. The development of IoT solutions depends on the integration and collaborative work between professionals from all of these areas. This has led to the development of methodologies to teach IoT, such as the three-phase methodology (TpM). This study presents a collaborative system that operationalizes the use of the TpM, aiding in the process of teaching IoT. This system guides and integrates teams developing IoT solutions while providing easy and structured access to information about the project. The system has been used in short and graduation courses. The results have demonstrated its efficiency in assisting students to develop solutions while applying the TpM.

3.1 Introduction

The Internet of Things (IoT) integrates distinct fields such as computer and data science, and telecommunications (Nižetić et al. 2020). This heterogeneous environment calls for collaboration between a range of areas. Consequently, such collaborative aspect must be incorporated into the IoT teaching process. Students from different fields must have the opportunity to collaborate, working as teams in the creation of IoT solutions (16).

This kind of collaborative work is often called crowdsourcing (Shergadwala et al. 2020), defined as the gathering of knowledge to solve a problem.

Teaching in the field of IoT would benefit from the development of methodologies specific for IoT that consider aspects such as heterogeneity and plurality of technologies, and the standards applied in IoT solutions (Tran-Dang et al. 2020).

The Three-Phase Methodology (TpM) (Ferreira et al. 2019), published in 2019, was developed specifically to teach and develop IoT solutions. The TpM is a guide to project development. It works on a conceptual level, as it does not specify technologies. Although the TpM is conceptually detailed, no tools have yet been defined for its application.

This paper presents a collaborative crowdsourcing-based system developed to aid in the teaching of IoT while applying TpM in the development of projects.

The system was modeled based on the TpM, seeking a systematic and structured dynamic that guides students to collaborative create solutions. The tool is meant to be shared by academic and non-academic communities interested in IoT, contributing to the standardization of IoT teaching.

This work hypothesizes that a collaborative system, created specifically to apply the TpM, will facilitate the methodology's use among IoT students, developers, and enthusiasts, ultimately promoting its dissemination. The use of the system could bring about the creation of a community collaborating in the development of IoT solutions.

The system was tested in a variety of courses, such as graduate courses and short-term distance learning courses. The results show that the tool helps students create projects efficiently and collaboratively.

The remaining of the paper is organized as follows: Section 3.2 discusses some works related to the subject, while Section 3.3 addresses concepts of the system. Section 3.4 describes the implementation of the proposed tool, and Section 3.5 presents and discusses some of the findings. Finally, Section 3.6 features concluding remarks.

3.2 Related Works

3.2.1 The Three-Phase Methodology

The TpM is a structured and systematic methodology, independent of manufacturer or technology, developed specifically for the teaching and development of IoT solutions. For example, the authors of (Chaves et al. 2021) used the TpM for the teaching of low-power wireless communications applied to IoT.

The TpM consists of three well-defined phases:

- Phase 1 (Understanding the Business);
- Phase 2 (Gathering the Requisites);
- Phase 3 (Implementation).

In Phase 1, the methodology follows the premise that, before any choice of technology is made, it is necessary to clearly define the problem and understand the business in need of the solution. To properly understand the business, the TpM considers four aspects:

- Business: description of the business in need of the IoT solution;
- Business Rules: rules and guidelines inherent to the business, such as definitions of alarms, and decision-making criteria;
- Specialist: professional(s) knowledgeable of the business that can aid in the elaboration of the business rules;
- Things: information, metrics, and other details to be monitored and controlled by the application.

Phases 2 and 3 use the IoT Open-Source Reference Model (IoT-OSRM) (Déo 2018), which considers six levels to link the Things to the Business. These levels can be seen in Figure 5.2 and are briefly described below.

- Level 1 – Sensor/Actuator: devices responsible for monitoring and controlling the Things;
- Level 2 – Connectivity: defines the connection between the Things and the Border;
- Level 3 – Border: element that links the local and outside networks. It also defines processing and storage functions for local data;
- Level 4 – Storage: defined by the system and data storage rules;
- Level 5 – Abstraction: layer where data processing is made suitable for use;
- Level 6 – Display: defines how the information is shown to the end user.

In Phase 2, the objective is to outline the requisites that should be met at each level of the IoT-OSRM. This phase precedes any technological choice, only defining the characteristics that will guide the solution's implementation. Phase 2 follows a top/down approach, starting at the Display level and covering all levels up to the Sensor/Actuator

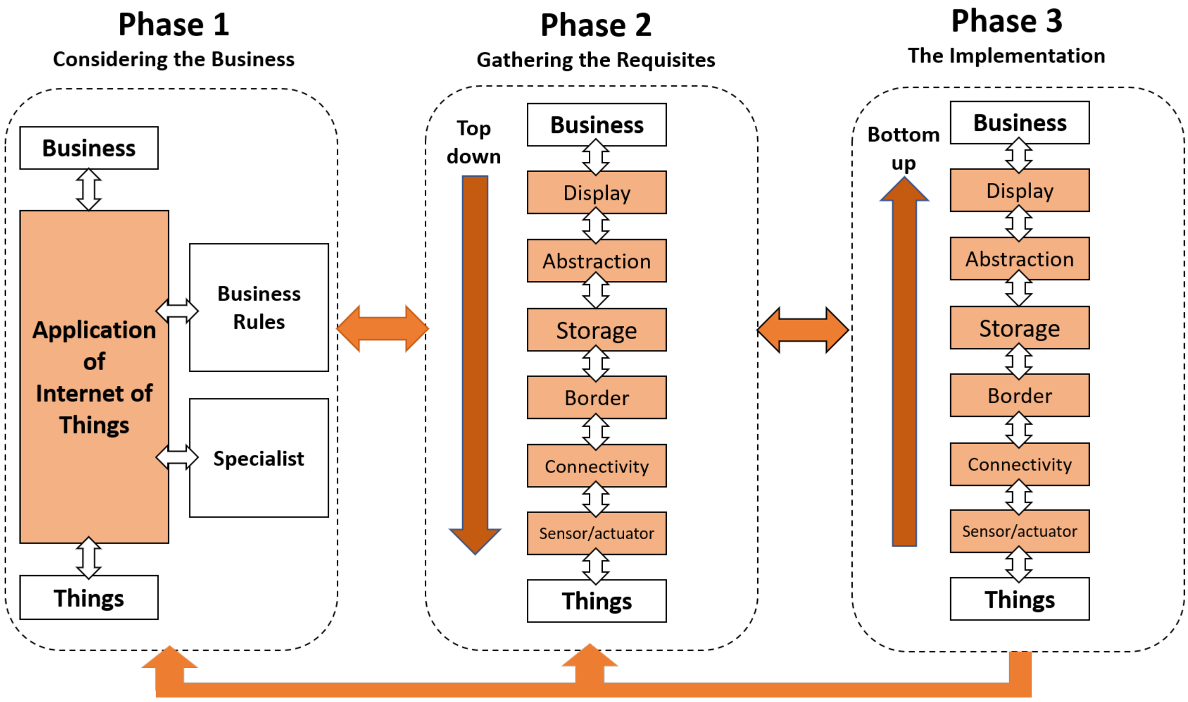

Figure 3.1 – The Three-Phase Methodology diagram encompassing the 6-level IoT-OSRM (adapted from (Ferreira et al. 2019)

level. The techniques and technologies that best meet the requirements defined in Phase 2 are only chosen in Phase 3. This phase follows a bottom/up approach, starting at the Sensor/Actuator level and moving up through all layers until the Display layer.

3.2.2 Development of Collaborative Projects for IoT

The IoT involves a vast array of fields, featuring professionals from many different areas. The integration of these professionals can be a real obstacle to ensure proper collaborative work.

In (Maiti 2019), a collaborative laboratory for IoT teaching is presented. It is used as a background to create an IoT solution for rural and farm environments. The work centers on allowing students to have an environment where they can work as a team, through the creation of IoT solutions. This work also shows a set of software and hardware that should be used by the students to create IoT solutions.

Another interesting work is shown in (Fernandes et al. 2015), which proposes the use of crowdsourcing for modeling and testing IoT solutions.

In (Hussein et al. 2019), a proposal for a platform to teach the concept of IoT is presented. This platform is also based on the concept of crowdsourcing and aims at passing down initial concepts of IoT to students, without addressing professional or technical aspects.

In (Brabham 2013) and (Liu et al. 2020), crowdsourcing is defined as an online service, which provides a distributed solution for problems. It boosts the collective intelligence of online communities established by organizations, be them corporate, public, or individual.

The authors of (Ziegler et al. 2017) propose a combination of crowdsourcing and IoT. Part of the objective is to create collaborative tools and allow the use of shared data by the crowd to develop solutions and research.

These works showcase the effort to apply methodologies that promote integration and cooperation among professionals of different areas to elaborate IoT solutions. The development of techniques, methodologies, and tools that promote this process plays a strategic role in the development and dissemination of the Internet of Things.

However, these proposals do not employ any standard for teaching and development. The system presented in this paper offers a collaborative system, based on a well-defined and structured methodology for IoT teaching and development, that organizes teamwork.

3.3 Underlying Concepts of the System

The TpM is a structured and systematic methodology for teaching and developing IoT. The creation of a tool to apply this methodology should follow specific and well-defined concepts. Moreover, the possibility of working collaboratively on IoT solutions is another premise of the system.

In this section, we describe the dynamics used to apply the TpM to develop IoT projects. These dynamics are the conceptual base used to model and develop this system.

These dynamics are well defined and through them, students are introduced to the inherent concepts of TpM. This approach is important to assure students will comprehend the methodology. The system is collaborative and allows students to gather as teams and work together on projects, creating and organizing documentation. This organization makes the search for information easier in any phase of TpM, ensuring that data are always updated and well structured.

The TpM is interactive and incremental, cycles could be repeated any number of times, creating updated versions of the project, with corrections and new functionalities. However, during the first cycle of application, students must follow the steps of each phase aiming at understanding the methodology and integrating the development team.

In the next section, we present the specific concepts for each phase of the methodology and how they work as a guide to model and implement the system.

3.3.1 Phase 1 – Understanding the Business

Phase 1 emphasizes the TpM. The main methodology is centered on a business/project. This premise has been inherited from Project-Based Learning (PBL) (Bell 2010) (Guo et al. 2020), an active teaching methodology that was used as basis for the TpM.

Phase 1 has all elements to clearly define the objective of the IoT solution, thus defining the problem that it is meant to solve. To do so, it has 4 items that should be defined before moving on to Phase 2, as shown in Figure 3.1: (i) Business, (ii) Business Rules, (iii) Specialist and (iv) Things.

Phase 1 must be concluded before progressing to Phase 2, because if the problem is not well determined, the next phase could follow an incorrect path as the requirements have not been properly taken into consideration.

Therefore, the system to be developed should not permit the user to advance to Phase 2 before completing Phase 1. Users are invited to fill in each item on Phase 1 before Phase 2 is available.

Moreover, the interface should be intuitive, instructing the user "to walk through” the methodology. After the first version of Phase 1 is concluded, the user can access Phase 2 of TpM.

3.3.2 Phase 2 – Requirement Definition

Phase 2, "Gathering the Requisites", seeks the characteristics to be observed in the implementation of each level of the reference model, as illustrated by Figure 3.1 and described in Section 3.2.

This second phase follows a top-down approach, beginning by defining the requirements from the highest level, Level 6 (display), and moving down until Level 1 (sensor/actuator). Thus, users are instructed to follow that path of definition. TpM states that this top-down approach is important for the integration of the development team. Each participant should take part and be aware of the requirements of each level. For example, the person responsible for Level 1 (sensor/actuator) works with hardware, but must also know the requirements for Level 6 (display).

This approach allows a more functional view of the solution, starting from the highest level, which is how the user should interact with the proposed solution.

The requirements for the IoT solution cannot be defined separately. The solution involves the integration of a vast array of techniques and technologies. The TpM creates this integration when defining a well-structured path that should be followed in the first iteration of the methodology.

Requirements are defined and documented in each level. This will be used in the implementation phase. The system should provide a way to fill the data into the development team, following the path established by TpM. Access to Phase 3 is granted once Phase 2 is completed.

3.3.3 Phase 3 – Implementation

Phase 3 involves choosing the techniques and technologies to be used, based on the requirements defined in the previous phase. Phase 3 follows a bottom-up approach, beginning with the implementation in Level 1 (sensor/actuator).

This approach is important because it involves all team members, from monitoring/controlling of the "things", which is the most physical level of the solution, until the most abstract level, where data are displayed to the end user (display). Starting at Level 1 (Sensor/Actuator), the use of a didactic hardware resource is handy, so the students have the first contact with the implementation, albeit in a basic version.

The system allows students to fill out the information related to each level of the model during the solution's implementation.

Students must follow the bottom-up approach on the first iteration of the methodology. At this point, the teams already have all the information needed to decide how the solution will be implemented.

Another feature of the TpM is that it is independent of manufacturer or technology. The solution is to be created in a systematic and structured way, regardless of the technology employed.

3.4 System Implementation

This section details the system implementation process. The system can be accessed on www.iotm3f.cc, as shown in Figure 3.2.

3.4.1 System Modeling

The Unified Modeling Language (UML) (Bork 2020) is a reference language for structuring and modeling software. It was elaborated as a use-case diagram (Figure 3.3), as described below:

- Maintain the User User sign-up, sign-in, and alteration. The user can sign-up, if not already, using his name, last name, email, and password. After signing up, the user can sign in with his e-mail and password;

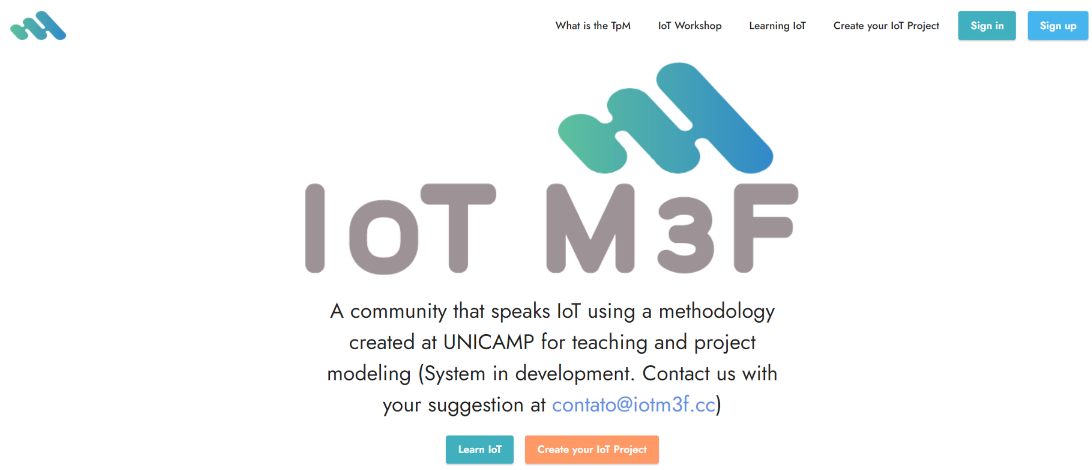

Figure 3.2 – System's landing page

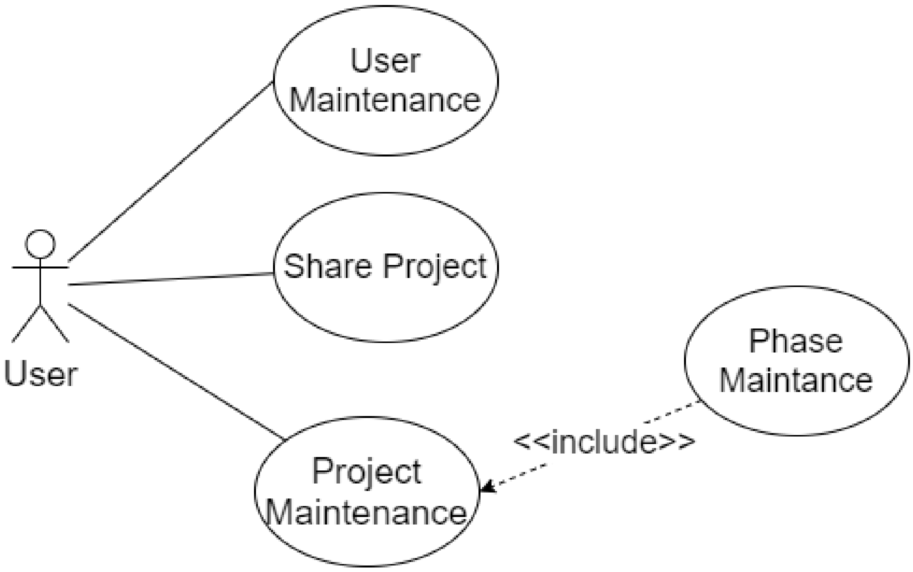

Figure 3.3 – User-Case.

- Maintain the Project A function that allows the user to create, edit and delete a project. The user can create a project in Phase 1 and name it;
- Maintain the Phase Possibility of writing and editing data in each of the three phases;
- Sharing of the Project Possibility of sharing a project with other users, granting permission to alter any phase or attribute, but not to delete it.

This Entity-Relationship data model is a graphic representation of the relationships and attributes within a database, as shown in Figure 3.4. The collaborative nature of the system can be seen through this diagram, where users share projects and work collaboratively with the data organized and updated continually, following what is expected on the TpM.

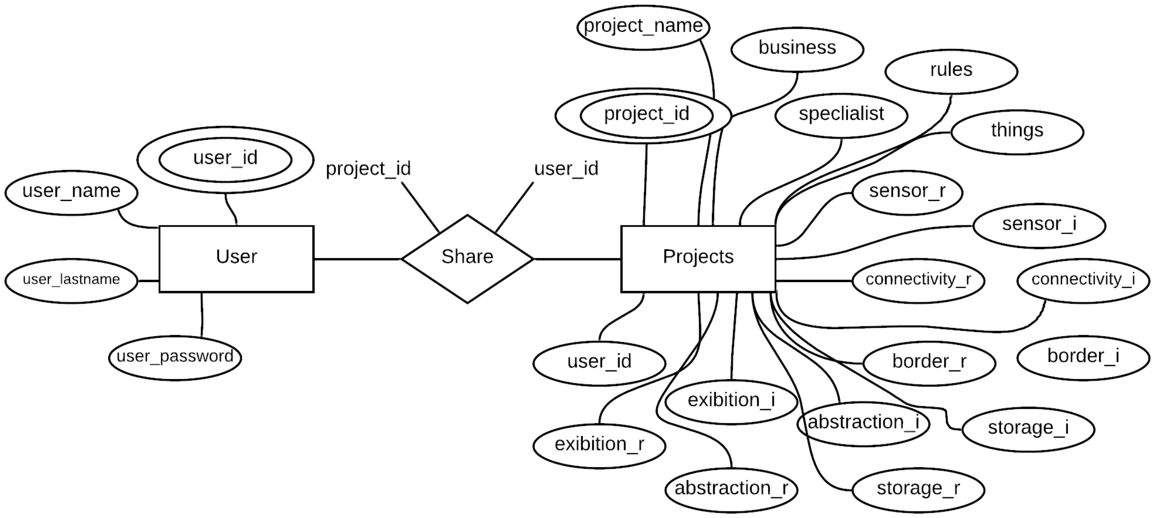

Figure 3.4 – Entity–Relationship Model.

The UML also presents the Class Diagram, a graphic representation of the objects and data structures within the system. This diagram shows the attributes and operations (methods) of each class, as well as their relationships, as shown in Figure 3.5. It also details the dependency established between the TpM phases and the project. The Class Diagram shows how the objects mimic the reference model defined in (Déo 2018).

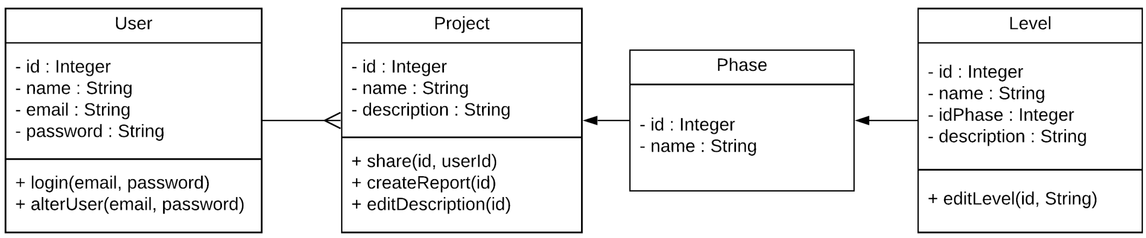

Figure 3.5 – Class Diagram.

3.4.2 Technologies

The system was implemented using a Linux machine with an Apache Server installed, which is an open-source web server, developed by an open community under the guidelines of the Apache Software Foundation. Netcraft has estimated that Apache is one of the most used types of web-server, present in approximately 25.60% of active websites (netcraft 2020).

Apache implements PHP, a programing language processed by a web server and displayed into HTML format, making it a web language. PHP is an open-source, community-driven language. It is used in approximately 79.2% of websites (w3techs 2021), according to the 2020 W3TCHS survey, making it the most popular language for web development.

JQuery was used to enhance PHP performance and make it more user-friendly. JQuery is a Javascript library that simplifies event handling, animations, and asynchronous associations between JavaScript and XML (AJAX). According to (w3techs 2021), JQuery is used in around 79% of websites.

Another key feature implemented in the web server was the database in MySQL. MySQL is an open-source, SQL-based relational database widely used in many web-related applications. The data from projects and users are stored on MySQL in accordance with the standards of the GDPR (Voigt e Bussche 2017), whereas all of the data are encrypted in disk combining the MD5 hash system of encryption with RSA public-key cryptography algorithm. The web-based system also implements the HTTPS protocol for further data protection.

The system implements the MVC concept (Supaartagorn 2011), which is a software design standard that divides the software developed into three components:

- Model: Components that implement the objects described in the class diagram;
- View: Components shown to the user. In our system, they are present in HTML format along with Javascript and JQuery;
- Controller: The controller is the middle-man between the Model and the View, responding to the user's input in the View component and processing the input data for the model component.

To develop the system, we adopted the Agile methodology, as it promotes continuous improvements and adaptive and flexible planning.

3.4.3 The System

The system is freely available for academic and corporate sectors, contributing to its enhancement and the creation of a community to teach and develop IoT.

The system was implemented following the concepts presented in Section 3.2. This subsection presents the interface, as shown in Figure 3.6. Navigation through the methodology's phases follows what was laid down in Section 3.2 (i.e., the phase order established on the TpM must be followed on the first iteration). The menus for other phases are not unlocked until the fields are filled in the proper order, as shown in Figure 3.7.

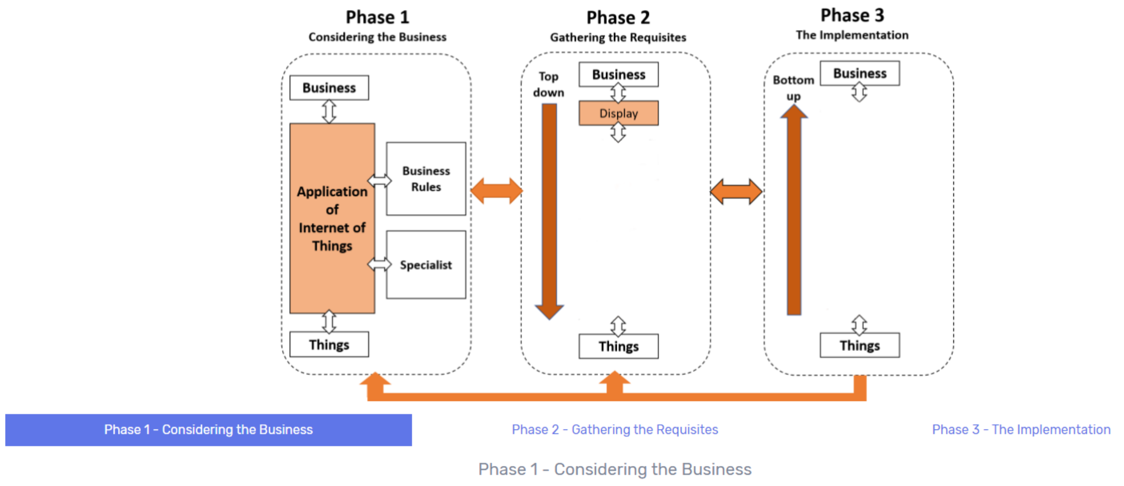

Figure 3.6 – System Screen.

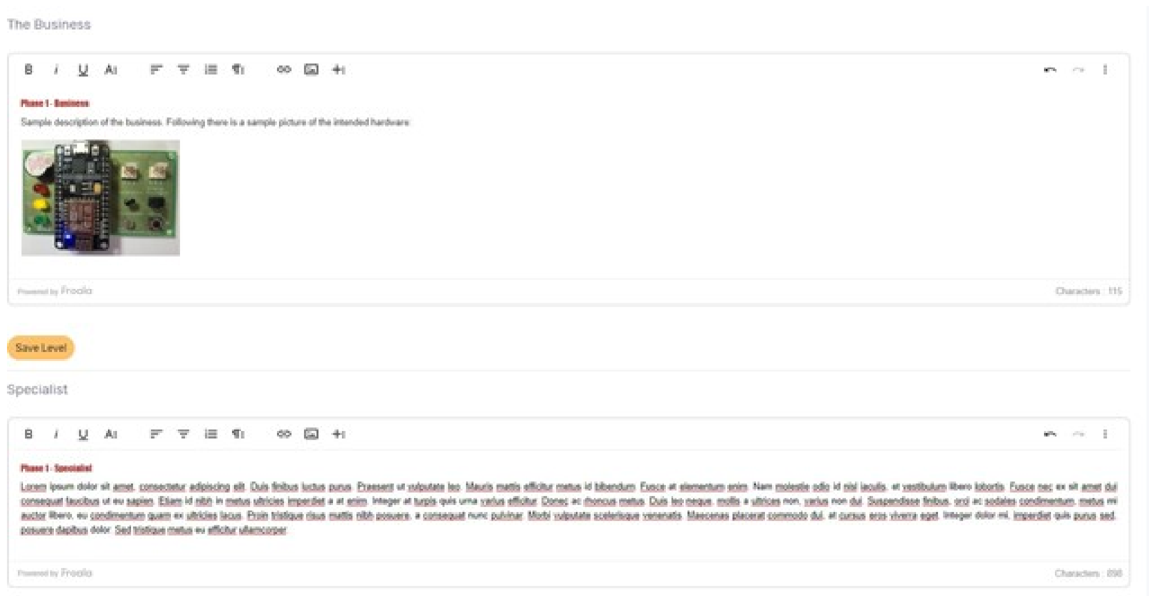

Figure 3.7 – Editing a project.

The flowchart of this first iteration is shown in Figure 3.8. The user can also have access to data inserted by other members with whom they have shared the project. The modal that is used to grant sharing permissions to other users is shown in Figure 3.9.

Once the project has been shared, it is available to members in the section Managing the Projects, as shown in Figure 3.10.

Another functionality is the possibility to generate reports. These reports summarize how the three phases of the TpM are applied by the student, in addition to showing the project owner and shared members. This feature is handy for students to submit their project deliverables to teachers for evaluation. An example of a report can be seen in Figure 3.11.

Figure 3.12 shows a field in the system, related to Phase 1 - Level 1. Each level

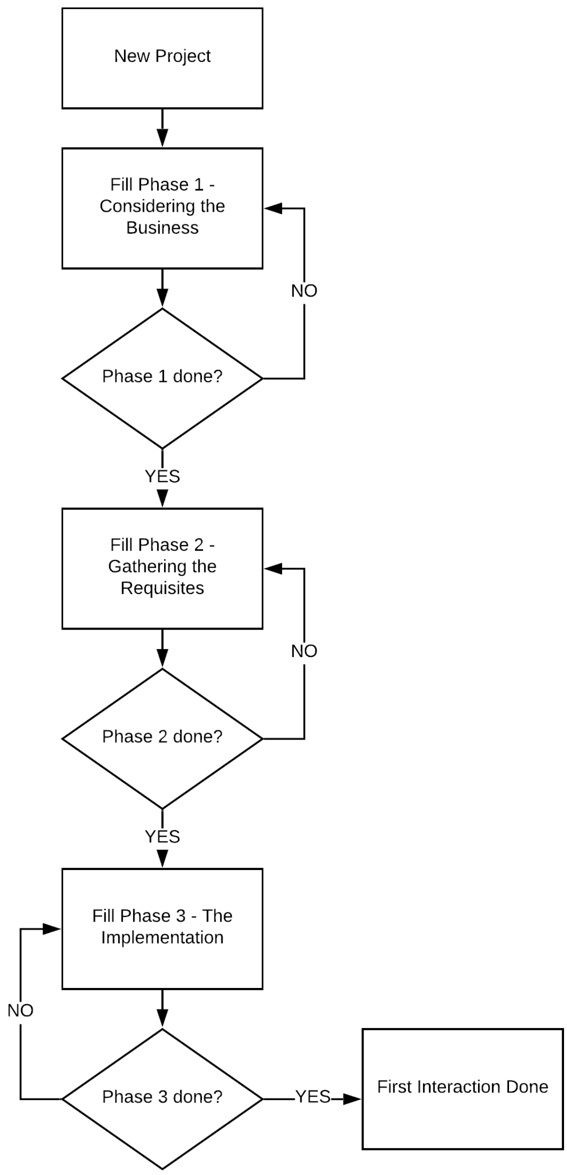

Figure 3.8 – Chart of the first iteration.

has its respective field documented, allowing the attachment of other types of information, such as videos, files, and code.

There is a "help" item with information on relevant aspects that should be considered when applying TpM. There is also an area that explains the TpM in detail.

3.5 Results and Discussion

An effective way to measure the efficiency of a teaching method is by surveying students' opinions, through a questionnaire, regarding some aspects of the method (McKeachie 1997) (Stroebe 2020). In the first opportunity TpM was applied, as presented

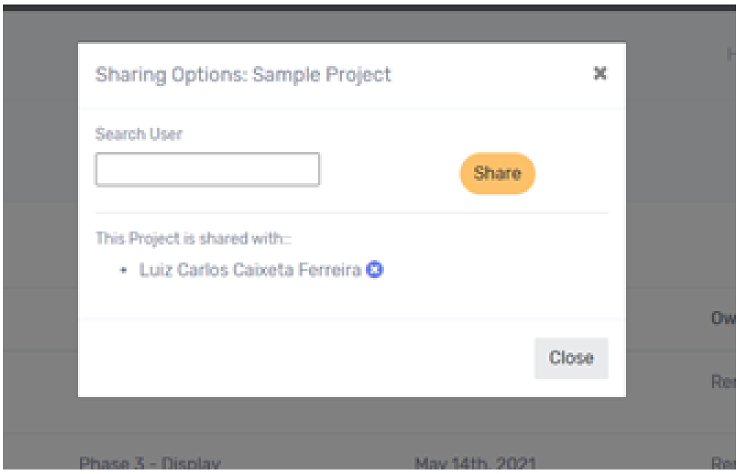

Figure 3.9 – Sharing options.

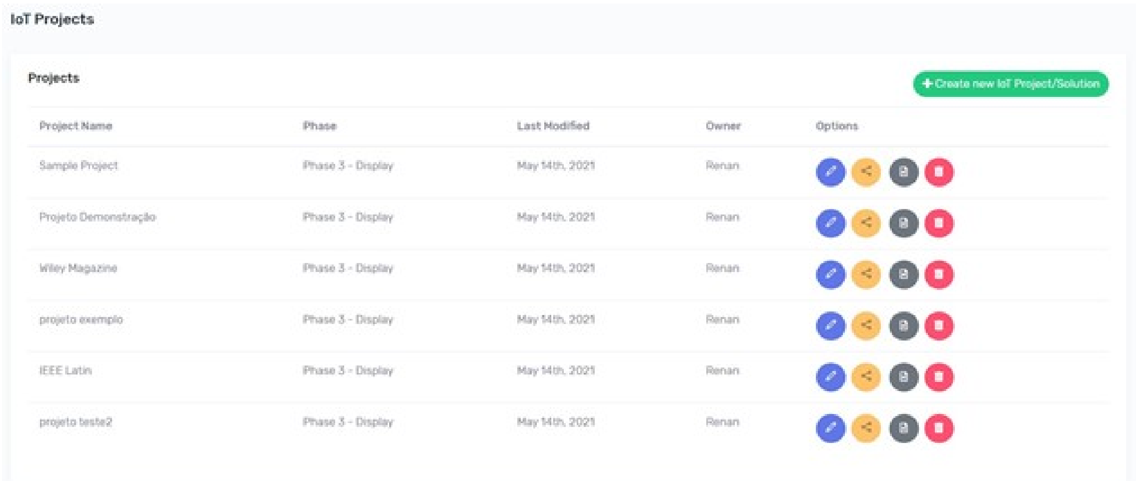

Figure 3.10 – Screenshot for edit and sharing projects.

in (Ferreira et al. 2019), no system dedicated to the methodology was employed. At that opportunity, a questionnaire was applied to assess the methodology, with some specific questions regarding the effectiveness of the methodology, the level of difficulty to employ it, among other aspects. Some of these questions, relevant to the present work, are shown in Table 3.1. The students scored each statement from 0 (strongly disagree) to 5 (strongly agree). Although the rates regarding the methodology itself were high, as shown in (Ferreira et al. 2019), students found some difficulty in applying the TpM. This result motivated the development of the system presented in this paper, as a tool to facilitate the application of the TpM.

The system has been tested in short-term and graduate courses at the University of Campinas (UNICAMP). Also, it has been used in distance courses offered by our development team. In these courses, students used the system to elaborate and collaboratively document their IoT projects.

An evaluation questionnaire, with six statements, shown in Table 3.2, was applied to a group of 23 students to initially assess the system's efficiency. The students

Report created on: May, 14th 2021

Author: Renan Yamaguti
Shared with: Carlinho Caixeta, Omar Branquinho

Sample Project

Description: This is a sample description for this project

Phase 1 - Considering the Business

Business

Phase 1 - Business

Sample description of the business. Following there is a sample picture of the intended hardware:

Specialist

Phase 1 - Specialist

Lorem ipsum dolor sit amet, consectetur adipiscing elit. Duis finibus luctus purus. Praesent ut vulputate leo. Mauris mattis efficitur metus id bibendum. Fusce at elementum enim. Nam molestie odio id nisl iaculis, et vestibulum libero lobortis. Fusce nec ex sit amet dui consequat faucibus ut eu sapien. Etiam id nibh in metus ultricies imperdiet a at enim. Integer at turpis quis urna varius efficitur. Donec ac rhoncus metus. Duis leo neque, mollis a ultrices non, varius non dui. Suspendisse finibus, orci ac sodales condimentum, metus mi auctor libero, eu condimentum quam ex ultricies lacus. Proin tristique risus mattis nibh posuere, a consequat nunc pulvinar. Morbi vulputate scelerisque venenatis. Maecenas placerat commodo dui, at cursus eros viverra eget. Integer dolor mi, imperdiet quis purus sed, posuere dapibus dolor. Sed tristique metus eu efficitur ullamcorper.

Figure 3.11 – Sample report generated from a sample project.

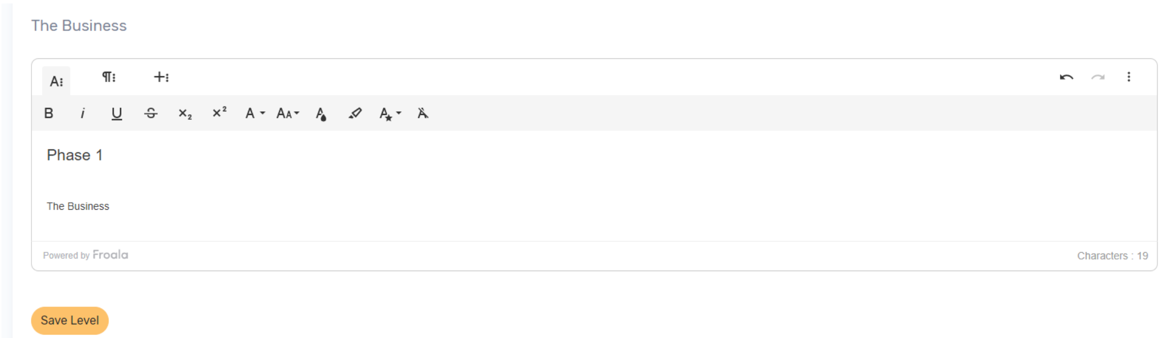

Figure 3.12 – System screen for describing a field of TpM.

scored each statement from 0 (strongly disagree) to 10 (strongly agree).

Two evaluation methodologies were used, as in (Chaves et al. 2021), as described below. The first methodology is based on the Customer Score Satisfaction (CSat) (Korneta 2014)(Ali 2018), whose score is expressed on a scale of 0 to 10. The mean score for each question is expressed on a scale of 0 to 100%. A score of 100% represents the student's total satisfaction. The CSat is calculated as follows:

$$Csat = (\frac{\sum Score}{Students}) * 10 \tag{3.1}$$

The second methodology is based on the Net Promoter Score (NPS) (Grisaffe 2007; Sasmito e Nishom 2019). This score ranges from –100 to 100 and measures the satisfaction and general willingness to recommend a product or a service to other people. To calculate the NPS, answers are grouped as detractors, for scores between 0 and 6; passives, for scores of 7 and 8, and promoters, for scores between 9 and 10. In our case, we used the

Table 3.1 – Questionnaire applied to students (© [2019] IEEE. Reprinted, with permission, from (Ferreira et al. 2019))

Assessment - Please Rank	**1**	**2**	**3**	**4**	**5**
The ease of understanding the methodology	0%	0%	5%	30%	65%
The effectiveness of the methodology in helping design your project	0%	0%	5%	40%	55%
The level of difficulty in applying the methodology	5%	20%	20%	30%	25%
The effectiveness of the methodology in helping understand IoT	0%	0%	5%	35%	60%
Your willingness to use this methodology again in a future work	0%	0%	15%	15%	70%
The usefulness of the teaching resources (practical experiments, IoT development kit)	0%	0%	7%	23%	70%

statement "I would recommend the use of the system to create and document IoT projects using TpM" to calculate the score NPS. The NPS is calculated as

$$NPS = (\frac{no.promoters - no.detractors}{Students}) * 100 \tag{3.2}$$

An NPS of -100 means that every student is a detractor, while an NPS score of 100 means that every student is a promoter. Usually, a score higher than zero is considered good, higher than 50 is considered excellent, and above 70 is exceptional.

The resulting values of CSat, for the first five questions, and the NPS, which was evaluated using the last statement, are shown in Table 3.2.

The results of the CSat hovered around 90%, showing that students were mostly satisfied with the system, suggesting that it has achieved this objective. It also shows that some students seem to prefer inductive teaching methods to standard approaches, as shown in (Hormigo e Rodriguez 2018).

The lowest score was on the aspect of providing an environment for collaborative projects in IoT. This information will be taken into consideration in future improvements of the tool, since being collaborative is one of the main features of the system.

The NPS score was 86%, which shows that most students would recommend the system to others. This result shows that, according to the students, the system is useful and relevant for creating IoT projects.

This analysis showed that the system is an efficient tool for the application of the TpM, contributing to the teaching of IoT.

Table 3.2 – Results of Csat and NPS

Affirmations	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**CSat**
The system is structured following the TpM.	-	-	-	-	-	-	-	4	13	22	61	94
The system helped me on the understanding of TpM.	-	-	-	-	-	-	4	4	26	4	62	91
The system helped me on maintain the structure of the project following the TpM.	-	-	-	-	-	-	-	4	17	22	57	93
The system provides a collaborative environment on IoT project (sharing projects).	4	-	-	-	-	-	-	4	22	13	57	87
The system helped me out on the creating and documentation of IoT projects.	-	-	-	-	-	-	-	13	9	26	52	92
												NPS
You would recommend the use of the system to creation and documentation of Iot projects using TpM.	-	-	-	-	-	-	-	-	13	22	66	86

3.6 Conclusions

In this paper, we presented a collaborative system that assists the application of the TpM. The main objective was to aid the development and documentation of projects in a collaborative way.

The system is freely available at the web address www.iotm3f.cc. Its use by the academic community and other sectors could contribute to the teaching and development of IoT solutions.

The system was tested in a variety of courses, from short-term distance to graduate disciplines. An initial evaluation has shown that the system is a promising initiative that meets the principles of the TpM.

The system is in constant development. Future work should include new features and improvements to make it a complete platform for IoT teaching and development.

3.7 Considerations about this paper

This article introduced the first tool developed specifically for the TpM. The system had an important role in this work, through the evaluation made by the users, it was possible to verify that the creation of customized tools for the TpM could significantly contribute to the dissemination and improvement of the methodology.

This first system was improved and became a Virtual Learning Environment, built entirely based on the TpM. This environment is currently in operation and constantly evolving.

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4 The Three-Phase Methodology for IoT Project Development

This chapter is a replica of the paper:

L. C. B. C. Ferreira, P. R. Chaves, R. M. Assumpção, O. C. Branquinho, F. Fruett and P. Cardieri, “The Three-Phase Methodology for IoT Project Development,” in Internet of Things; Engineering Cyber Physical Human Systems, October 2022. Impact Factor: 5.711.

Following the application of the TpM in the academy, we noticed that the TpM had characteristics similar to methodologies for project development. Therefore, the possibility of using the TpM for developing IoT projects, in corporate environments, was explored.

Throughout the research, the TpM was improved to make it applicable outside the academy. Actors, artifacts and tools were added to make the TpM more suited for this purpose. These changes resulted in a version named TpM-Pro, which was applied in a corporate project. These results are presented in this paper.

Abstract

The development of IoT solutions requires the expertise from professionals from several areas. This multidisciplinary aspect can be better served with an integrated process to structure the development of these solutions. There are several software development methodologies, such as Ignite and ELDAMeth, that have been adapted for this end. However, most lack some fundamental functionalities. The Three-Phase Methodology for Project Development (TpM-Pro) was originally developed as an IoT teaching methodology that proved ideal for solution development. It is a generic, agile, interactive, technology-independent and incremental methodology that splits the development of solutions into three distinct phases: Business, Requirements, and Implementation. This segmentation has proved invaluable and can become a standard for IoT solution development. In this paper, we present the TpM-Pro, gauge it against five other methodologies proposed for IoT solution development and detail its application on a corporate IoT project.

4.1 Introduction

The Internet of Things (IoT) is a reality. Reports indicate that billions of objects are going to be connected in the coming years, exchanging information and interacting with the environment intelligently (Lombardi 2021)(Tunstel et al. 2021). In March 2022, the author of (Wegner 2022) wrote at IoT Analytics, a German publication specialized in market information and strategic business intelligence for the IoT, that companies' expenditure on IoT grew 22.4% in 2021 to US$158 billion. The author also forecasts that the IoT market value, including security, hardware, services, and software will grow to US$525 billion by 2027.

However, there are also challenges, according to Why IoT Projects Fail report (Woolley 2020), a survey conducted with 637 representatives of 250 companies distributed across 42 countries, showed that one of the barriers to success in the development of IoT projects was the higher level of knowledge in design and architecture needed. This indicated that methodologies and architectures that simplify the development process can play a decisive role. Another important finding was that often the definition of the business, its objectives, and expected returns are not taken into account, seriously contributing to the failure of IoT projects. The report concludes stating that focusing the solution on technology only is a mistake.

Also, according to (Jha 2016), "eight out of ten IoT projects fail even before they are launched" and most new projects of IoT solutions are "in search of a business problem". The author of (Jha 2016) adds that companies are developing solutions first and then offering them to solve business problems that may not exist yet.

IoT solutions often have many features and architectures, as a multiplicity of sensors/transducers connectivity technology, reconfigurability, connectivity to the Internet, distributed functionality, flexibility, and interoperability. Although most of these features are present in IoT systems, the criticality of each depends on the application requirements, making it difficult to define one architecture for all IoT solutions (Chakravarthi 2021).

Methods and frameworks for creating IoT applications have been objects of research over the years. There is a concern about how to create and develop IoT solutions that need to consider the heterogeneity of techniques and technologies that must be used in an integrated manner (Dias e Restivo 2022). These include frameworks for the creation of solutions for IoT in smart cities (Jin et al. 2014), frameworks for health and safety monitoring (Hayward e Katherine 2022) and methods and technologies for geologic hazard prevention (Mei et al. 2019).

Also, currently, most IoT solution development depends on conventional techniques adapted from software engineering. A project methodology that considers the specificity of the IoT would be a significant contribution to the industry.

The Three-Phase Methodology for IoT Project Development (TpM-Pro) presented in this work addresses these shortcomings. The TpM-Pro was specifically formulated for the IoT, it is flexible and can be used in the development of any kind of solution. Its main differential is that it focuses on a complete understanding of the business in need of a solution and on the end-user needs.

The TpM-Pro has its origins in academia as the TpM (Ferreira et al. 2019), originally published in November 2019. It is a technology-independent methodology, used by students to manage the many disciplines involved in developing IoT solutions. The TpM presents a generic way to structure and plan a project, as well as manage and integrate the development team.

The TpM follows a consolidated three-phase process that starts with the Considering the Business Phase, followed by the Gathering of Requirements Phase, and concludes with the Implementation Phase. The TpM encompasses the IoT Open-Source Reference Model (IoT-OSRM) (Déo 2018). This model helps to analyse the IoT solution logically thus facilitating requirement acquisition and identification of possible implementation difficulties. The open nature of the IoT-OSRM ensures the TpM's flexibility and adaptability.

The TpM has been extensively applied in the academic environment over the last three years, in extension and postgraduate courses, with more than a hundred students, as seen in (Ferreira et al. 2019), (Chaves et al. 2021) and (Ferreira et al. 2021). During its academic use, it was observed that the methodology has great potential to be used in the development of corporate IoT solutions.

This led to the development of the TpM-Pro, an expansion of the original TpM. The TpM-Pro adds to the original TpM as it incorporates project specific attributes like agents, roles, artifacts, and the TpM-IoT-Canvas.

Thus, an contribution of this work is to present the TpM-Pro as a methodology for corporate IoT projects, drawing from the experience acquired during its use in the academic world.

The TpM-Pro could be used by teams developing IoT projects in virtually all areas, such as banking, finance, energy, manufacturing, mining, etc.

To test the TpM-Pro in corporate projects, a consultancy was offered to a startup company developing temperature and mechanical vibration monitoring devices for industrial rotating machines. The consultancy covered all aspects of the TpM-Pro. The results of a survey carried out with the development team, at the end of the project, showed that the methodology was well accepted.

Therefore, the main contributions of this work are:

- A literature review of development methodologies used for IoT is presented;
- Description of the TpM-Pro, an original, consolidated and generic methodology for developing IoT projects, focused on the business and the problem in need of a

solution;

- An analysis of the TpM-Pro in relation to the development methodologies covered in the literature review;
- A description of its application in a corporate project.

The rest of this article is organized as follows: Section II presents five different development methodologies for IoT solutions, comparing them to the TpM-Pro, while Section III details the TpM-Pro for IoT project development. Section IV presents a case when the TpM-Pro was used in the development of a corporate project. The article ends with the conclusions in Section V.

4.2 System Development Methodologies - Literature Review

The selection of works covered in this literature review favoured the following criteria: shortest time since publication, higher publication impact factor, larger number of citations and better known authors, following what is presented in the work of (Edwards e Barron 1994).

The literature lists some characteristics considered by (Miorandi et al. 2012) (Wang et al. 2020) (Fortino et al. 2020) when classifying IoT methodologies, namely: interoperability, autonomy, scalability, and smartness.

a) Interoperability: "The extent to which systems or products can exchange and use the information that has been exchanged" (Noura Mahda 2019). In IoT, interoperability entails that, regardless of their characteristics, systems can communicate and interact with each other

b) Autonomy: The authors of (Albus e Antsaklis 1998) define autonomy as an operating domain constrained by parameters that guarantee the operation without supervision. In the IoT context, autonomy implies that systems are independent to operate and self-manage.

c) Smartness: It is defined by (Alter 2020) as the capability of a system to autonomously act on data gathering, information processing, knowledge acquisition, and actuation. For the IoT, smartness relates to emulating the human behaviour and the processes of learning and adapting.

d) Scalability: "Ability to handle an increasing amount of work while adapting to environmental change" (Gupta Anisha 2017). Any IoT system must offer support for an increasing number of devices and applications without affecting its performance.

Table 4.1 – Comparison between IoT Development Methodologies

Methodology - Origin	Characteristics
TpM-Pro – Academy	**Objective:** to offer a flexible and adaptable technology independent project methodology for IoT project. **Main Aspects:** considers the complexities of IoT solutions and the need for a manufacturer independent approach. Approaches the solution as a whole, with the business at its core. Covers agents and roles, business, requirements gathering and implementation. Emphasis on documentation. **Interoperability:** supported. **Autonomy:** supported. **Smartness:** supported. **Scalability:** supported.
Resilient-IoT – Academy	**Objective:** develop and implement components that will work at the edge of an IoT solution. **Main aspects:** proposes that some basic entities like Environment, Problems, Actors and Coordinators must be defined. **Interoperability:** limited. **Autonomy:** supported. **Smartness:** supported. **Scalability:** supported.
SPP – Academy	**Objective:** identify similarities between agents to develop a reference architecture; cost and implementation time reduction, and better quality. **Main aspects:** in-line production of software; use of agents and product line engineering software. Does not consider the business, nor the implementation. **Interoperability:** supported. **Autonomy:** limited. **Smartness:** supported. **Scalability:** supported.
HLAD – Academy	**Objective:** application development based on Model Driven Design approach and on the work in macro programming of sensor networks. **Main aspects:** identifies different interests in a conceptual model. Implements the methodology as a development framework. Segments the process into areas of interest. Does not consider business needs. **Interoperability:** supported. **Autonomy:** supported. **Smartness:** limited. **Scalability:** supported.
ELDAMeth – Academy	**Objective:** to enable rapid prototyping based on visual programming, validation and automatic code generation. **Main aspects:** defines high-level characteristics and technical aspects. Can include problem statement, define “things”, agents, etc. Does not consider the business or the requirements. **Interoperability:** supported. **Autonomy:** limited. **Smartness:** limited. **Scalability:** supported.
Ignite – Industry	**Objective:** to deliver best practices in the form of reusable, technology-independent and open-source methodology. **Main aspects:** provides project templates, checklists and solution architecture schemes.Defines the process until delivery of the operational IoT system. Does not provide technical support. **Interoperability:** supported. **Autonomy:** limited. **Smartness:** limited. **Scalability:** limited.

The development of software systems benefits from the use of Systems Development Methodologies (SDMs), as they help the final product to meet functional and non-functional project requirements (Pressman e Maxim 2016).

SDMs guide the development of systems, providing guidelines on different aspects such as stakeholders' roles and artifacts to be produced. SDMs also formalize procedures, ensuring consistency in the development phases, logically ordering processes, and preventing important aspects from being neglected (Saeed et al. 2019)(Fortino et al. 2017). SDMs provide a set of standards and goals to be achieved and make it easy to verify if the final solution meets the previously defined requirements, allowing the monitoring of the project's progress and contributing to the coordination of different teams (Song e Osterweil 1994).

The IoT involves software, hardware, and communication components. The development of IoT projects can capitalize on some aspects of the SDMs created for the development of software projects. The IoT, however, needs a broader approach, as its inherent multidisciplinary nature makes the development process of these projects more complex, as it involves professionals from different areas of knowledge (Lee e Lee 2015).

The function of an IoT system is to connect a user to a virtual representation of an entity in the physical world, i.e. the representation of a "thing", be it a sensor, actuator, tag or physical magnitude (Greengard 2021).

In addition to SDMs, there are generic options for developing complex distributed systems. An example is the Reference Model of Open Distributed Processing (RM-ODP), defined by ITU-T Rec. X.901-X.904, ISO/IEC 10746 (Vallecillo et al. 2001). The RM-ODP is a framework for system specification that incorporates viewpoints, such as computational and enterprise viewpoints. However, it is a generic standard, developed in 1998, with several documents and specifications. It is an example of a framework that was not specifically created for the IoT that can be adapted to that end.

The literature lists some SDMs already adapted to the development of IoT systems, originating both in the industry and in academia. We have identified five SDMs that have a detailed structure that can serve as a benchmark for the TpM-Pro. Table 4.1 presents the comparison between the TpM-Pro and these methodologies according to their characteristics.

Interoperability was measured taking into account the level of abstraction and independence of technologies, provided by the methodology. Most of them call upon model-driven engineering (MDE), which offers an approach to engineering interoperable solutions by means of Object Management Group´s (OMG) established modeling standards, such as the unified modeling language (UML) and metalanguages, such as XML-like.

The autonomy in IoT systems is largely acknowledged as a cross-domain and cross-layer key feature. It is interesting that the SDMs provide a methodological approach to this aspect. The scale, dynamics and complexity of IoT systems make a fully human management difficult, often, the management of the solution must be hybrid, divided into human aspects (administrators, developers, users) and software and hardware agents. To assess this characteristic, the SDMs were verified in order to find a way to define these responsibilities, either at a methodological level (high level of abstraction) or implementation (programming languages, technologies and techniques).

IoT methodologies address the issue of scalability from both programming and architectural perspectives. From a programming perspective, this view takes into account technology aspects, such as macro-programming approaches to group devices in hierarchical clusters based on their spatial relationships. The architectural perspective involves how the methodology provides a generic framework for scalability to be thought through and planned. This approach is the focus of this work and was the focus of the analysis of the SDMs presented.

These were evaluated as a way to implement intelligence in IoT solutions. These must be generic, leaving space to plan the actions according to the needs of the problem to be solved by the solution. The more independent of specific techniques (e.g., deep learning and reinforcement techniques), the better, since techniques and technologies are constantly changing, for that reason, it is not interesting to set standards.

Development methodologies are basically a set of phases in the life cycle of a project. Some emphasize requirements engineering and development, not concentrating on the business aspects, such as SPP, which only covers software development aspects for components, or HLAD, which produces an implementation specification and support for the maintenance phase; or even ELDAMeth, composed of three distinct phases, which uses software operating autonomously. Other methodologies, such as Ignite, address the solution development cycle, including aspects of the business, project management, feasibility, requirements engineering, and design, but do not provide details on how to develop and test solutions.

4.2.1 Engineering Resilient Collaborative Edge-enabled IoT

The Engineering Resilient Collaborative Edge-enabled IoT (Resilient-IoT) was published by Casadei et al. (Casadei et al. 2019) in 2019. It presents a methodology for resilient collaborative engineering systems, focused on the development of heterogeneous components that can be implemented on different devices. These devices can work collaboratively to perform functions. It is a specific methodology for developing and implementing components that will work at the edge of an IoT solution, i.e., closer to the target environment.

The methodology assumes that there are domains of knowledge and problems that are already known, which can serve as a standard for the use and reuse of implementations and solutions. It proposes a technical implementation based on Aggregate Computing, a formal programming paradigm able to capture adaptive behaviour of agent collectives.

The work proposes some basic entities that must be defined:

- Environment: a domain where the solution is going to operate.
- Problems: challenges that must be overcome by the solution.
- Actors: entities that will interact in the IoT solution, such as humans, sensors, actuators, and robots.
- Coordinators: structure with greater computational capacity that acts at the edge, coordinating and managing actors.

This SDM does not present explicit interoperability characteristics. Although the model itself describes how interactions should occur between components, interoperability solutions are not presented. Regarding autonomy, the approach used says that IoT devices (re)act autonomously to stimuli, through data-oriented techniques, i.e., machine learning, artificial intelligence, etc., and coordination mechanisms (consensus). Scalability is achieved with a macro-programming approach to grouping devices into clusters, based on their spatial relationships, e.g., smart room objects. This scale abstraction is treated through spatial operators and middleware components, which allow logical scopes and support IoT systems ranging from a few to several components (horizontal scalability). The methodology meets the intelligence requirement, proposing the use of deep learning and reinforcement techniques to perform the detection of patterns and anomalies, in addition to the use of predictive analysis and resource optimization.

4.2.2 Software Production Process

The Software Production Process (SPP) for the development of agents has its origins in academia and was proposed in 2015 by Ayala et al. (Ayala et al. 2015). It can be understood as an in-line software product production process designed to improve the development of IoT applications using agents and Software Product Line Engineering (SPLE). SPP follows the two main processes established in SPLE: Domain Engineering, used to establish common characteristics in the platform, and Application Engineering, used to derive applications created specifically for the platform. The objective of the initiative is to identify similarities between agents and develop a common reference architecture, providing a reduction in cost and implementation time, and an increase in quality. The SPP is documented by journal articles and conference documents.

The SPLE seeks to develop software and identify common and distinct points in a family of software products. Common points ensure platform re-usability while distinctions refer to specific characteristics of certain software within the scope of a product family. A multi-agent IoT system architecture, which presents similarities and distinctions, is produced after a variability model is defined. Therefore, a multi-agent system architecture acts as a base model, forming the common platform and points of difference to be configured in each autonomous software component (agent). Developing software components for “things” using agents can be convenient due to their distributed nature.

4.2.3 High-level Application Development for the IoT

The High-level Application Development for the IoT (HLAD) was presented by Patel and Cassou (Patel e Cassou 2015), originating in academia. HLAD is documented in a doctoral thesis and a journal article. This SDM aims to facilitate the development of IoT applications, based on the Model-Driven Design approach and the work in macro programming of sensor networks. The proposal identifies different interests represented in a conceptual model. The identified concepts are linked together in a well-defined methodology that can be used as a development framework. The HLAD segments the development process into four areas of interest, namely:

1. Domain Area: deals with the specific concepts of IoT systems.
2. Functional Interest Area: looks at the system architecture and how its implementation should take place.
3. Deployment Area: specifies the "things" that will be addressed by the solution.
4. Platform Area: addresses the development of specific drivers for each type of virtual entity or "thing".

4.2.4 Event-driven Lightweight Distilled State Charts-based Agents Methodology

The Event-driven Lightweight Distilled State Charts-based Agents Methodology (ELDAMeth) project(Fortino e Russo 2012) was conceived in academia and aims to provide a simulation-based methodology. This proposal uses an agent to drive software development into the "things" in IoT systems. These agents can be defined as software operating autonomously in a networked environment.

The ELDA model is based on three main concepts to enable distributed computing: Agent Behavior, driven by events that trigger reactive and proactive computing;

Agent Interaction, based on multiple coordination spaces that are explored by agents; and Mobility, which allows agents to migrate autonomously or to be passively migrated between servers. This methodology comprises three distinct phases:

1. The Modelling Phase produces the Multi-Agent System (MAS) specification. The ELDA-MAS can be converted to platform-independent code through the ELDA Framework, a set of Java classes that formalize modelling.
2. The Simulation Phase produces the simulation assessment document, including performance indices to be assessed against functional and non-functional requirements.
3. The Implementation Phase produces a code based on the MAS. Testing the MAS code implemented allows the assessment of functional and non-functional requirements. If issues are detected, this assessment can trigger a new iteration process.

The ELDAMeth focuses only on the technical aspects of the solution, it does not cover the business aspects or in-depth definition of requirements.

4.2.5 Ignite-IoT Methodology

The Ignite Methodology (Slama et al. 2015) had its origins in the industry and is documented through a book that defines the method and provides information on business projects. Ignite aims to deliver IoT best practices in the form of a technology-independent, reusable, open-source methodology. It aspires to support the design, configuration, and management of IoT projects by providing project templates, checklists, and solution architecture schemes.

Ignite, however, does not provide technical details on how to develop and test software. The methodology is divided into two phases.

In Phase A the strategy is outlined, the business opportunity is identified and the management is defined.

Phase B comprises the delivery of the IoT solution. In this phase, the individual IoT solution and related projects are analysed. This phase is subdivided as follows:

1. Solution Life-cycle - Comprises planning, construction, testing and commissioning of the IoT solution:
   a) Initial Design: based on the elements defined in previous designs contained in the Generic Building Blocks.
   b) Workflows: define the flows to be implemented in the project. A checklist for each workflow is provided, as well as a list of common dependencies between the workflows.

2. Generic Building Blocks - Repository with reusable models of successful projects, including:

    a) Project Dimensions: precursor of the project's formal requirements. Used for project evaluation, comparisons between projects and architectures, technologies selection, etc.

    b) Architectural Schemes: builds on existing architectures, adds new perspectives needed to the design and provides a superstructure to integrate the different perspectives needed.

    c) Technology Profiles: identifies and describes technologies for IoT projects. It uses the perspectives of the IoT architecture to describe where different technologies fit together.

3. Project Database: a repository of reference projects analysed to extract best practices for the Building Blocks and Solution Life-cycle perspectives.

Ignite allows different platforms to interoperate. Objects defined and written to Ignite by one platform can be read and used by another platform.

4.3 The Three-Phase Methodology for IoT Project Development

Traditionally, Methods Engineering deals with the processes of designing, building, and adapting methods directed to the development of information systems (Bucher et al. 2007). According to (Alter 2006), an information system can be understood as a subtype specific to a work system. Objects that must be designed, integrated, or transformed through a methodology can be defined as a work system. An IoT solution involves the integration of several subsystems, making it a work system.

To be applicable to the development of IoT solutions, methods need to be adapted to the characteristics of the development or project situation. This approach is commonly called Situational Methods Engineering (Harmsen Anton Frank 1997; Kumar e Welke 1992; Slooten e Hodes 1996).

For the development of the TpM-Pro, the Situational Method Composition approach was employed (Bucher et al. 2007). The fundamental idea behind this method is the selection and orchestration of artifact fragments with respect to the specifics of the development of a class of projects. This methodology composition process aims at combining several levels to establish new construction results. This approach to methods engineering is widely used and discussed in the literature (Harmsen Anton Frank 1997; Slooten e Hodes 1996; Baumoel 2005; Brinkkemper Sjaak 1998).

The Situational Method Composition follows three steps to create a methodology:

1. Identify situational characteristics: these characteristics can be used to identify types of projects to be developed with the methodology, as well as artifacts and artifact fragments.

2. Breakdown generic artifacts into artifact fragments: to elaborate the methodology, generic artifacts need to be broken into artifact fragments. In addition, artifact fragments and their interrelationships need to be identified.

3. Assemble the artifact fragments in a methodology: the actual composition of a methodology occurs by choosing and orchestrating fragments of artifacts according to well-defined construction or composition principles, to suit the characteristics of the projects to be developed with the methodology.

On the TpM-Pro, step 1 is represented by IoT projects, as these have specific characteristics, i.e., heterogeneity of technologies and techniques, and the need for hardware/firmware/software integration. Artifacts in the TpM-Pro are defined as the three phases that make up the methodology.

In step 2, the phases (artifacts) are broken-down into artifact fragments. These fragments are represented by the information regarding the business and the IoT-OSRM reference model. The relationships between these fragments are also defined.

In step 3, the organization of the methodology happens. There the flows, actors, and products generated by TpM-Pro are defined.

Therefore, the TpM-Pro is based on a well-defined and consolidated engineering method.

Figure 4.1 shows the diagram of the phases that make up the TpM-Pro, as well as the agents and roles identified in the methodology.

It is important to highlight that the TpM-Pro is an iterative and incremental methodology. There is a cycle that can repeat itself until a suitable solution is found. This feature makes the TpM-Pro flexible, as it can be used during the lifetime of solution, from delivery to updates and enhancements.

Figure 4.2 shows this cycle, where the team can go from one phase to another, to adjust objectives, clarify doubts, meet new demands or for any situation where feedback is required. Therefore, the three phases that constitute the TpM-Pro are enough to meet all the stages of creation and development of an IoT solution. This makes the methodology simple, systematic and structured, making it an important contribution to the IoT.

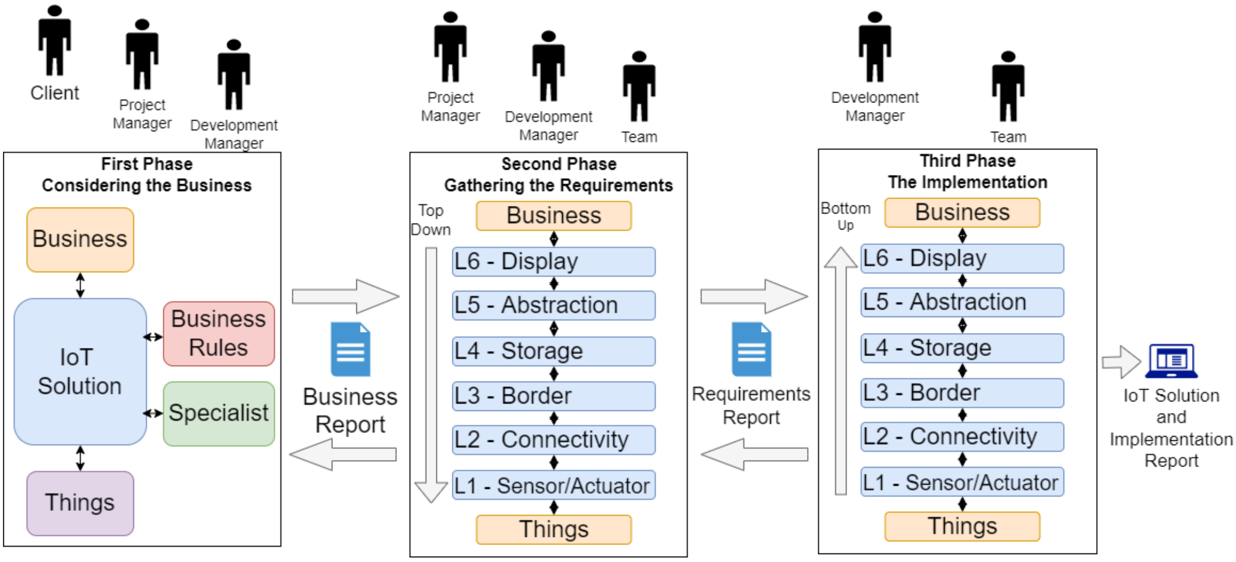

Figure 4.1 – TpM-Pro Iterations Diagram Showing Roles, Phases and Deliverables.

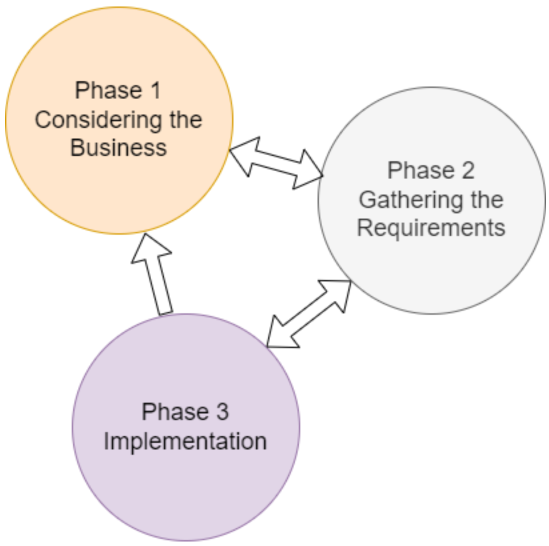

Figure 4.2 – Iterations between the TpM-Pro phases.

A system to assist in the documentation of IoT projects according to the TpM-Pro has been developed, validated, and tested. It is meant to be a guide where development teams can collaboratively apply the TpM-Pro, documenting and organizing the project. In addition, the system also aims to connect the TpM-Pro using the community. There, professionals, academics, and others interested in IoT can exchange experiences and knowledge. The system can be accessed at http://www.iotm3f.cc. More information can be found in (Ferreira et al. 2021).

4.3.1 Agents and Roles

Every development methodology needs to have its agents and roles well defined. This definition is important for the organization and structuring of solutions (Vlietland e Vliet 2015). The TpM-Pro has the following agents performing the following roles, as shown in Figure 4.3:

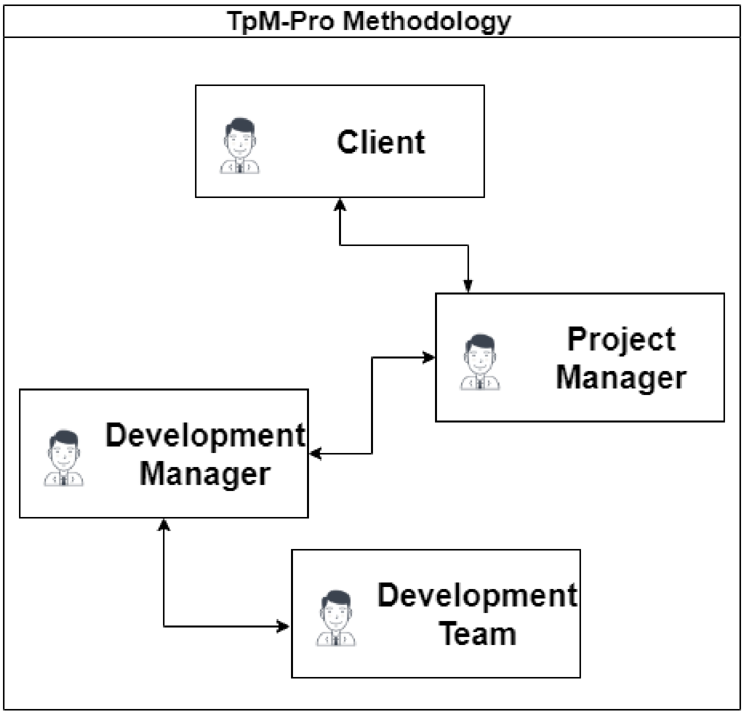

Figure 4.3 – Interactions between Agents in the TpM-Pro.

- Client: includes all parts served by the solution;
- Project Manager: acts as the link between the Client and the Development Manager. Responsible for extracting information of the business and verifying the feasibility of the solution together with the other players. All communication between the Client and the Development Manager is handled through the Project Manager;
- Development Manager: responsible for managing the multidisciplinary team. Defines the parameters related to the development of the solution. This role also defines responsibilities at every level of the IoT-OSRM and tracks the project development. Responsible for organizing the requirements gathering on Phase 2, acts as a bridge between the multidisciplinary team and the Project Manager. Can also be in contact with the Client;
- Multidisciplinary Development Team: formed by professionals with knowledge at the different levels of the IoT-OSRM, is responsible for the development process.

Defining roles is important for the organization and communication hierarchy in the development process. This organization helps to integrate the team, as the responsibilities and needs are made explicit and well delineated. Figure 4.4 presents the flowchart of a TpM-Pro iteration indicating the relationship between agents, roles, processes, and deliverables.

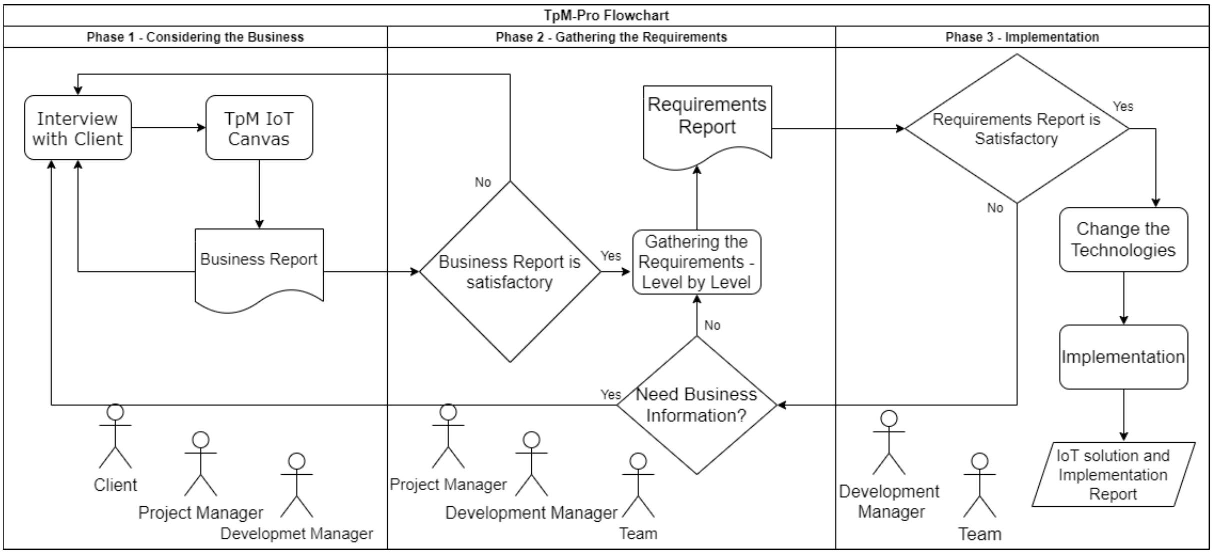

Figure 4.4 – Flowchart Showing the IoT Development Solution Process.

4.3.2 Phase 1 - Considering the Business

In Phase 1, the business is understood and the problems to be addressed by the solution are outlined. The TpM-Pro is mainly concerned with the value brought by the IoT solution to the business. This is its main differential in relation to other IoT methodologies. The principle is that if the business is not well defined and understood, the solution developed will not meet the customer's needs. This approach's main objective is to meet the customers' needs in its entirety, understanding their anxieties and expectations. To define the problem to be solved, the following aspects are considered:

- The Business: varies from project to project, even when dealing with projects in the same area of activity, as each will have its peculiarities. If not well pondered, the end solution may not satisfy the end-user necessities;

- The Things: objects of interest to the business; entity or set of entities to be quantified, measured or controlled, can be physical or virtual. In this phase, the Project Manager must define what the "things" are;

- The Specialist: every solution requires the involvement of specialised personnel who will provide information to support the business decision-making processes. These can be in-house professionals or hired for this purpose;

- The Business Rules: assumptions and restrictions applied to the operation of any business. Therefore, these rules must be taken into consideration throughout the solution development process. Business rules can be determined by analysing the target scenario in which the solution is to be employed. Developing an IoT solution begins with a clear understanding of the rules that govern the business and should be consistent with the customer's needs.

To carry out Phase 1, we developed the TpM-IoT-Canvas, a tool conceived to assist in extracting the necessary information about the business and expected solution. The TpM-IoT-Canvas was specifically designed for IoT projects.

The TpM-IoT-Canvas is based on the Project Model Canvas (PM-Canvas) (Júnior 2013). It encourages the whole team to help planning a project with the use of post-its pasted on a board. The TpM-IoT-Canvas also simplifies the understanding of the business and solution by relying on small groups of key information presented in a visual model.

There are 8 blocks that cover the following topics: business, justification, benefits, product, things, solution requirements, client, and team. Each block is directly related to its neighbour. This feature allows easier identification of the impacts changes in one area have on others; in case any inconsistencies are found in the project.

The TpM-IoT-Canvas shown in Figure 4.8 provides a colour coded visual understanding of the project´s key information grouping, seeking to respond to three defining questions:

1. Why? - (In orange) - Encompasses the justifications, objectives and expected benefits of the project. It should clarify the relevance of the solution, considering:
   a) Business: defines the enterprise's area of expertise, core activity, area in which the proposed solution operates, and its relevance to the company's activities;
   b) Justification: lists the problems that the solution must address;
   c) Benefits: Tangible and intangible value proposition to be achieved with the project. These propositions should justify the development of the solution.
2. What? - (In grey) - Describes the solution to be delivered to the customer. It is essential to consider the expectations of sponsors and customers, while also considering the following:
   a) Product: definition of the solution in terms of its basic form e.g., equipment, software platform, systems integration, service platform;
   b) Things: in addition to a list of the things that interact with the solution per se, it is important to list what should be measured, controlled or quantified of each thing;
   c) Solution requirements: everything that is required from the solution must be listed here. This field reflects the business rules, and justifications. This field will also serve as a starting point for Phase 2.
3. Who? - (In green) - Defines the incumbents, as previously defined in sub-section Agents and Roles.

The result of Phase 1 is consolidated in an artifact called Business Report, prepared by the Project Manager with the Development Manager and team. This document feeds into Phase 2 of requirements gathering.

The Business Report is then evaluated by those responsible. If approved, Phase 2 begins, otherwise, a new analysis of the business is carried out. Therefore, the Business Report is the artifact used to validate a Phase 1 interaction.

4.3.3 Phase 2 - Gathering of Requirements

Phase 2 starts right after the approval of the Business Report. With the business well understood, it is possible to define the functional and non-functional requirements. The functional requirements define the functions or services that the system must encompass, that is, what the solution must do in terms of tasks and services. The non-functional requirements, on the other hand, define properties and restrictions on the system design, with no direct relation to the functionality, that need to be incorporated into the system, such as the technical standard to be followed and forms of system updating.

In this phase, the process is divided into six levels, following the IoT-OSRM reference model. Developers can use past cases or techniques such as interviews to get the information. This is an important step in the development process in which the structured format of the IoT-OSRM is an asset.

A top-down approach is used in this phase. It starts by defining the requirements on the level closer to the business, moving down the levels to the one closer to the "things". All information gathered must be documented:

- Level 6 - Display: handles how information is to be displayed to the end-user. Information can be presented in tables, graphs, or numbers, for example. Emergency and other urgent actions are also flagged and dealt with at this level;
- Level 5 - Abstraction: stored data is used at this level to convert raw data into information. At this level that the expertise of a specialist is required. Developers depend on expert information to decide how to extract abstraction from the available information. Techniques such as artificial intelligence, data mining, and machine learning, can be employed at this level;
- Level 4 - Storage: defines how the collected data should be stored. Data can be stored in the cloud, on the client's system, or both, depending on the required level of availability and security and the amount of data. Aspects such as redundancy, data security, and storage location are also defined at this level;
- Level 3 - Border: defines the characteristics of the element that connects the solution to the Internet, the so-called border element. This element warrants the connection

between the "things" with the part of the system that is on the Internet. Therefore, the border element must always be present in an IoT system. In addition, this element may be required to perform functions as middleware and networking using more advanced strategies (including software-defined networks and virtualization of network functions). Developers should pay attention to this level, as it will guide the implementation phase;

- Level 2 - Connectivity: focus on the connectivity between “things” and border element. This level can be considered the bottleneck of any IoT system. The connectivity can be wired, wireless, or hybrid. Wireless technology is typically employed in the context of IoT, especially when many sensors/actuators are distributed over a large area. However, the decision on the type of technology to be employed must consider some other issues, including costs, number of items to be monitored or controlled, operating environment, required capacity, and reliability of the transmission system. Requirements at this level are defined by developers with knowledge in the field of data communications;

- Level 1 - Sensor/Actuator Node: refers to the devices responsible for data collection or action in the environment. At this point, developers specify the capabilities expected from sensors and actuators, based on the customer necessities. Must consider local processing, use of edge or fog computing concepts, etc. Documentation must be created describing what is to be measured, controlled, etc.

Security and data privacy are perennial concerns regarding IoT solutions. This topic has been addressed by government and regulatory institutions, as in (Kelly 2019) and (NIST 2022). The TpM-Pro is prepared to meet this demand. In it, security must be defined at each level of reference model. There is no single tool that provides security for an IoT solution, but rather, a set of tools and techniques that, working together, provide the necessary security and privacy.

Figure 4.5 shows that on the TpM-Pro, the security and privacy of the solution is transversal. Each level has its specific requirements of security. Proper definition of security for each level will ensure the privacy and security of the whole solution. Therefore, in the Gathering of Requirements phase, security and privacy concerns must also be considered.

Once each level of the IoT-OSRM reference model has been defined, a Requirements Report is prepared. It is a document that gathers all functional and non-functional requirements. The Requirements Report is then validated by the Project Manager, Development Manager, and development team. If the report is approved, Phase 3 begins, otherwise, a new round of Phase 2 is carried out to resolve any pending issues. Therefore,

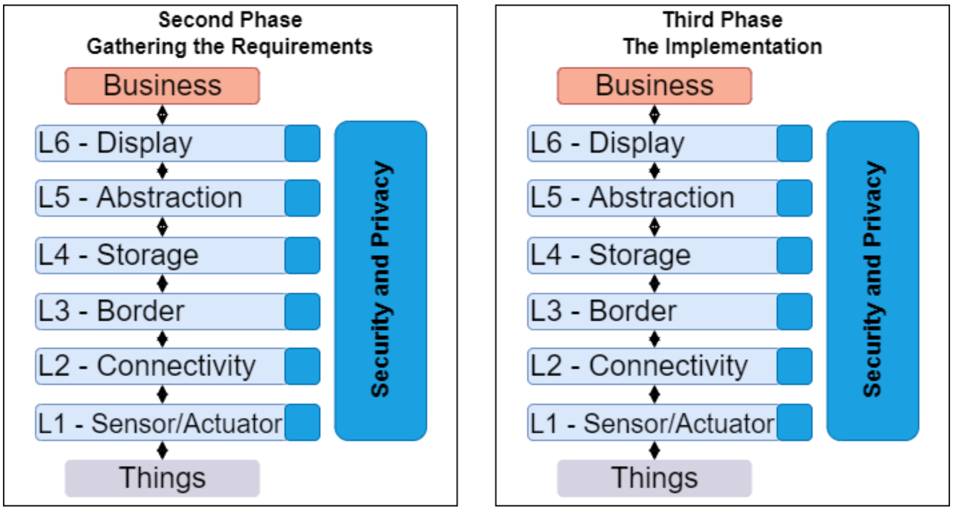

Figure 4.5 – Security and Privacy in TpM-Pro.

the Requirements Report is the artifact used to validate the completion of an iteration of Phase 2.

The TpM-Pro has different characteristics from the other methodologies, for example, its requirements gathering method is not rigid. The path to be followed, i.e., the IoT-OSRM, is indeed systematic, but the techniques used can vary, as shown in Figure 4.6. This brings flexibility. The actors involved can use knowledge previously acquired to use the TpM-Pro.

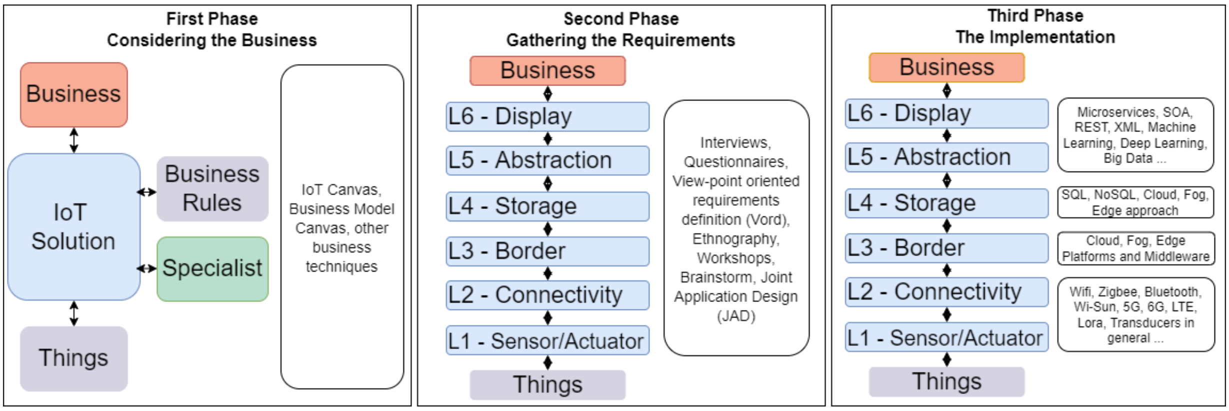

Figure 4.6 – Examples of techniques and technologies that can be used with the TpM-Pro.

4.3.4 Phase 3 - Implementation

Phase 3 only starts once the Requirements Report is approved. Developers must now evaluate the technology options available and choose what best meets the specifications defined in the previous phase. The Implementation Phase also follows the IoT-OSRM reference model, however, a bottom-up approach is used in this phase, as it is first necessary to define how the "things" are to be monitored and controlled and how this information is to reach the end-user. The evaluation follows the sequence:

- Level 1 - Sensor/Actuator Node: at this level the sensors/actuators that will be used are defined and developed. The micro-controllers, memories, connectors and transducers are chosen here.
- Level 2 - Connectivity: the transceivers, communication protocols, antennas and all equipment needed to establish the communication between the Things and the edge element are selected at this level.
- Level 3 - Border: the edge element is selected at this level. It can be a single board computer if an edge computing approach is chosen, or it can be a cloud server if a inter cloud computing approach is decided for. According to the requirements raised in Phase 2, the choice of technology to be used is defined at this level.
- Level 4 - Storage: based on the requirements, the data storage strategy that best fits the solution is chosen at this level. It could be a single local database or a local database and others in the cloud. These can be relational or non-relational databases.
- Level 5 - Abstraction: data-handling techniques are implemented at this level. These can be machine learning, deep learning or big data, to mention just a few. Here the data is processed to generate useful information for the end user, i.e., the Client.
- Level 6 - Display: this is where the tools that will deliver the results to the Client are put in place. These can be apps, websites, phone messages, etc., showing graphs, alerts, tables, etc.

It is important to emphasise that techniques of security and privacy are implemented at each level. From Level 1, where physical security measures are applied to sensors/actuators, up to Level 6, where user access controls are implemented. All tools and techniques implemented at each level should provide the appropriate level of security, as shown in Figure 4.5.

The TpM-Pro is technology independent, it differs from other methodologies as it is flexible, adaptable, and can make use of documentation and implementation techniques already consolidated in the literature. However, it always follows the same structure, and always uses the business as a starting point. This concept integrates all techniques and knowledge needed to develop a solution.

Phase 3 results in the delivery of the Implementation Report and the implementation of the solution itself. If needed, the process of refinement and improvement can then begin, going through all three phases again. The TpM-Pro is iterative and incremental, through it, the process can be repeated as many times as necessary until the solution meets the business needs.

In summary, as shown in Figure 4.6, the TpM-Pro can be a guide for the development team. Known techniques and architectures can be used during Phases 1, 2, and 3. The main differential, however, is that the TpM-Pro makes it clear how these techniques must be integrated to meet the objective of any IoT solution, that is to attend to the needs of a business.

4.4 Results

The mainly descriptive and exploratory case study presented in this section followed the Association for Computing Machinery guidelines for conducting and reporting case studies (Runeson e Höst 2009). These guidelines set down the structure a study should have, i.e., objectives, data collection and analysis mechanisms, presentation and interpretation practices, and the way information should be gathered, i.e. qualitative and/or quantitative methods.

Differently from the methodologies presented in Section 4.2, the TpM-Pro follows the premise that before any choice of technology is made, it is necessary to clearly define the problem and understand the business in need of the solution. The TpM-Pro is a generic, manufacturer, and technology-independent methodology that facilitates the identification of possible difficulties during the project's development cycle. The TpM-Pro encompasses the main aspects that must be considered in the development of any solution, namely: business, "things", team, requirements, technologies, implementation strategies, and documentation.

The TpM-Pro was adopted by a start-up company developing *i-Machine*, a government-funded project to provide an online predictive maintenance service for electrical machines, with the use of fuzzy logic in the analysis of vibration and temperature parameters. The service relies on autonomous wireless sensor networks. Each sensor node incorporates a thermoelectric generator (TEG) to power the system, a DC-AC converter to manage the power, a super-capacitor to store the energy, and a micro-controller (MCU) to manage the communication module, as shown in 4.7. Potential customers include enterprises that rely on difficult to reach rotating machines in their processes, such as wind power operators and companies that employ industrial pumps and cranes.

As previously indicated, when using the TpM-Pro, it is essential to start with a well-defined problem. In the i-Machine´s project, the problem was "the detection of physical signals that indicate possible future equipment failure". As reported by the company, the main difficulties to address the problem were the unavailability of electric power at the point of installation and the impracticality of using intrusive sensors.

There were seven members in the *i-Machine* team, all experienced professionals who had previously worked with IoT. There was a data scientist, a technician, and

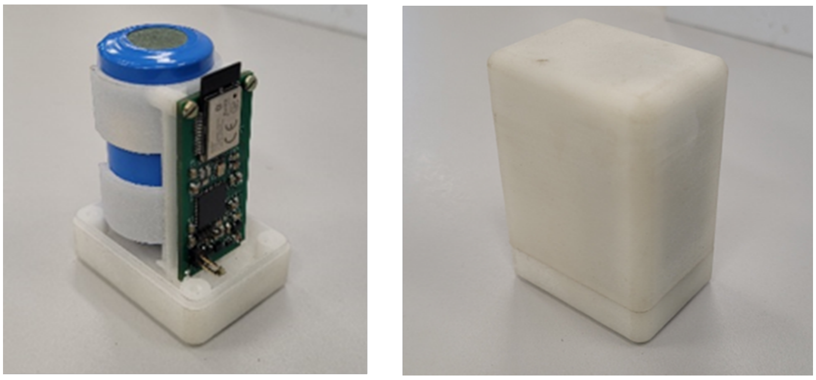

Figure 4.7 – On the left, the complete i-Machine sensor node, including the battery, on the right, the encapsulated sensor node. [Adapted from the i-Machine project].

electrical, telecommunications and mechanical engineers. The roles of project manager and a development manager were taken by the senior members. The remaining members worked as the development team and consultants. The project's main expected results were:

- Increased availability and operational efficiency of electrical machines;
- Early detection of failures and reduced maintenance costs;
- Reduction of accidents with personnel.

The project was split into three main attributes, namely:

1. Continuous vibration and temperature sensing.
2. Energy self sufficiency (environmental energy harvesting).
3. Wireless communication capability.

During Phase 1, the team produced a TpM-IoT-Canvas where business, solution description, justifications, objectives, and expected benefits were laid down, as shown in Figure 4.8.

This information allowed the preparation of the Business Report.

Regarding Phase 2, the main requirements documented in the Requirements Report were:

- Graphical interfaces to show the evolution of equipment wear and tear;
- Intelligent and accurate data processing;
- Local and cloud storage;

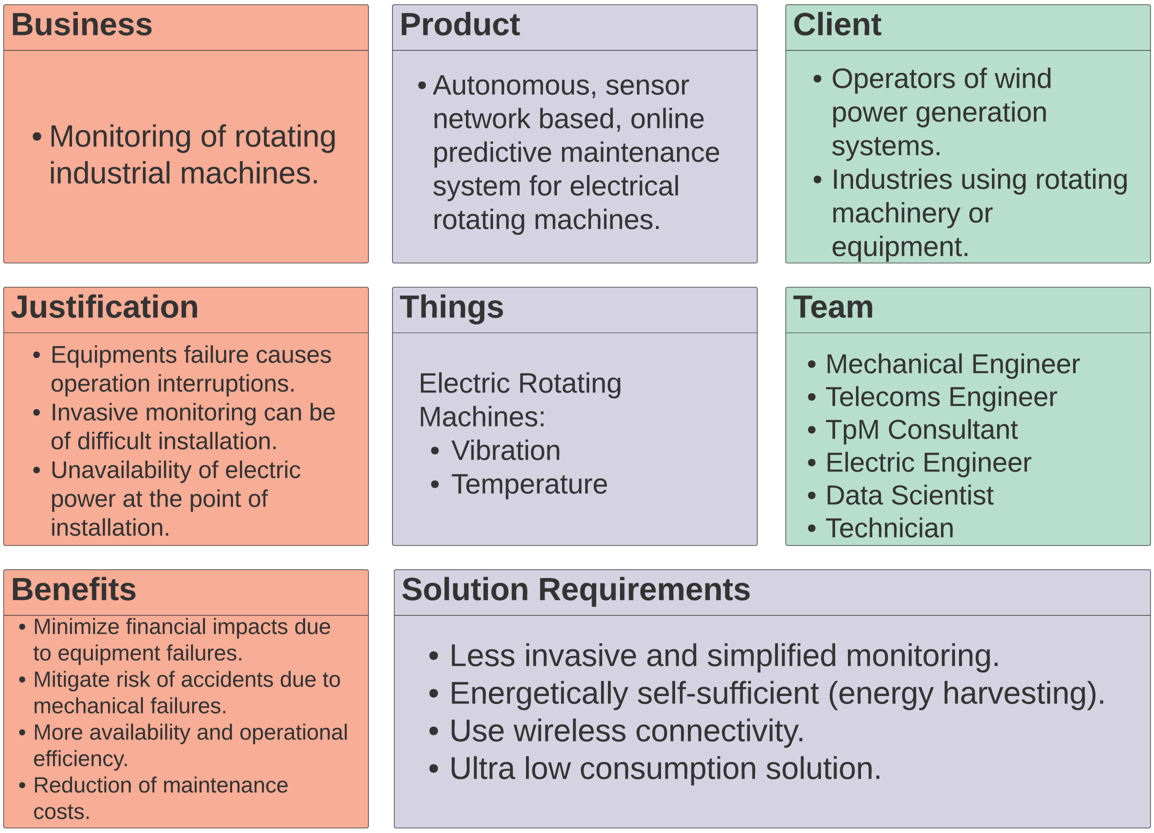

Figure 4.8 – The i-Machine Project TpM-IoT-Canvas.

- Low energy consumption;
- Wireless connectivity capability;
- Level of precision and accuracy in sensor data;
- Devices small size and low mass;
- Low cost.

Phase 3 concludes with the writing of the Implementation Report, which details the implementation and technological choices. The actual implementation details and technologies used are not presented in this paper due to confidentiality issues. However, this fact does not influence the results of this work as the objective is to evaluate the use of the methodology. The *i-Machine* project started in November 2020 and has just cleared the prototyping stage. The project is set to finish by the end of October 2022.

The team´s perception regarding the TpM-Pro was assessed once Phase 3 was over.

Following the guidelines set down by the Association for Computing Machinery, we used methodological triangulation, i.e., we combined qualitative (interview and observation) and quantitative (survey) methods to increase the precision of this empirical research.

First, each member was interviewed. There were no questions as such but an open conversation that gave them the opportunity to express their opinion about the methodology. Then a 5-point Likert Scale questionnaire was applied to all members of the team. In these questionnaires the team members could rate specific aspects of the methodology. It included the following statements and questions:

1. The TpM-Pro was easy to understand and assimilate.
2. The TpM-Pro helped me to better understand what IoT is.
3. The TpM-Pro helped the team to better understand the project.
4. The TpM-Pro helped integrate the team members.
5. The TpM-Pro contributed to increasing the team's productivity.
6. The TpM-Pro provided a better quality of service (technical competence, reliability, delivery time).
7. The iterative and incremental nature of the TpM-Pro provided the necessary flexibility for the development of the project.
8. What was the level of difficulty applying Phase 1 of TpM-Pro?
9. What was the level of difficulty applying Phase 2 of TpM-Pro?
10. What was the level of difficulty applying Phase 3 of TpM-Pro?

Approval of the TpM-Pro as a development methodology was attested by the answers given by most interviewees. During the conversations, it was a recurrent observation that the TPM-Pro provided a clear path to be followed, giving them the confidence that no short cuts were being taken, albeit inadvertently. Some respondents mentioned that the TpM-Pro's flexibility and manufacturer and technology independence were its main contributions and that the TpM-Pro served them well as a project guide. There was however, one interviewee that expressed a certain resistance to use the methodology indicating that it was difficult to follow.

The survey results also indicate that the methodology was well accepted by the *i-Machine* team, as presented in Table 4.2.

In the following analysis of the data resulting from the survey, we refer to the ratings Agree and Somewhat Agree as positive ratings.

Table 4.2 – i-Machine Team Survey Results

Statement	**Agree**	**Somewhat Agree**	**Neither Agree nor Disagree**	**Somewhat Disagree**	**Disagree**
1	80	20	0	0	0
2	80	20	0	0	0
3	100	0	0	0	0
4	80	20	0	0	0
5	100	0	0	0	0
6	100	0	0	0	0
7	100	0	0	0	0
Question	**Very Easy**	**Easy**	**Adequate**	**Hard**	**Very Hard**
8	60	40	0	0	0
9	80	20	0	0	0
10	80	0	20	0	0

The results pointed out that the general perception was positive. The same rates were assigned to statements 1 and 2, indicating that the TpM-Pro was helpful and easy to comprehend. Respondents also wrote that the TpM-Pro allowed for a better work organization.

There was a consistency of positive ratings for statements 3, 4, 5, and 6 concerning the benefits of the methodology with regard to cohesion, productivity, and QoS, corroborating our belief that the TpM-Pro delivers a better-integrated team. All respondents agreed with statement 7, that the TpM-Pro granted flexibility to the development process.

The answers to questions 8 to 10, about the level of difficulty in handling the phases, told us that the users considered this the hardest aspect to grasp. Probably this was caused by the novelty of the methodology and shortage of training time.

In addition, our perception regarding the team´s take on the TpM-Pro was that it indeed helped them to see the project as a whole, bridging the business necessity to the solution developed.

4.5 Conclusion

Developing IoT systems is a process more complex than traditional software development, as these systems often encompass software, hardware, and communication components. Validation of development methodologies that seek to attend IoT systems needs are also an important topic that needs to be addressed.

Of the six methodologies presented in this article, only Ignite and the TpM-Pro have been validated in real-world projects. Although the original TpM has been used by over 100 students in extension and postgraduate IoT courses, the TpM-Pro had not yet been tested for projects in a corporate environment. Its adoption by the i-Machine team allowed us to test its applicability in real-world projects. This validation has allowed us to assess and improve the TpM-Pro.

None of the methodologies identified in this paper can be considered a complete blueprint that contemplates everything in the development process of IoT solutions. However, we feel that, out of these methodologies, the TpM-Pro could be considered the more holistic one, as it presents the clearest way to develop IoT solutions, starting at the business, all the way to a running solution, while keeping full project documentation (activities, artifacts, roles, requirements, technologies and testing). The TpM-Pro presents a way of organizing the flow of decisions made during all stages of an IoT project.

The development of the TpM-IoT-Canvas within the TpM-Pro domain granted the methodology an unique way to easily extract information about the business and expected solution, while, at the same time, encouraging the team to get involved in the project planning process.

The TpM-Pro is devoid of any commercial bias, focusing foremost on the client's needs. The methodology proved to be a useful instrument, especially for teams with little experience in the IoT area. It is not necessary to learn new techniques or specific tools, as the TpM-Pro offers the possibility of using all the team's previous knowledge, guiding it through a common and integrated path.

The feedback received from the *i-Machine* team suggests that the TpM-Pro is a promising development methodology for IoT. Nevertheless, we recognize that it is a preliminary assessment. Further testing should bring new contributions, consolidating and validating the methodology. However, this will happen only when developers consider the TpM-Pro as an option and make use of it on their IoT projects.

Acknowledgement

The authors wish to thank the *i-Machine* Project (Techplus Automação), initiative financed by the Innovative Research in Small Enterprises Programme (PIPE) from the São Paulo Research Foundation (FAPESP), and the Brazilian National Council for Scientific and Technological Development (CNPq), grants numbers 161999/2018-2 and 141231/2017-3, for partly financing this study.

4.6 Considerations about this paper

This paper presented the version of TpM for the corporate world, called the TpM-Pro. During its development, several improvements were made to the methodology.

These improvements were done on structural aspects, such as actors, artifacts and tools for the application of the methodology. In addition, there were advances in relation to its presentation. Diagrams and flowcharts were optimized and modernized, taking functional and design aspects into account. The evolution of these aspects is evident when comparing the diagrams of Chapter 2 to the ones in Chapter 4.

Thus, the methodology matured by the end of the research. Now we have a version for teaching and another for project development. Both versions have been tested, validated and are available for use by the IoT community.

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5 Analysis and Discussion of Recent Initiatives on Teaching Internet of Things Concepts

This chapter is a replica of the paper:

L. C. B. C. Ferreira, P. R. Chaves, R. M. Assumpção, O. C. Branquinho, F. Fruett and P. Cardieri, "Analysis and Discussion of Recent Initiatives on Teaching Internet of Things Concepts," in XL Simpósio Brasileiro de Telecomunicações e Processamento de Sinais (SBrT2022), 2022.

This paper presents a summary of this doctoral work. Initiatives, courses, methodologies, dissertations, thesis and publications generated by the research group´s effort are presented.

In addition, important points are raised regarding the subject, which can be explored in future works. This work shows what has been done, serving as inspiration for new proposals and improvements of the works developed so far.

Abstract

The teaching of IoT has brought about new challenges due to its inherent multidisciplinary nature. Also, this training must consider the particularities of wireless communications, as it is essential to guarantee communication in any IoT solution. In this article, we present and discuss part of the recent work on IoT teaching carried out by a team of researchers from the School of Electrical and Computer Engineering at the University of Campinas, Brazil. The group has been active since 2017 and its effort resulted in training projects, extension and postgraduate courses, and articles published.

5.1 Introduction

Recent reports indicate that billions of objects are going to be online in the coming years, smartly interacting with its surroundings (13)(Tunstel et al. 2021). IoT Analytics, a German company specialised in IoT market information and business intelligence, reported in its March 2022 edition that companies' expenditure on IoT grew 22.4% in 2021 to US$158 billion. The company forecasts the market value for IoT, including software, hardware, security, and services to grow to US$525 billion by 2027.

However, according to the report *Why IoT Projects Fail* (Woolley 2020), a survey showed that the higher level of knowledge in design and architecture required in the development of IoT projects was a major hindrance. This survey was conducted with 250 companies distributed across 42 countries. The report also stated that often the definition of the business associated to the IoT project, its objectives, and expected returns are not taken into account, contributing to the failure of IoT projects. The report concludes that focusing the solution only on technology is a mistake.

Also, according to Jha (Jha 2016), "80% of IoT projects fail before they are rolled out". The author adds that companies are developing solutions first and then searching for the problems for them to solve.

These facts are forcing educational institutions around the world to modernise and offer training consistent with the challenges of our times. In Brazil, federal law No. 9394, from 1996, established the bases and guidelines for a more flexible and innovative educational model, the National Curriculum Guidelines (DCN) (CNI SESI 2020). Also, the National Workgroup for the Strengthening of Engineering, created in 2016, now also dedicated to science, technology, engineering, the arts, and mathematics (STEAM), has contributed to the publication of the new DCN for Undergraduate Engineering Courses, in force since in 2019. These guidelines emphasise competence development, project-based learning, and better communication with society. The DCN proposed that engineering courses should be based on practical and active learning experiences, in a process in which the students are fundamental agents. The DCN also endeavour to modernise the assessment process from a generic evaluation process to a continuous, diversified one, in tune with academic activities, based on competencies. This assessment process should reinforce what has been learnt while promoting feedback from teachers (CNI SESI 2020).

Furthermore, the National Internet of Things Plan, from June 2019, encourages the development of programs, methodologies, and tools for the teaching of IoT. The plan is an initiative of the Ministry of Science, Technology, and Innovation and the Brazilian National Development Bank, and aims to improve the quality of life and promote efficiency and productivity gains through IoT. The plan's objective is to implement and develop IoT in the country and integrate it into the international IoT scenario.

The projects, courses, and articles presented in this paper follow the DCN and are aligned with the main objectives laid down in the National Internet of Things Plan. These constitute part of the original work on IoT and science teaching carried out by researchers, graduate and undergraduate students from the Departament of Semiconductors, Instruments and Photonics, and the Department of Communications of the School of Electrical and Computer Engineering at the University of Campinas (UNICAMP), Brazil.

The main contributions of this paper are:

- A literature review of some recent teaching initiatives on science and IoT at FEEC;

- An analysis and discussion regarding these works' main contributions.

The rest of this article is organised as follows: Section 5.2 brings some recent original research carried out at FEEC, while the discussions are presented in Section 5.3. The article ends with the conclusions in Section 5.4.

5.2 Research Initiatives

Since 2017, there has been a concentrated effort by some researchers at FEEC to develop teaching initiatives that follow the DCN and adhere to the National Internet of Things Plan, oriented to academics and industry professionals. This effort resulted in two teaching projects:

1. The Project School 4.0:

   This project aimed to offer training to elementary and secondary school teachers in the use of accessible technologies. The objective was to allow teachers to explore and develop multidisciplinary skills with their students. To that end, there was a 60-hour, distance learning course entitled "Development of Maker Activities to Support the Teaching of Science, Technology, Engineering, Arts and Mathematics (STEAM) at Elementary and Secondary Schools" (FEE217). During the course, students used solely open-source software and hardware solutions developed to this end, which they were encouraged to modify, improve and create new components. This course was geared to use recycled materials including electronic scrap. There have been three editions of the FEE217 so far, attending 70 students. Also, the success of this initiative has led to the publication of an article entitled "A Contribution to the Training of Elementary and Secondary Education Teachers in the Development of Maker Activities Using STEAM", presented in the next subsection. The FEE217 is currently being reworked as a Massive Open Online Course (MOOC) to be offered at the Coursera platform. More information can be found at https://www.escola4pontozero.com.br.

2. The Project IoT Workshop School

   The use of traditional teaching strategies, presenting content and then carrying out experiments, proved inadequate for IoT teaching. IoT solutions are multidisciplinary, which differs from the traditional ways that generally favour technologies. The IoT Workshop School follows a structured methodology along four axes, so to ease the understanding and development of IoT projects:

   Conceptual – Theoretical and practical framework for the preparation and presentation of contents, with special attention to the learning process. This axis is subdivided into three parts: the Three-Phase Methodology for IoT, a Project-Based Learning (PBL) (Campos 2014) based project, and planning and assessment.

Organisational – Structure how the contents are to be organised and how they are to be taught. The IoT Workshop School is organised into intermediate, professional, undergraduate, and graduate levels; courses and subjects; and workshops. In terms of disciplines, it follows a classic way of identifying themes and contents. However, the workshops follow a new structure, in which content and experiments are mixed.
Modalities – Identifies how the content is to be offered. Courses are offered through one or more disciplines, with each discipline comprising workshops. This is an important point, as the workshops employ PBL and Bloom's taxonomy (Campos 2014) in their preparation. The strategy always seeks to involve the students in what is being treated. Courses can be on-site, distance, and blended learning.
Materials – Apparatus needed to support teaching and learning strategies. There are different materials, including customised kits. During the workshops, students have access to an IoT Platform. More information can be found at http://www.iotm3f.cc.

Building upon the expertise gained with these projects, three extension and postgraduate courses were created:

1. Fundamentals and Workshops on the Implementation of IoT Applications in Smart Cities (FEE215): this 24-hour, on-site extension course aimed to introduce students to theoretical and practical aspects of IoT applications, using the IoT Open Source Reference Model (IoT-OSRM). The objective was to present students to different technologies used in applications. The experimental part of the course used an open-source platform (software, firmware, hardware) for the project development. The codes were made available, allowing the students to develop their own IoT projects. During the classes, the following topics were addressed: collection and processing of data through sensors; wireless communication techniques, including signal propagation, antennas, media access control, routing, architecture, and network; management and connection to the Internet and provision of data in the cloud, with storage, abstraction and display, and business aspects. In the final part of the course, the students developed group IoT projects.

2. Introduction to Wireless Data Networks (INF505): the objective of this 24-hour, on-site extension course was to present the basic concepts of wireless networks and the main technologies that implement them. It provided the basis to design wireless networks while conceptually approaching the physical and MAC layers. The INF505 was also covered the analyse of antennas systems and propagation conditions in different environments. During the course, students carried out a link budget (power balance) for a network, considering antenna, modes of communication, transmission power, and sensitivity. The approach starts with the analysis of operating conditions and then the presentation of main over-the-air interfaces available on the market,

covering the necessary concepts for the design of this type of network. The students also carried out experiments with laboratory networks and simulations.

3. IoT Fundamentals and Workshop - A Practical Approach Using the Flipped Classroom (IE309X): the objective of this 60-hour, remote postgraduate course was to promote the understanding of the principles governing wireless connectivity applied to IoT solutions, as well as its management and security, enabling participants to design and implement wireless connectivity in order to meet different IoT needs. The classes followed flipped classroom concepts for interaction, discussion, and knowledge sharing. The course sought to enable the students to: (i) Employ the IoT Reference Model to identify the parts that make up an IoT application; (ii) Discuss the nature of transducers and signal conditioning for IoT applications; (iii) Learn how to choose antennas and understand the conversion of guided into non-guided signals and vice versa; (iv) Discuss some data transmission techniques, among the many used in wireless networks applied to IoT; (v) Characterise signals using statistical concepts; (vi) Understand the phenomena inherent to the propagation of signals; (vii) Evaluate wireless network management concepts; (viii) Design and prototype wireless solutions applied to IoT.

   The IE309X proposal was of a course where participants had the opportunity to run experiments to validate concepts. To that end, the Network Environment Workbench, presented in the next subsection, was made available. The study material for each meeting was made available the week before, giving students a week to familiarise with the content.

The successful outcome of these courses led to the publication of one master degree dissertation and six articles in international scientific magazines:

1. A Proposal of an Open Source Reference Model for the IoT (Déo 2018) - This master dissertation, published in December 2018, presents the six-layered Open Source Reference Model for IoT (IoT-OSRM) applications development. The main focus was to create an architecture using only open source solutions, bench-marked by the reference model. The IoT-OSRM served the needs of small and medium-sized enterprises, as these, often, do not have the resources to invest in the costly solutions offered by large developers. Several paradigms about the adoption of IoT solutions were analysed, including the claim that IoT solutions are just plug and play. The work sought to combat this assumption, while at the same time, aimed to demonstrate that to succeed in the development of a platform, it is necessary to understand that IoT solutions need management since no solution is perennial, infallible, or foolproof. The IoT-OSRM was evaluated and tested in case studies. The results

demonstrated the feasibility of the model in the implementation of IoT solutions in different scenarios.

2. A PBL-Based Methodology for IoT Teaching (Ferreira et al. 2019) - This article was published in IEEE Communications Magazine, in November 2019 and presents the Three-Phase Methodology (TpM), an IoT teaching methodology that relies on the Project-Based Learning (PBL) approach, and uses the IoT-OSRM to cover all aspects of IoT solutions, from sensors to end-user interfaces. The methodology focuses on the complete understanding of the business behind the application and on the end-user needs. Following a top-down requisite gathering approach, and a bottom-up specification phase, the TpM allows students to have a thorough view of all components involved in any IoT application. The TpM has been applied in graduate and extension courses at the University of Campinas and has proven extremely useful.

3. A Remote Emulation Environment for the Teaching of Low-Power Wireless Communications (Chaves et al. 2021) - This article from February 2021 presents the Network Environment Workbench (NEWBen). The NEWBen is a remote, low-cost, open-source network emulation environment capable of reproducing the behaviour of non-guided, low-power links under different configurations. The NEWBen can be of great interest to education institutions, specially in poorer counties, as it can be replicated for around US$280,00. The emulation environment incorporates inductive approaches in the experimentation with wireless connectivity while following a consolidated project methodology. The environment was offered at the IE309X postgraduate course in 2020 and 2021. An end-of-course survey with the students indicated that the environment contributed positively to the comprehension of the principles governing the over-the-air connectivity. The evidence suggests that this remote environment is a useful tool for academic investigations of the particularities of low-power wireless channels.

4. The Integrated Digital Learning Environment for IoT (Yamaguti et al. 2021) - This article, published in September 2021, presents the development of the Integrated Digital Learning Environment (IDLE-IoT), for distance teaching of IoT, based on the TpM and Bloom's Taxonomy. The IDLE-IoT offers an integrated hardware platform in which students can implement their IoT projects. Hence, the IDLE-IoT platform allows the thorough use of the TpM, access to an array of innovative IoT teaching techniques, and an environment where the creation and sharing of projects can be guided by TpM, i.e., a single environment for learning and project sharing.

5. A Contribution to the Training of Elementary and Secondary Education Teachers in the Development of Maker Activities Using STEAM (al 2022): training teachers to

use digital technologies in the teaching environment has been an important task in the Brazilian education scenario since the introduction of the computer on education. It is important to prepare teachers to innovate and introduce new challenges in the teaching process. This article, from 2021, presents a systematic and structured approach to the training of elementary and secondary school teachers in the use of maker tools to assist in pedagogical practices, thus improving the teaching and learning process. The three basic premises are: low cost of implementation, no specialised technical knowledge required, and customised remote support offered. In addition, the article discusses the past three editions of the FEE217 course, presenting some preliminary results on both teachers´ training and in the interdisciplinary development of curricular content.

6. The Three-Phase Methodology for IoT Project Development (Ferreira et al. 2022) - This article, still under revision by the magazine, presents the Three-Phase Methodology for Project Development (TpM-Pro), originally developed as an IoT teaching methodology that proved ideal for solution development. It is a generic, agile, interactive, technology-independent, and incremental methodology that splits the development of solutions into three distinct phases: Business, Requirements, and Implementation. This segmentation has proved invaluable and can become a standard for IoT solution development. In this paper, the TpM-Pro is gauged against five other methodologies proposed for IoT solution development. The article also details a case study when the TpM-Pro was used on a corporate IoT project.

7. Advancing Engineering Education: Using the Three-Phase Methodology to Teach IoT (Assumpção et al. 2022) - This article, already accepted by a magazine to be published, presents a new learning approach that uses the TpM and the Flipped Classroom approach in a postgraduate course in IoT (IE309X) where students are introduced to the concepts required to design, build, and test IoT solutions. To evaluate the effectiveness of the proposal, the results of an earlier edition of the course (2019), when the learning approach was not used, are compered to two more recent ones (2020 and 2021) when it was. The same syllabus and rubrics were used in all three editions of the course. The final group projects' grades and satisfaction surveys were used to evaluate the students' performance and motivation. Findings indicate that the 2020 and 2021 classes performed better than the 2019´s, as their final group projects grades were considerably higher, indicating that the approach has an impact on the development of students' transversal skills.

5.3 Discussions

Several schemes have recently been put forward to tackle the deficiencies found in our teaching programmes at all levels. Studies, like the one from (Escalona Zamorano 2018) concluded that STEAM education still lacks a clear conceptual framework with broad consensus within the scientific-educational community. Initiatives like the training of elementary and secondary school teachers to use digital technologies in teaching can be a game-changer for an entire generation. This can make the use of technology commonplace among our teachers, preparing the next generation of professionals that will develop the IoT solutions that we will increasingly be dependent on.

However, the IoT is a multidisciplinary and comprehensive area that involves concepts, techniques, technologies, and approaches from several areas of engineering. In addition, an IoT solution can be useful in any area of knowledge. Figure 5.1 presents an infographic that shows the variety of themes related to IoT.

The main difficulty often encountered in IoT teaching projects was the integration of these concepts, techniques, technologies, and approaches. We observed that, often, IoT courses offer content in isolation, without a direct relationship between them, consequently, failing to show how each discipline fits within the IoT concept.

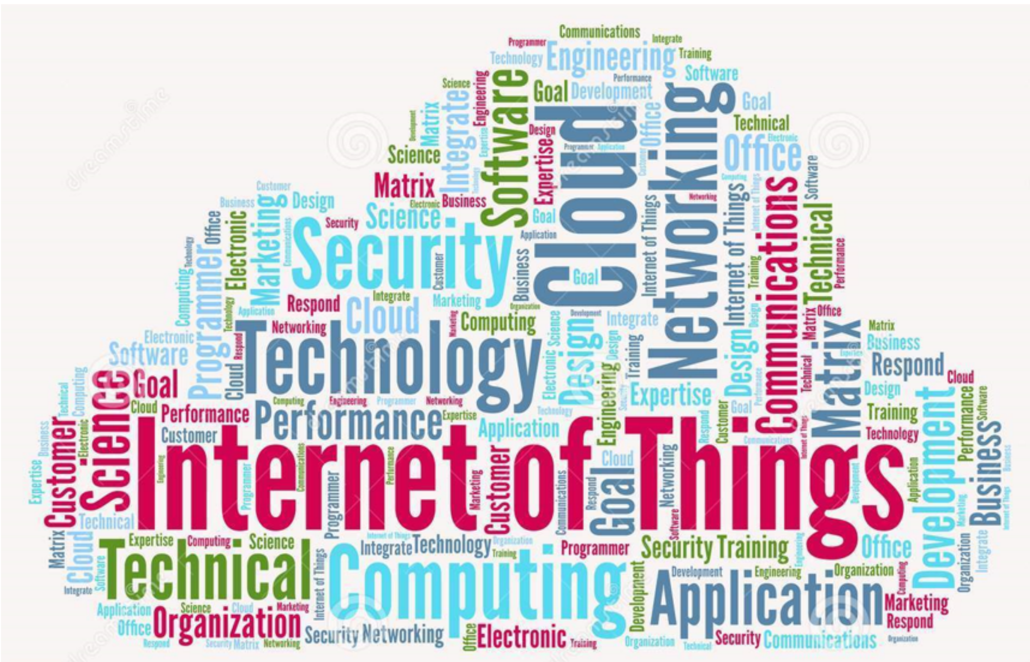

Figure 5.1 – Infographic.

Another challenging aspect is that the professionals who will work in IoT have a variety of specialities, including computer and data scientists, electrical, mechanical, telecommunications, and computer engineers. This heterogeneous aspect of IoT professionals also influences the way IoT is taught.

Thus, we noticed the necessity of a way to structure IoT solutions in a systematic way, so that it is possible to link the necessary know-how for the development of applications and, consequently, consolidate the understanding of IoT.

The first move towards this goal was the work of (Déo 2018), describing the creation of the IoT-OSRM for IoT solutions. The model has six levels, where each one is responsible for a specific function/component of the IoT application.

Any IoT solution can be divided into these six levels, regardless of the complexity of the solution. In this way, the OSRM is useful for structuring IoT solutions, linking the know-how by level.

Another concern regarding the IoT teaching process was how to present the specific contents of each level of the OSRM model in an integrated way, related to the IoT concept.

The answer was to resort to active teaching methodologies, such as PBL. The new DNCs for engineering and technology courses suggest using these approaches. However, PBL is a generic methodology applicable to a variety of scenarios. So, a specific methodology for teaching IoT could be an important contribution.

Therefore, the TpM was created in 2019. A methodology based on PBL but created specifically for IoT teaching. It incorporates the OSRM reference model but also includes an important feature, the need to define the problem/business to be addressed by the IoT solution. Figure 5.2 presents the TpM diagram.

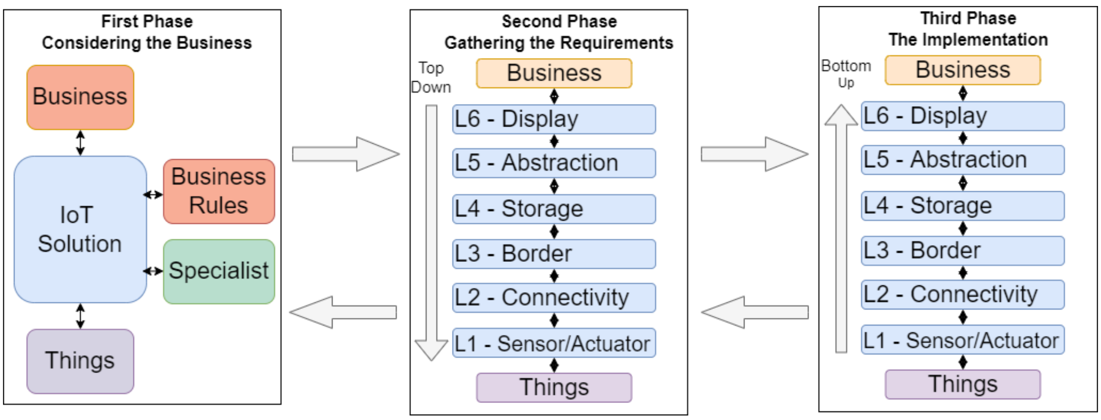

Figure 5.2 – The Three-Phase Methodology diagram encompassing the 6-level IoT-OSRM (adapted from (Ferreira et al. 2019))

The TpM was successful in treating IoT as a tool to achieve a goal, not just a technology. This approach proved to be efficient, as students understood what IoT offers to solve a problem. It is only after this understanding is consolidated that the technologies for implementation are discussed.

The areas involved in the creation of IoT applications are already consolidated and in full development by industry and academia. There was a need for a way to organise and systematise the role of these areas within the IoT concept. The TpM was a proposal that addresses this issue.

With the TpM, IoT courses can be offered with a focus on a certain area, emphasising specific contents, without neglecting the importance of other areas and other contents.

A practical example of this statement is the work of (Chaves et al. 2021), where an emulation environment for teaching low-power wireless communications for IoT, the NEWBen, is presented. The author uses the TpM to contextualise the importance of this area in IoT, making it clear where wireless connectivity is in an application. In this work, there is an effort to offer students and educational institutions around the world, a low-cost alternative for wireless experimentation that can be replicated locally.

Also, to assist in the teaching process, a project development tool was developed using the TpM (Ferreira et al. 2021). This system was improved and became a complete Virtual Learning Environment (VLE) based on the TpM, the Integrated Digital Learning Environment (IDLE-IoT) (Yamaguti et al. 2021).

The TpM has been tested in courses for the last 3 years, in extension and postgraduate courses, with more than 100 students. The work of (Assumpção et al. 2022) for example, analyses three editions of the postgraduate course IE309X at FEEC. The work shows that the approach encourages active participation in the activities and facilitates the retention of the concepts studied.

Thus, considering the experiences presented in this paper, we offer some observations that can contribute to further research and guide new initiatives in the area of IoT teaching:

- We must prepare our students from the elementary years, allowing interaction with technologies an concepts. This should increase their interest in the areas of technology and engineering.

- For that, elementary and secondary school teachers must also be prepared. Methodologies, such as the TpM, can help in this process, as they deal with the subjects in a more conceptual way, focusing on the project/problem. This is a friendly approach to get into more complex topics.

- The IoT requires different skill sets to pull together, however, sometimes this can be difficult to coordinate. The methodologies and tools presented in this paper can help in this integration process. In addition, they can serve as inspiration for new proposals.

- We believe that the IoT will only fully develop when all these aspects have been considered.

5.4 Conclusion

"The difficulty lies not so much in developing new ideas as in escaping from old ones"(Keynes 2022). This sentence resumes what we encountered when proposing new ways to do something. It is clear that we need to investigate new ways to transfer knowledge, more in line with the new possibilities offered by new technologies. We hope that the initiatives presented in this paper contribute to changing the perceptions of science and IoT teaching. We believe that further research should concentrate on providing our education professionals with the tools to prepare our students to face the challenges the 21st century has to throw at them.

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6 Conclusions and Future Work

This chapter presents an overview of the work developed in this study, highlights its contributions, and proposes ways to further develop it.

6.1 Overview

This work sought to contribute to the teaching of IoT by proposing the TpM, an innovative methodology developed specifically for this area. The methodology was applied to several classes and corporate projects, in order to be evaluated and validated.

IoT Teaching is a research area that presents several challenges, particularly due to its multidisciplinary nature. A literature review shows several training initiatives to prepare professionals to work in this area. However, none of them presents a systematic and structured form, which could serve as a standard at any level of education and for any IoT application.

The TpM proposes a unique way of teaching and developing IoT, regardless of the complexity level of the subjects and proposed solutions. The TpM is a systematic and structured methodology developed for this purpose.

The TpM was applied in extension and postgraduate courses for three consecutive years, with over 150 students. In its first application, in 2019, the results were promising. The first published work (Chapter 2) showed that the methodology facilitated student learning, being a friendly methodology to work with complex topics. The work also presented a development kit for didactic purposes, which was used during the application of the methodology.

Despite the good results presented in the first application, we noticed that students had some difficulties in applying the methodology. Much of this was due to the lack of specific tools to use the methodology. Therefore, a system was then developed to facilitate the application of the TpM. The development and validation process of this tool is presented in Chapter 3. The system is used for documentation and information sharing during the development of an IoT solution. Students used this system during the courses.

During the application and validation process, it was observed that the TpM could go beyond teaching. It was noticed that the TpM could be used as a specific project methodology for IoT. The methodology was applied to a corporate project and the results were promising. The feedback from the development team was positive, as can be seen in Chapter 4, which was published by Elsevier, in the Journal of Internet Of Things.

The paper presented in Chapter 5 presents an overview of the research and the initiatives aimed at teaching IoT. It summarizes and offers an analysis of all actions carried out during the last four years. The chapter highlights the difficulties, and suggests future research topics, offering guidance for researchers interested in contributing to this area.

6.2 Contributions

The main contribution of this work is the TpM, a structured and systematic methodology for IoT teaching and development. From the methodology, several other contributions were achieved.

The experience with the application and development of the methodology was used in the creation of tools and application models, and opened new possibilities for teaching and development in IoT. Some of these contributions are:

- Courses in IoT, which can be replicated and/or improved;
- Complete systems for applying the methodology in distance learning or on-site courses.
- The methodology can be used as a single language to discuss IoT, regardless of the complexity or scope of the topic.
- The TpM as a specific agile methodology for the development of IoT applications.
- The TpM can serve as a basis for the creation of other techniques and tools for the development of IoT solutions.

In short, the TpM was applied in extension and postgraduate courses. Tools and environments were developed using the methodology as their basic structures. The results showed that the TpM was successful in facilitating students' understanding of how several areas must interact to build IoT solutions.

The TpM's main premise is that technology should be seen as a means to IoT, not an end. The success of the methodology is largely due to its focus on the problem to be solved, before any technological choice. This approach makes the subject more interesting to students and professionals. Once the problem is understood, the technological and conceptual choices flow more naturally, following a well-defined path. In addition, the definition of phases and levels makes the work more systematic and structured, showing a generic path for creating IoT solutions of any size.

6.3 Future Work

The TpM is still under development and has several aspects that can be explored:

- Use of TpM in elementary and high schools: Students of elementary and high schools must be encouraged to follow a career in technology and engineering. The TpM can be a tool that helps this process, as it is a friendly way to approach complex issues.
- Application as a methodology for developing corporate projects: The TpM should be tested in more scenarios, with solutions in different areas, aiming to fully validate it as a project methodology.
- Creation and improvement of tools for its application: The tools and environments created for the TpM can be further developed, proposing improvements and variations. This will create an ecosystem of tools and options that will allow the methodology to be more widely adopted.

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Appendix

APPENDIX A – Aprovação pelo Comitê de Ética

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PARECER CONSUBSTANCIADO DO CEP

DADOS DO PROJETO DE PESQUISA

Título da Pesquisa: Metodologia em Três Fases (MTF): Metodologia Baseada em Project Based Learning para Ensino de Internet das Coisas

Pesquisador: Luiz Carlos Branquinho Caixeta Ferreira

Área Temática:

Versão: 2

CAAE: 26437819.0.0000.5404

Instituição Proponente: Faculdade de Engenharia Elétrica e de Computação

Patrocinador Principal: Financiamento Próprio

DADOS DO PARECER

Número do Parecer: 3.816.212

Apresentação do Projeto:

As informações contidas nos campos "Apresentação do Projeto", "Objetivo da Pesquisa" e "Avaliação dos Riscos e Benefícios" foram obtidas dos documentos apresentados para apreciação ética e das informações inseridas pelo Pesquisador Responsável do estudo na Plataforma Brasil.

Introdução:

A internet das coisas (IoT) é uma realidade. Nos próximos anos são esperados bilhões de novos objetos conectados, trocando informações einteragindo com o ambiente de maneira inteligente.A capacitação de profissionais para atuarem em IoT é uma preocupação. Em é apresentado um modelo de micro-operadoras em redes 5G, ondeexistem pequenas empresas que fornecem serviços específicos dentro da área de cobertura 5G de grandes operadoras. Esse é um modelo quemostra a necessidade de profissionais capacitados para atuarem nesse contexto, onde a IoT se torna atraente para o oferecimento destes serviços.O ensino de IoT nas instituições de ensino enfrenta o desafio de selecionar uma metodologia que se adeque à complexidade do tema, que envolveconhecimento de várias áreas e que não dependa de tecnologias de um só fabricante.Em IoT, uma solução desenvolvida deve ser pensada de acordo com necessidades especificas do usuário/cliente, sempre para atender um negócio.A interdisciplinaridade é uma das grandes dificuldades encontradas para o ensino de IoT.Devido a essa característica, a forma de ensino de IoT deve preparar o aluno para utilizar técnicas e metodologias que visam esse objetivo, criaruma solução para uma demanda/problema específico.Hoje existem diversos produtos de IoT no mercado, de inúmeros fabricantes e cada um usando uma estratégia diferente de implementação eaplicação. Isso dificulta ainda mais o processo de ensino, pois o profissional pode ficar refém de uma determinada solução.Esse projeto apresenta uma proposta de metodologia de ensino para IoT, baseado em PBL (Project Based Learning) usando três ciclos bemdefinidos, sendo eles: Negócio, Requerimentos e Implementação.O objetivo é propor uma metodologia que atenda o ensino de IoT de forma sistemática e abrangente, não dependente de fabricante e que sirvacomo uma opção para cursos de graduação, pós-graduação e capacitação profissional.

Hipótese:
O uso de uma metodologia sistemática e estruturada facilita o ensino de IoT.

Metodologia Proposta:
A Metodologia de Três Fases (MTF) proposta difere de outras metodologias encontradas na literatura. Alguns trabalhos já foram propostos na literatura para ensino de IoT usando PBL. Entretanto, cada um usa uma lógica diferente e uma estrutura diferente, conforme apresentadona seção de referências bibliográ#cas. A metodologia proposta neste trabalho é uma opção para ensino de IoT, cuja principal característica é ter uma abordagem sistemática e estuturada, que pode ser usada em qualquer nível de ensino, sem ser dependente de tecnologia e com aplicação em qualquer área do conhecimento. Esta metodologia é baseada em um Modelo de Referência Aberto (DÉO, 2018), independente de tecnologia . Com a MTF, os alunos são provocados a questionar e propor idéias sobre um determinado projeto escolhido. Ao invés de usar a abordagem clássica do PBL, a MTF segue etapas bem de#nidas como um guia para projetar, especi#car e implementar soluções de IoT em geral. Essas três etapas são: (i) Entendimento do Negócio, (ii) De#nição de Requisitos e (iii) Implementação. A MTF baseia-se na premissa de que sempre há um problema bem de#nido a ser resolvido por uma solução de IoT. As razões para uma empresa buscar uma solução baseada em IoT incluem adicionar valor a um produto, melhorar um processo existente, e oferecer um novo serviço, entre outros. Portanto, a compreensão dos negócios relacionados ao problema a ser resolvido pode fornecer orientações importantes ao projetar uma solução de IoT. O processo de compreensão do negócio é a primeira fase da metodologia MTF, como mostra a Figura 3.2, evisa obter as necessidades e expectativas do cliente. Este passo deve preceder qualquer escolha tecnológica. Nesse sentido, o papel do especialista surge no processo. O especialista é um pro#ssional com conhecimento do negócio e é o

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responsável por fornecer informações detalhadas sobre o problema a ser resolvido. Por exemplo, se o negócio é na área da agricultura, um pro#ssional neste campo é necessário para produzir apoio prático e teórico para as escolhas a serem feitas no desenvolvimento da solução IoT. Este especialista pode ser alguém da própria empresa ou outra pessoa contratada para esse #m. O especialista ajuda a de#nir as regras de negócio, que são premissas e restrições aplicadas a uma operação comercial de uma empresa que precisam ser atendidas para que o negócio funcione de maneira esperada. Portanto, as regras devem fazer parte do processo de desenvolvimento da solução. Depois que a conexão entre negócios e coisas é entendida, os requisitos para a solução podem ser de#nidos, com base nos objetivos estabelecidos na fase anterior. Este processo é executado na fase De#nição de Requisitos, como mostra a Figura 3.2, quando os componentes do sistema IoT também são de#nidos, embora nenhuma escolha de tecnologia seja feita ainda. Cada nível do modelo diz respeito a uma funcionalidade da solução:• Nível 6 - Exibição: Como é apresentado ao usuário as informações que ajudarão n a tomada de decisão;• Nível 5 - Abstração: Tratamento aplicado aos dados brutos para gerar informação;• Nível 4 - Armazenamento: Onde e como serão armazenados os dados obtidos;• Nível 3 - Borda: Elemento que é responsável por interligar e gerenciar a conexão entre a rede local (RSSF) e a Internet;• Nível 2 - Conectividade: Como será a conexão e transmissão das informações geradas pelas Coisas;• Nível 1 - Processo Local Sensor/Atuador: Como as Coisas serão monitoradas ou controladas. A última fase do TPM é a fase de Implementação, apresentada na Figura 3.2, quando as tecnologias que melhor atendem às especi#cações de#nidas nas etapas anteriores são investigadase a solução é implementada. Essas três fases são iterativas e incrementais, de tal forma que durante a vida útil da solução, as três etapas podem ser repetidas para atender às novas demandas de negócios ou para corrigir falhas.

Critério de Inclusão:
Alunos dos cursos oferecidos pelos pesquisadores do projeto e com a aplicação da metodologia proposta. Não se aplicam a um instituto ou faculdade em específico.

Critério de Exclusão:
Somente cursos onde a metodologia for aplicada e tenha a participação dos pesquisadores do projeto.

Objetivo da Pesquisa:

Objetivo Primário:

Propor uma metodologia de ensino e desenvolvimento para Internet das coisas.

Avaliação dos Riscos e Benefícios:

Riscos:

Não há riscos previsíveis. São apenas questionários online não identificados.

Benefícios:

Criação de uma metodologia de ensino eficiente para o ramo de internet das coisas.

Comentários e Considerações sobre a Pesquisa:

Este protocolo se refere ao Projeto de Pesquisa intitulado "Metodologia em Três Fases (MTF): Metodologia Baseada em Project Based Learning para Ensino de Internet das Coisas", cujo Pesquisador responsável é o aluno de doutorado Luiz Carlos Branquinho Caixeta Ferreira, com a colaboração do Prof. Dr. Paulo Cardieri (orientador). A Instituição Proponente é a Faculdade de Engenharia Elétrica e de Computação da Universidade Estadual de Campinas. Segundo as Informações Básicas do Projeto, a pesquisa tem orçamento estimado em R$ 100,00 (cem reais) e o cronograma apresentado contempla início da obtenção de respostas aos questionários no dia 28/02/2020, com término no dia 30/12/2021. Serão abordadas ao todo 150 pessoas.

Considerações sobre os Termos de apresentação obrigatória:

Foram analisados os seguintes documentos de apresentação obrigatória:

1 - Folha de Rosto Para Pesquisa Envolvendo Seres Humanos: Foi apresentado o documento "folha_rosto.pdf" devidamente preenchido, datado e assinado.

2 - Projeto de Pesquisa: Foram analisados os documentos “projeto_comite_versao2.pdf” e "PB_INFORMAÇÕES_BÁSICAS_DO_PROJETO_1454752.pdf”. Adequado.

3 - Orçamento financeiro e fontes de financiamento: Informações sobre orçamento financeiro incluídas nos documentos “projeto_comite_versao2.pdf” e "PB_INFORMAÇÕES_BÁSICAS_DO_PROJETO_1454752.pdf”. Adequado.

4 - Cronograma: Informações sobre o cronograma incluídas nos documentos

“projeto_comite_versao2.pdf” e "PB_INFORMAÇÕES_BÁSICAS_DO_PROJETO_1454752.pdf”. Adequado.

5 - TERMOS DE CONSENTIMENTO LIVRE E ESCLARECIDO: documento “tcle_v2.docx”. Adequado (Vide Recomendações).

6 - Atestado de matrícula do Pesquisador responsável “AtestadoMatricula.pdf“. Adequado.

7 – Carta de resposta às pendências: documento “CartaResposta.pdf”. Adequado.

Recomendações:

Antes de iniciar a pesquisa adequar a seguinte frase do item "Ressarcimento e Indenização": "Caso haja qualquer tipo de custo em participar da pesquisa, você terá a garantia ao direito à indenização diante de eventuais danos decorrentes da pesquisa." para "Caso haja qualquer tipo de custo para você participar da pesquisa, como por exemplo transporte e alimentação, você será ressarcido integralmente de suas despesas. Você terá a garantia ao direito á indenização diante de eventuais danos decorrentes da participação na pesquisa”

Conclusões ou Pendências e Lista de Inadequações:

Aprovado com Recomendações (Vide item acima "Recomendações")

Considerações Finais a critério do CEP:

- O participante da pesquisa deve receber uma via do Termo de Consentimento Livre e Esclarecido, na íntegra, por ele assinado (quando aplicável).

- O participante da pesquisa tem a liberdade de recusar-se a participar ou de retirar seu consentimento em qualquer fase da pesquisa, sem penalização alguma e sem prejuízo ao seu cuidado (quando aplicável).

- O pesquisador deve desenvolver a pesquisa conforme delineada no protocolo aprovado. Se o pesquisador considerar a descontinuação do estudo, esta deve ser justificada e somente ser realizada após análise das razões da descontinuidade pelo CEP que o aprovou. O pesquisador deve aguardar o parecer do CEP quanto à descontinuação, exceto quando perceber risco ou dano não previsto ao participante ou quando constatar a superioridade de uma estratégia diagnóstica ou terapêutica oferecida a um dos grupos da pesquisa, isto é, somente em caso de necessidade de ação imediata com intuito de proteger os participantes.

- O CEP deve ser informado de todos os efeitos adversos ou fatos relevantes que alterem o curso normal do estudo. É papel do pesquisador assegurar medidas imediatas adequadas frente a evento adverso grave ocorrido (mesmo que tenha sido em outro centro) e enviar notificação ao CEP e à Agência Nacional de Vigilância Sanitária – ANVISA – junto com seu posicionamento.

- Eventuais modificações ou emendas ao protocolo devem ser apresentadas ao CEP de forma clara e sucinta, identificando a parte do protocolo a ser modificada e suas justificativas e aguardando a aprovação do CEP para continuidade da pesquisa. Em caso de projetos do Grupo I ou II apresentados anteriormente à ANVISA, o pesquisador ou patrocinador deve enviá-las também à mesma, junto com o parecer aprovatório do CEP, para serem juntadas ao protocolo inicial.

- Relatórios parciais e final devem ser apresentados ao CEP, inicialmente seis meses após a data deste parecer de aprovação e ao término do estudo.

-Lembramos que segundo a Resolução 466/2012 , item XI.2 letra e, “cabe ao pesquisador apresentar dados solicitados pelo CEP ou pela CONEP a qualquer momento”.

-O pesquisador deve manter os dados da pesquisa em arquivo, físico ou digital, sob sua guarda e responsabilidade, por um período de 5 anos após o término da pesquisa.

Este parecer foi elaborado baseado nos documentos abaixo relacionados:

Tipo Documento	Arquivo	Postagem	Autor	Situação
Informações Básicas do Projeto	PB_INFORMAÇÕES_BÁSICAS_DO_PROJETO_1454752.pdf	14/01/2020 17:37:33		Aceito
Outros	CartaResposta.pdf	14/01/2020 17:34:12	Luiz Carlos Branquinho Caixeta Ferreira	Aceito
Projeto Detalhado / Brochura Investigador	projeto_comite_versao2.pdf	14/01/2020 17:28:32	Luiz Carlos Branquinho Caixeta Ferreira	Aceito
TCLE / Termos de Assentimento /	tcle_v2.docx	14/01/2020 17:23:46	Luiz Carlos Branquinho Caixeta	Aceito

Justificativa de Ausência	tcle_v2.docx	14/01/2020 17:23:46	Ferreira	Aceito
Folha de Rosto	folha_rosto.pdf	29/11/2019 14:59:12	Luiz Carlos Branquinho Caixeta Ferreira	Aceito

Situação do Parecer:
Aprovado

Necessita Apreciação da CONEP:
Não

CAMPINAS, 30 de Janeiro de 2020

Assinado por:
Renata Maria dos Santos Celeghini
(Coordenador(a))

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APPENDIX B – Termo De Consentimento Livre e Esclarecido (TCLE)

TERMO DE CONSENTIMENTO LIVRE E ESCLARECIDO

Metodologia em Três Fases (MTF): Metodologia Baseada em Project Based Learning para Ensino de Internet das Coisas
Luiz Carlos Branquinho Caixeta Ferreira
Paulo Cardieri
Número do CAAE: 26437819.0.0000.5404

Você está sendo convidado a participar de uma pesquisa. Este documento, chamado Termo de Consentimento Livre e Esclarecido, visa assegurar seus direitos como participante da pesquisa e é elaborado em duas vias, assinadas e rubricadas pelo pesquisador e pelo participante/responsável legal, sendo que uma via deverá ficar com você e outra com o pesquisador.

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Justificativa e objetivos:

O Objeivo é avaliar a metodologia de ensino denominada metodologia em três fases. A metodologia consiste no uso de três fases para a criação de uma aplicação em internet das coisas. As fases são:

- Entendendo o negócio: Busca levantar as necessidades do negócio que será beneficiado com a aplicação.
- Levantamento de requisitos: Fase em que é feito o levantamento dos requisitos funcionais da aplicação.
- Implementação: fase onde a aplicação é desenvolvida, levando em conta os requisitos da fase "Levantamento de Requisitos".

Procedimentos:

Voce é convidado a responder o questionário online, que tem questões relacionadas a sua experiência em utilizar a metodologia proposta. O questionário tem duração estimada em 10 minutos. Não existem questões obrigatórias no questionário.

Benefícios:

Você está ajudando a desenvolver uma metodologia nova para ensino de Internet das Coisas, que tem o objetivo de ser padrão de ensino para essa tecnologia. Os participantes não terão benefícios diretos em participar desta pesquisa.

Riscos:

Não existe risco previsível.

Ressarcimento e indenização:

Caso haja qualquer tipo de custo em participar da pesquisa, você terá a garantia ao direito à indenização diante de eventuais danos decorrentes da pesquisa.

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Contato:

Em caso de dúvidas sobre a pesquisa, você poderá entrar em contato com os pesquisadores pelo email carlinhocaixeta@gmail.com.

Em caso de denúncias ou reclamações sobre sua participação e sobre questões éticas do estudo, você poderá entrar em contato com a secretaria do Comitê de Ética em Pesquisa (CEP) da UNICAMP das 08:00hs às 11:30hs e das 13:00hs as 17:30hs na Rua: Tessália Vieira de Camargo, 126; CEP 13083-887 Campinas – SP; telefone (19) 3521-8936 ou (19) 3521-7187; e-mail: cep@fcm.unicamp.br.

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Consentimento livre e esclarecido:

Após ter recebidoesclarecimentos sobre a natureza da pesquisa, seus objetivos, métodos, benefícios previstos, potenciais riscos e o incômodo que esta possa acarretar, aceito participar:

Nome do (a) participanteda pesquisa:

____

____Data: ____/_____/______.

(Assinatura doparticipanteda pesquisa ou nome e assinatura do seu RESPONSÁVEL LEGAL)

Responsabilidade do Pesquisador:

Asseguro ter cumprido as exigências da resolução 466/2012 CNS/MS e complementares na elaboração do protocolo e na obtenção deste Termo de Consentimento Livre e Esclarecido. Asseguro, também, ter explicado e fornecido uma viadeste documento ao participanteda pesquisa. Informo que o estudo foi aprovado pelo CEP perante o qual o projeto foi apresentado e pela CONEP, quando pertinente. Comprometo-me a utilizar o material e os dados obtidos nesta pesquisa exclusivamente para as finalidades previstas neste documento ou conforme o consentimento dado pelo participanteda pesquisa.

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(Assinatura do pesquisador)

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