TÉCNICO
LISBOA

Smart Thermometer for Food Safety Management

Tiago Teixeira de Almeida

Thesis to obtain the Master of Science Degree in

Electrical and Computer Engineering

Supervisor: Prof. João Nuno de Oliveira e Silva

Examination Committee

Chairperson: Prof. Teresa Maria Sá Ferreira Vazão Vasques

Supervisor: Prof. João Nuno de Oliveira e Silva

Members of Committee: Prof. Renato Jorge Caleira Nunes

Janeiro 2021

I declare that this document is an original work of my own authorship and that it fulfills all the requirements of the Code of Conduct and Good Practices of the Universidade de Lisboa.

Acknowledgements

First of all I would like to thank the HACCP consulting company whose support and feedback was essential for the development of this dissertation.

I would like to start by expressing my gratitude to my supervisor Prof. João Nuno Oliveira e Silva, for the support, guidance and availability shown, not only during the time we spent working on this dissertation but also during all the other courses I had with him. I truly enjoyed your classes.

To Dra. Margarida Ferreira, and all the IPO Lisboa staff, thank you for everything you have done for me. Without you I would not have the opportunity to achieve this, and much more. Keep making the difference in people's life.

To my parents, thank you for all the support you ever gave me in my life. For the comprehension , the kindness and love. Without you I would not be who I am today.

To my brother, whom I adore, thank you for being present everyday.

To my uncles and cousins thank you for being part of my life. For caring and for supporting me even at a distance.

To my girlfriend Marta, thank you for never leaving my side. Thank for your love and for being here for me when I needed the most in the past five years. Thank you for pushing me to finish this work.

To everyone at IST Tennis Team, thank you for all the great times and good memories. I will forever carry this team in my heart.

To all my closest friends thank you for being there in the good and the bad times. Your support means the world to me.

Abstract

Efficient food safety measures, namely temperature control, can contribute to mitigating the global problem of foodborne diseases. Temperature control procedures are in place in many establishments but often lack efficiency and can strongly benefit from process optimization, both on the perspective of temperature control and record taking, mainly when measurements are required to be taken through the use of a thermometer. With this work, the objective is to create a functional prototype of a smart thermometer used to control temperatures more efficiently and reliably, enabling greater control over the measurements that food safety management systems, including HACCP and traceability systems, require. The proposed solution includes features such as allowing user authentication, machine and product RFID identification, presentation of daily tasks, and automatic remote submission to a database. Feedback was received from an HACCP consulting company responsible for more than 400 establishments. A survey was also conducted to four food safety managers from different sectors of the food industry, together responsible for food safety in more than 700 establishments. The received feedback confirmed that food safety managers see value in the presented solution and it's their belief that it can be used to prevent possible errors caused by the human factor and optimize the temperature control processes. The prototype developed met the requirements defined and presents new and improved features when compared to existent solutions in the market.

Keywords

HACCP, FSMS, Temperature Control, IoT, RFID, Food Safety

Resumo

Medidas eficazes de segurança alimentar, nomeadamente controlo de temperatura, podem contribuir para mitigar o problema global das doenças de origem alimentar. Muitos estabelecimentos seguem um conjunto de procedimentos, mas a maior parte carece de eficiência e podem beneficiar da otimização desses mesmos processos, tanto na perspetiva de controlo de temperaturas como no registo de dados, em particular quando as medições são feitas com recurso a um termómetro. O objetivo desta tese é criar um protótipo funcional de um termómetro inteligente utilizado para controlar temperaturas de forma mais eficiente e fiável, permitindo maior controlo sobre as medições de temperatura que os sistemas de gestão de segurança alimentar requerem, incluindo sistemas HACCP e rastreabilidade. A solução proposta inclui funcionalidades como possibilitar a autenticação do utilizador, identificação de máquinas e produtos através de etiquetas RFID, disponibilização do horário de tarefas diárias, e submissão remota dos dados na base de dados. Foi considerado feedback de uma empresa de consultoria em sistemas HACCP responsável por mais de 400 estabelecimentos. Foi também efetuado um questionário a quatro gestores de segurança alimentar, de diferentes atores da indústria alimentar, responsáveis por um total superior a 700 estabelecimentos. O feedback recebido confirmou que os gestores de segurança alimentar encontram valor na solução proposta. Acreditam ainda que a solução proposta pode ser utilizada para prevenir possíveis erros provocados pelo fator humano e otimizar os processos de controlo de temperatura atuais. O protótipo desenvolvido cumpriu os requisitos definidos e apresenta novas e melhoradas funcionalidades quando comparado com soluções existentes no mercado.

Palavras-chave

HACCP, FSMS, Controlo de Temperatura, IoT, Segurança Alimentar

Table of Contents

List of Figures

List of Tables

List of Acronyms

ADC	Analog to Digital Conversion
API	Application Programming Interface
CCPs	Critical Control Points
Codex	Codex Alimentarius collection of food standards
DRF	Django REST Framework
EC	European Commission
FBD	Foodborne Diseases
FBDO	Foodborne Disease outbreaks
FSMS	Food Safety Management Systems
GHP	Good Hygiene Practices
HACCP	Hazard Analysis and Critical Control Points
IoT	Internet of Things
IR	Infrared
ISO	International Organization for Standardization
ITU	International Telecommunication Union
JSON	JavaScript Object Notation
JWT	JSON Web Tokens
NASA	National Aeronautics and Space Admnistration
NFC	Near Field Communication
PRPs	Prerequisite Programs
REST	Representational State Transfer
RFID	Radio Frequency Identification
RTC	Real-Time Clock
SoC	System on Chip
TLS	Transport Layer Security
TRUs	Traceable Resource Units
UID	Unique Identifier
URIs	Unique Resource Identifiers
WHO	World Health Organization
WSN	Wireless Sensor Networks
XML	Extensible Markup Language

Chapter 1

Introduction

This Chapter gives a brief overview of the work carried out for this dissertation. It starts by describing the problem that foodborne diseases represent to the public health and the world economy, followed by the motivation. The impact of foodborne disease outbreaks is briefly analyzed, showing that restaurants and other food operators have an added responsibility in preventing outbreaks. Temperature abuse is appointed as one of the leading causes of foodborne disease outbreaks with origin in these establishments. A solution to improve temperature control is proposed and these dissertation objectives are presented. This Chapter finishes by giving the outline of the document.

1.1 Overview

Every year, about 600 million people, almost 1 in 10, fall ill, 420 thousand die, and 33 million disability-free life years are lost due to foodborne illnesses[1]. In the World Health Organization (WHO) European region alone, it is estimated that over 23 million people suffer from the same problem. From these, 5 thousand die, and 400 thousand disability-free life years are also lost [2].

Several studies have estimated the public health burden due to any illness caused by the consumption of food contaminated at any stage of its production, i.e., foodborne diseases (FBD). These numbers underestimate the total amount as only a small percentage of the actual FBD cases are known and reported worldwide. Although prevalent in low and middle-income countries, FBDs are a worldwide concern, common across all countries[3]. For example, due to FBDs, in the US, 48.000.000 people fall ill each year, and 3000 die[4]. In France, each year, between 1.280.000 to 2.230.000 fall sick and 250 die[5]. In the United Kingdom, 2.400.000 fall ill and 180 die [6], and in Canada, 4.000.000 fall ill [7]. In today's interconnected world, this issue is foreseen to keep growing as global trade, changes in eating habits, farming practices, and climate change are expected to increase [3].

Unsafe food represents not only a burden on world public health but also a burden on the world economy. A study from the World Bank [8] states that the impact of FBDs on low- and medium-income countries is about US$ 110 billion, where US$ 95.2 billion are attributed to productivity loss and US$ 15 billion to the cost of treating FBDs. In developed countries, FBDs equally represent an economic burden: in the United States the burden reaches the US$ 77 billion each year [9]. In the UK, the Food Standards Agency conducted a study based on 2018 case estimates that stated FBD costs society approximately £9.1 billion each year[6]. These numbers show that regardless of the methodology used by each study to measure its impact, FBD are an important public health problem, and there is still a long way to control it worldwide.

By comparing developed countries and low and middle-income countries, the numbers also show that FBD are preventable. Countries can minimize the burden of FBD by adopting proactive strategies and by prioritizing problems and measures, thus avoiding economic losses of hundreds of millions, or even billions, a year [8]. For this to happen, shared responsibility is required from everyone involved throughout all food chain, from farmers to consumers.

1.2 Motivation

Foodborne disease outbreaks (FBDO) happen when two or more people get the same illness from the same contaminated food or drink. Several FBDOs have been reported worldwide in recent years: in Germany, in 2011, an outbreak of Escherichia coli O104:H4 caused at least 3186 cases and 54 deaths

[10]; a Listeriosis outbreak, in Spain, in 2019, made 200 people ill and three deaths [11]; another Listeriosis outbreak happened between 2017 and 2018 in South Africa, at that time the biggest in the world with more than 1000 cases and over 200 deaths [12]. Outbreaks like these are thought to be largely underreported, unrecognized, or un-investigated [1][13]. Many more have happened, and many more will happen if preventive measures are not taken.

Different studies show that, in developed countries, a large percentage of FBDOs occur in restaurants[14], [15][16]. Therefore, restaurants and other foodservice establishments have increased responsibility when handling or preparing food. The most common factors contributing to FBDOs in foodservice establishments are situations or operations that allow the contamination, survival, or proliferation of etiologic agents responsible for FBDs. Some of these factors include infected workers, bare-hand contact by handlers/workers/preppers, cross-contamination between products, inadequate hygienic conditions, and temperature abuse of many kinds [17][16][18].

Costs to establishments where FBDOs arise can be exceptionally high: lawsuits, legal fees, fines, and even loss of revenue derived from FBDOs can represent a cost equivalent to a large portion of a restaurant's annual profits [19]. In a world that is increasingly more interconnected each day, where the public is more aware of food safety hazards and is demanding safer food, factors like infection prevention, control measures, and proper Food Safety Management Systems (FSMS) are of the utmost importance and can have a significant impact.

Different studies appoint temperature abuses as a critical contributing factor that leads to FBD [16][20][21]. Some examples of temperature abuse that contribute to the survival and/or proliferation of etiologic agents responsible for FBDs are insufficient time and/or temperature during cooking/heating process, insufficient time and/or temperature during reheating, inadequate thawing (followed by insufficient cooking), allowing foods to remain at room or warm outdoor temperature for several hours, inadequate cold-holding temperature, insufficient time and/or temperature during hot holding [18].

To better control and prevent the issues mentioned above, Hazard Analysis and Critical Control Points (HACCP) based FSMS along with traceability systems are mandatory in several countries. In these countries, some foodservice establishments implement not only the minimum required systems to comply with laws and regulations, but many have even implemented extra, complementary, non-regulatory FSMS[22]. With the implementation of extra non-regulatory FSMS, there is an improvement in product traceability, food safety awareness by employees, client maintenance, a decrease in wastage (and its cost impact), and a reduction of customer complaints [22].

1.3 Problem Statement

In many cases, the systems mentioned at the end of the previous section are poorly implemented and far from perfect. Several obstacles and barriers to effective implementation and application of HACCP principles and management systems have been appointed throughout the years by several studies [23][24][22]. Some of the significant problems that were pointed out include increased paperwork, difficulties in record keeping, incomplete or forged records, failure to monitor Critical Control Points (CCP) adequately, difficulty or impossibility in assessing who made the records, personnel training, lack of verification if the controls are being done and difficulty in maintaining the system, among others [23].

In this dissertation's scope, a HACCP consulting company responsible for more than 400 establishments supported the development of the smart thermometer prototype by providing relevant feedback regarding their experience on implementing HACCP system with their clients.

The company highlighted that, in fact, one of the most common issues that foodservice establishments had with their HACCP FSMS was the efficient and proper control of temperatures, mainly the ones that should be controlled through the use of handheld thermometers. In some cases, processes were manual, and the records kept on paper; in others, there was a degree of automation with records inserted in a database through a smartphone or tablet at the time of the control or at a later time.

In the case of establishments that had a manual process and relied on paper, the difficulty of keeping straight records was higher: employees made mistakes when monitoring; records were made just before authorities went by to verify them; records were lost, and in the event of an issue being identified the analysis and traceability of the problem was almost impossible to achieve. Daily monitoring of operations was also difficult, as managers could not be sure if the records were made correctly and on time. If something wrong happened during a process, it would sometimes take weeks or months for someone to realize it. Costs were also higher, given that more resources are needed: for example, employees spent more time doing temperature controls and recording them.

When a tablet or smartphone was used, the main issues were that employees had to carry a device in-store, records could still be forged, and mistakes could be made when entering data on the database.

Either way, it can be concluded that flaws arose from either of these processes, showing that exists room for improvement.

1.4 Objectives & Solution Proposal

Taking the identified issues in Section 1.3, the objectives of this dissertation is to present a solution that relies on Internet of Thing (IoT) to mitigate some of the factors shown above and solve the challenge of accurately controlling food temperature in restaurants and other food service establishments, especially temperatures that need to be measured using a handheld thermometer.

The system developed within this dissertation's scope focuses on a new approach to temperature control. It is meant to improve the way food temperature control is made in current HACCP and traceability systems.

The objective is to create a functional prototype of a smart thermometer that will be used to control temperatures more efficiently and reliably, enabling greater control over the measures that HACCP FSMS requires.

The system comprises a smart thermometer and an additional backend that will provide an application programming interface (API) that can either be deployed on-premises, on the cloud, or even using a hybrid approach.

The smart thermometer includes the following functionalities:

- Have the option to work as a simple thermometer.
- Allow users to authenticate and facilitate the tracking of the employee that made each measure.
- Guarantee proximity to what is pretended to be measured, looking to help mitigate registry forgery.
- Allow quick registers of temperature readings from different machines and products with proper identification of what is being measured.
- Have the possibility to present the daily measures that staff should do, allowing staff to complete them and automatically register the results.
- Possibility of submitting results directly to a database.
- Allow taking offline temperature control measures.

The handheld thermometer is supported by a backend and API that:

- Be able to be deployed in the customer facilities, the cloud, or in a hybrid environment.
- Give the smart thermometer the ability to be used as a standalone service.
- Give the smart thermometer the ability to be integrated into the companies services.
- Allow the update of the smart thermometer database.

Results from the survey conducted confirmed the feedback from the HACCP consulting company that foodservice establishment value a solution like the one proposed to help tackle the challenge of temperature control, allowing them to not only follow regulations, but also manage their resources more efficiently while, at the same time, contributing to diminish the worldwide issue of foodborne diseases. Adding to that, informal conversations with food quality managers from diverse food establishments were held, and the interest shown in the solution very significant. It was recognized that it had great potential and that it would help them in daily activities.

1.5 Document Outline

The current thesis is organized into six chapters:

- Chapter 1 is the introductory Chapter that has just been presented. An overview of the problem that foodborne diseases present to the world has been made followed by the description of the problems that motivated this work. Objectives are outlined and a solution is proposed.
- Chapter 2 will focus on a literature review relevant to further understand the topic this dissertation focuses on, as well as the technologies used to implement the proposed solution.
- Chapter 3 will present the requirements of the system.
- Chapter 4 will detail the architecture of the system.
- Chapter 5 will discuss the implementation of the system, accounting for what was defined in the

previous two chapters.

- Chapter 6 will present the final results and discuss if the requirements were completed.
- Chapter 7 contains the conclusions of this work as well as suggestions for future work.

Chapter 2

Literature Review

This Chapter introduces the concepts of HACCP and Food Traceability Systems, followed by an analysis of the impact that temperature has on food and how HACCP and Food Traceability Systems can help control it. It finishes by reviewing existing modern technologies and their applications in Food Safety Management Systems.

2.1 HACCP

HACCP is a systematized, science-based, documented method internationally recognized as the best way to control significant food safety hazards[25]. Focusing on prevention instead of end-product testing, using a systematic approach, hazards are identified, and assessment and control of risk are made through the definition and control of CCPs [2]. This enables companies to reduce contamination risks to an acceptable level while reducing the dependency on final product inspection [26].

HACCP is widely adopted around the world. In the last few decades, several countries have made HACCP principles mandatory by introducing legislation requiring to apply HACCP principles to varying degrees [25]. For example, in the US, HACCP is required by law for manufacturers of meat and poultry, seafood, and juice products [27]. From 2006 onwards, in the European Union, it became mandatory for all food operators to implement an FSMS based on the HACCP principles. Article 5 of Regulation (EC) No 852/2004 states that "Food business operators shall put in place, implement and maintain a permanent procedure based on the Codex HACCP principles" [28]. Also specified in regulations is the fact that before implementing HACCP, food companies must already implement good hygiene practices (GHP) corresponding to prerequisite programs (PRPs) [29]. HACCP is mandatory in several other countries. Nevertheless, in those where it is not (or even in places where it is but just at some minimum degree), food operators implement HACCP based systems to improve food safety [22]. This shows how well HACCP is accepted and implemented worldwide.

To further understand HACCP and the motivations behind it, a brief overview of its origins, principles, PRPs, benefits and main problems are given in the next subsections.

2.1.1 Brief history

In 1959, at the beginning of the US manned space program, the National Aeronautics and Space Administration (NASA) needed a way to guarantee safe food for astronauts in future space expeditions. Considering the high importance of assuring that there wasn't any microbiological, chemical, or physical hazard that could cause any harm to astronauts mid-mission, the needed degree of certainty that food was completely safe was close to 100% [30]. For that purpose, NASA jointed efforts with the Pillsbury Company, the US Army Laboratories, and the US Air Force Laboratory Project Group, and quickly concluded that the processes used at the time would not reach the required standards. The fact that quality control was made only through the test of a minimal subset of raw materials and through in-line and end-product testing generated significant doubts about the efficacy of the systems in use. To solve this issue, a model used for medical supplies, called "modes of failure", was adapted from the US Armed Forces Natick Laboratories [31]. This was the first time where a preventive (instead of a reactive), control-based approach was implemented to assure food safety. The dependence on finished product sampling and testing was reduced and instead took place the identification of hazards and CCPs that could be monitored and recorded [30].

Although this approach has proven to be a success, its acceptance by mainstream food producers took a long time: in 1971, it was presented to the food industry; in 1973, the first document on HACCP was published and used to train Food and Drug Administration inspectors; in 1974 the Pillsbury company was using HACCP in all its food plants and its Burger King restaurants with great success [31]; it was only in 1992 that the National Advisory Committee on Microbiological Criteria for Foods (NACMCF) stated in a report that HACCP could be used in an effective way to assure food safety from farm to table. Right after, in 1993, the Codex Alimentarius Commission Committee on Food Hygiene (Codex) released a definitive report on HACCP [32]. Both these reports described the current HACCP seven principles, which will be discussed in section 2.1.3. From this point on, in the last decades, HACCP has been spread worldwide and its use has been largely adopted by the food industry to ensure safe food for billions of consumers [30].

2.1.2 Seven Principles

As mentioned in section 2.1.1, HACCP's seven principles were first described by the NACMCF and by the Codex. These seven principles set the basis for the requirements for the application of HACCP [33].

Principle 1: Conduct a Hazard Analysis

This is the first step when implementing a HACCP-based FSMS. A hazard (something that has the potential to cause harm) analysis should be made with the objective of identifying all biological, physical, or chemical hazards that can be originated during the manufacturing or handling of the product. A hazard should be taken into consideration when it is significant. This means when its prevention, elimination or reduction to suitable levels proves essential to the production of safe food [34]. To identify a significant hazard, it is necessary to consider two parameters: the likelihood of its occurrence and the severity of the impact it imposes on consumer health[32]. Control measures for each hazard should also be detailed and justified [32]. The strength of a HACCP plan will be determined by the hazard analysis, making this a fundamental HACCP element.

In Table 1, a Hazard Analysis Chart is presented. It allows to further understand what a hazard analysis should be focusing on.

Table 1 *- Hazard analysis chart headings. Source: [32]*

Process Step	Hazard: source, cause, and manifestation	Likelihood of occurrence (high/low)	Severity of outcome (high/low)	Significant? (yes/no)	Justification of significance decision	Control measure(s)	Justification of control measures

Principle 2: Determine the Critical Control Points (CCPs)

The Codex defines a CCP as "a step at which control can be applied and is essential to prevent or eliminate a food safety hazard or reduce it to an acceptable level" [33]. After the hazard analysis is made and all significant hazards are identified, these should be addressed, and their CCPs should be found and documented [34]. Some CCPs are defined by regulations and, therefore, easier to identify [32]. For the remaining, a decision tree can be used. In **Error! Not a valid bookmark self-reference.** it is presented the Codex CCP decision tree used to determine if a certain point in the process is a CCP or

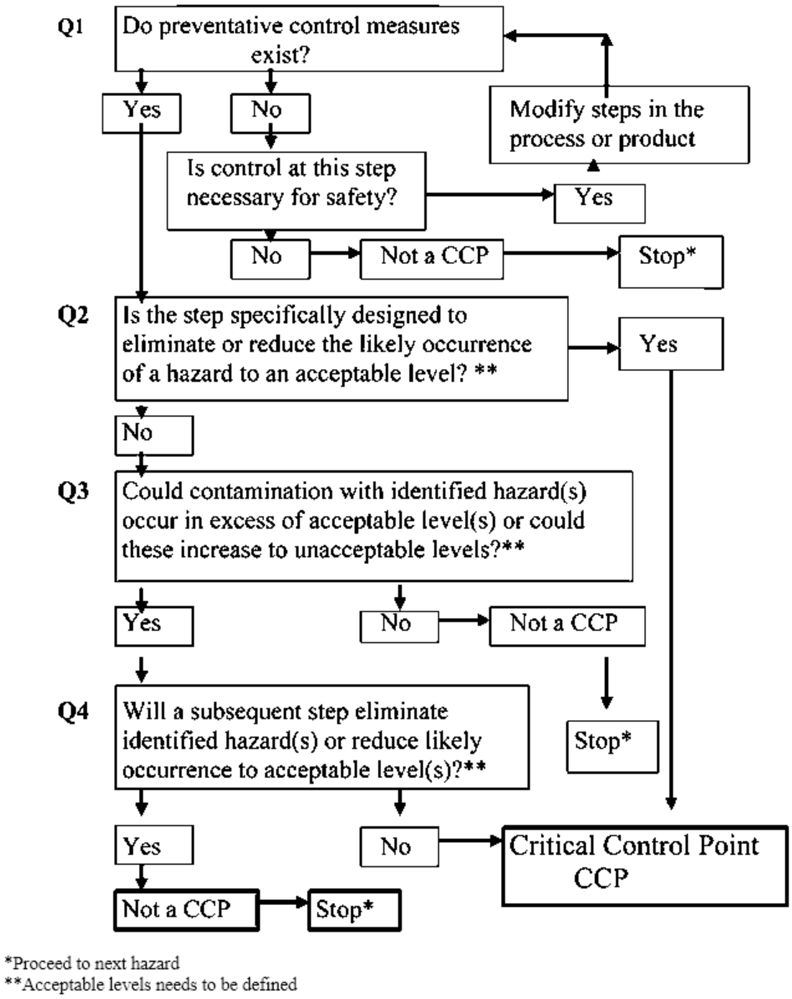

Figure 1- *CCPs decision tree. Source: extracted from Codex [33]*

not.

Principle 3: Establish Critical Limits

To ensure food safety, for each CCP, it is necessary to define and validate a critical limit[33]. The Codex defines a critical limit as "a criterion which separates acceptability from unacceptability" [33]. In other words, critical limits are the thresholds (temperature, ph, humidity, and many others) that must be set and not exceeded to consider that a product is safe [34]. Critical limits should not be expressed as an interval. They should be defined as an absolute value, e.g., critical temperature to kill *Salmonella* spp. in raw eggs is 70ºC for 2 minutes in the center of the egg [32]. It is essential to realize that these are the extreme limits necessary to ensure safe food; a margin of error should always be given. Critical limits should be based on science, experimental data, legislation, and historical evidence [32].

Principle 4: Establish a monitoring system for each CCP

After having the critical limits defined, it is needed to monitor them to check if the boundaries are not broken, and if the CCPs are under control [34]. The Codex definition of monitoring is "the act of conducting a planned sequence of observations or measurements of control parameters to assess whether a CCP is under control" [33]. Each of the monitoring activities should be made by a designated person responsible for recording the results and, if necessary, by taking corrective actions. These activities should be realized with an adequate frequency. Ideally, they would be continuous and would work together with an alarm and action system. In cases where a continuous system is not possible, the frequency depends on the process's nature. Supposing it is a process with a big throughput, the frequency with which the monitoring is made should be higher. This is due to the fact that in a high throughput process if a critical limit is exceeded and the frequency of the monitoring is low, the probability of having a larger number of unsafe products is more significant [33].

Principle 5: Establish Corrective Actions

When deviations occur, and critical limits are exceeded, corrective actions should take place [33]. The Codex defines a corrective action as "any action to be taken when the results of monitoring at the CCP indicate a loss of control" [33]. If a loss of control is identified, the non-compliant products, if any, must be dealt with and the cause that led to the CCP being out of control identified and corrected [34]. This step represents the last defense before a product reaches the consumer. Therefore the corrective actions for each CCP must be verified and challenged in order to check that the established corrective actions are strong enough to protect the consumer [32].

Principle 6: Establish Verification Procedures

Although the main purpose of this principle is to verify the HACCP system, it also refers to the need to validate it. The Codex refers to verification as "the application of methods, procedures, tests and other evaluations, in addition to monitoring to determine compliance with the HACCP plan" and to validation as "obtaining evidence that the elements of the HACCP plan are effective" [33].

To validate a HACCP system, it is necessary to verify if all the principles are being correctly applied and confirm that all the hazards will be effectively controlled by demonstrating that: suitable control measures are in practice; CCPs have been correctly identified; literature and scientific and technical data were used to ensure that critical limits are correctly set for each hazard; monitoring is capable of detecting a deviation and that the corrective actions prevent unsafe food from reach the client and being consumed. In the end, the question "Will it work?" should be answered [32].

For the verification step, the goal is to answer the question, "Is it working in practice?" [32]. To ensure that the HACCP system is working according to plan, it is necessary to use verification and auditing methods, procedures, and tests with a high enough frequency that allows determining if the system complies or if any changes are needed in order for it to work correctly [33][34]. Microbiological and chemical product testing should be done, as well as the review of CCPs, monitoring records, deviations that have occurred and correspondent corrective actions that have been made, and of complaints from consumers and customers.

Principle 7: Establish Documentation and Record Keeping

The seventh and last principle refers to the fact that HACCP procedures should be documented, and efficient and accurate records made and kept [33]. Some of the documentation that should be made has already been mentioned in the previous principles, such as hazard analysis, CCPs, and critical limits determination [33]. After the HACCP plan is implemented, records should be made and kept with an adequate frequency. These include CCP monitoring records (temperatures, PH, humidity, and others), records of corrective actions when a critical limit is exceeded, records of every verification activity, and of modifications to HACCP processes. These records should be sufficient to prove that the HACCP system is working effectively [32]. Different types of archival can be made: some companies use only paper, others use more advanced technologies to save the records, either by scanning or inserting the paperwork data into a database or by having more complete and automated systems including monitoring through handheld devices that communicate the data directly the company database or by using a wireless sensor network [32].

2.1.3 Prerequisite Programs

HACCP, by itself, is not enough to ensure safe food. Strong prerequisite programs (PRPs) should be in place before implementing a HACCP system [29]. From farm to fork, HACCP can be applied through the different sectors of the food chain, but in some cases, after conducting a hazard analysis, it is found out that no CCPs are available at specific steps. In this case, or in cases where the hazard is not significant and can be controlled by a robust prerequisite program (PRP), then the hazard should be controlled through the use of a PRP[29][32].

PRPs will be the foundation of an effective system and are focused on good hygienic practices such as cleaning and sanitation; allergen control; pest control; waste management; proper building and facilities layout; water, air, and energy supply; adequate materials to handle food; and even personnel training and education[32][35]. PRPs control cross-contamination, minimize the growth of microbiological hazards, and let HACCP control hazards specific to the process [36].

PRPs are also set to deal with food defects, from quality or regulatory point of view, that do not represent an immediate and significant threat to the customer health in case of consumption [32]. Some examples are food with bad taste, looks or smell, due to spoilage microorganisms that do not cause harm if consumed. As they do not pose a significant hazard, these defects are not controlled by CCPs and instead are controlled through PRPs [32].

Another important category of PRPs are operational PRPs (oPRPs). While PRPs are put in place to deal with generic hazards that do not represent an immediate and significant threat to food safety, oPRPs are specific to a hazard(s) and/or process that represent a more substantial threat [29]. An example of a PRP is, for example, the requirement to keep a surface where raw food is prepared cleaned to prevent cross-contamination between raw products. But if the objective is to prevent cross-contamination due to the presence of specific allergens between specific products that are being produced, then this represents an oPRP as it is particular to that product, and the hazard represents a more immediate and severe threat to the consumer [29][32][36]. The relation between HACCP, PRPs, and oPRPs is visible in Figure 2.

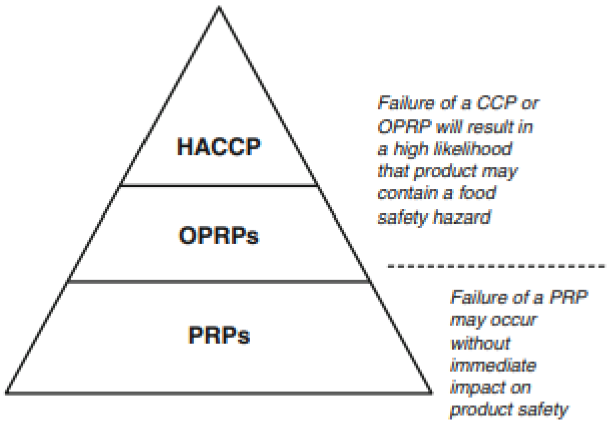

Figure 2 *- Relation between HACCP, oPRPs and PRPs. Source: [36]*

OPRPs should work together with CCPs to prevent more significant hazards [36]. To better understand the decision process regarding if a hazard should be managed through a PRP, an oPRPs, or a CCP, the decision tree in Figure 3 proves to be useful.

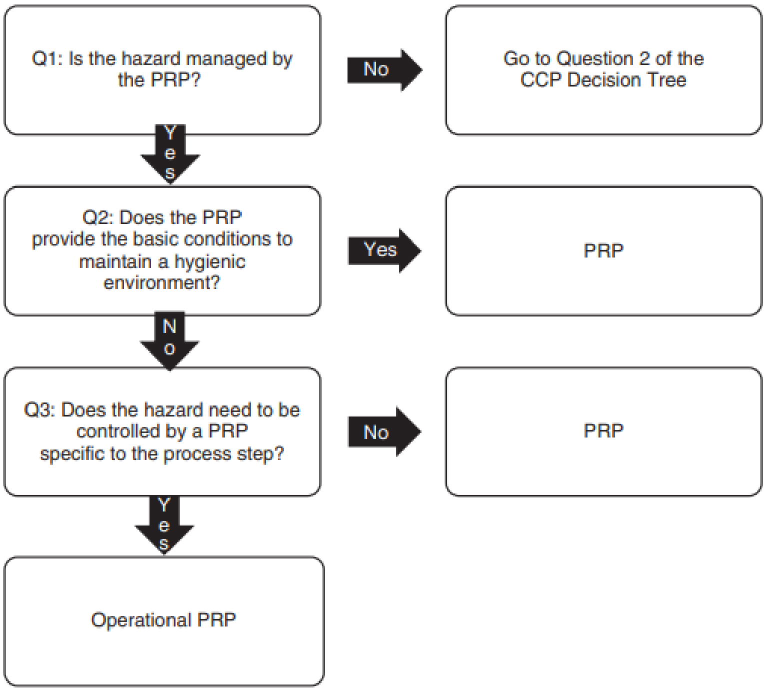

Figure 3 *- Decision tree for PRPs, oPRPs and CCPs. Source: [32]*

2.1.4 Benefits

HACCP proves to be an excellent tool to prevent food safety issues. It can be used by everyone, and when properly planned, implemented and maintained, FSMS with HACCP at their core can generate several benefits [32][36].

Some of the highlighted benefits reported in the literature are:

- The improvement in food safety due to better production procedures, greater control of critical points, constant monitoring, and higher hygienic and cleaning standards [37][38]. This is the number one benefit and must be the goal when implementing HACCP based system. By being accepted and used worldwide and succeeding at preventing FBD, HACCP-based FSMS contribute to resolving the public health burden detailed in chapter 1. Consequently, all the economic benefits will follow.
- New customers are attracted to the business due to better practices and improved quality [39].
- Retaining old customers and increasing their confidence in the brand [22][37].
- It reduced customer complaints. By having a process that focuses on prevention instead of end-product testing, the probability of a defective product reaching a client is lower, which is equal to fewer complaints [22][38][39].
- Brand protection. FBDO are less likely to happen, and therefore the brand is less likely to get hurt [32].
- Access to new local and international markets due to compliance with laws and regulations from different countries, standards imposed by other client companies, or even client expectations[22][32][37].
- It improved product traceability. With accurate and adequate records traceability is easier to make. In the event of something wrong happen and a recall of the product or warning of customers is needed, this will be easier to achieve [22].
- Economic benefits. Implementing an effective HACCP-based FSMS leads to increased profitability, improved sales, and reduced costs [26][32].

Several other benefits can arise from the proper implementation of a HACCP based system. Nevertheless, it is important to refer that these will only happen if everyone is committed to make the system work, from management to employees [32].

2.1.5 Problems and Difficulties

As seen in the previous subsection, when properly planned, implemented, and maintained, a HACCP based FSMS can bring several benefits. Nevertheless, that does not mean benefits are the only thing that exists. Several difficulties and barriers to a proper implementation exist, as well as problems derived from a poorly implemented, monitored, and/or maintained system [32].

The most obvious problem is related to food safety. If a system is not properly implemented, instead of contributing to the solution, it will probably contribute to worsening it. Hazard analysis and CCP determination can be challenging to get done correctly without the right knowledge, and if these are done wrong or if after planned they are neglected or controlled the wrong way then the system will most likely fail [36]. Low maintenance and no frequent revision of the system can also hinder the way it performs. HACCP should not be a "one-time activity". Instead, it should be supported by a continuous improvement [23].

Some of the main causes reported in the literature that contribute to the failure of a HACCP based FSMS are related to human factors. Lack of knowledge and lack of motivation can all contribute to it [32][38][39]. To avoid these, training is essential and all personnel, from operators to managers, should get proper training in order to make the system work properly. Every element should well understand their roles and know their importance in the implementation of HACCP [25][40].

Several studies also point that one of the most problematic areas is documentation and record-keeping [37][38]. The elevated number of paperwork, different types of forms, procedures, and instructions made the system difficult to maintain, and it can turn into a source of staff demotivation[37][23]. Records are sometimes incomplete, and the user who made them unidentifiable [23]. The use of technology and electronic documentation has been proved to make the process more user-friendly and easier for staff [37]. Live monitoring, automated warnings in case of out-of-bond parameters, electronic records, and others will reduce human error and improve FSMS.

Finally, it is worthy of mention that applying HACCP from farm to fork is not an easy task. Information associated with products is not always shared among stakeholders, coordination between each link of the chain can be difficult to obtain, and when needed, traceability is challenging to achieve [32]. Emerging technologies will make the sharing of information along with the extent of the food supply chain easier. With real-time monitoring and digital records, the information about a product will be easier to share and access. Therefore, coordination between different food supply chain steps, which until a few years ago was one of the main hurdles to a global HACCP system, will be easier and FSMS more efficient. Some of these new technologies will be further analyzed in subsection 2.4.

2.2 Traceability in the Food Supply Chain

As seen in the previous section, implementing a HACCP system implies that documentation and records are made, providing useful information that can also be used in a traceability system. Nevertheless, by themselves, these do not guarantee the existence of such a system. HACCP's objective is to analyze hazards, make sure that they are under control, and when CCPs get out-of-bounds to apply corrective measures, including the recall of products when needed. On the other hand, traceability systems are focused on tracking and documenting a product's history along the entirety of the food supply chain [41].

The International Organization for Standardization (ISO) defines traceability as the "ability to trace the history, application, or location of that which is under consideration" and traceability system as "totality of data and operations that is capable of maintaining desired information about a product and its components through all or part of its production and utilization chain" [42]. Applied to the food supply chain, this translates into knowing who, what, where, when, and why something happened to a particular product or ingredient [43].

2.2.1 Traceability systems - Overview

A final food product can contain ingredients of the most variated origins. Ingredients can come from other food sectors, different manufacturers, be simple or complex, and converted into final different products. To deal with this complexity and ensure food safety, FSMS are put in place, and traceability systems make a fundamental part of it [36]. To better understand traceability, it is important to have a view of what composes a traceability system.

To ensure a reliable and efficient traceability system, it is necessary to have an identification mechanism. Examples of identification mechanisms are RFID and barcodes. These are used to identify traceable resource units (TRUs), which can be any traceable object from a single item, a container, or even an entire batch [44]. It is also necessary a mechanism for documenting TRUs transformations, this is, when a process is applied to a TRU transforming it in other TRU (e.g., mincing a piece of meat), when two different TRUs are used in conjunction and produce a single TRU(e.g., different ingredients to bake a cake) or when a TRU is separated into several (e.g., a batch of cereal being transformed into several smaller batches that go to different buyers). Finally, the possibility to record TRU attributes along its lifecycle. Attributes can be the TRU name, address, identification number, certification schemes, results from tests, time and temperature logs, size and weight, records related to livestock, and many others that food operators consider relevant [45]. Not less important is the existence of an efficient and transparent communication mechanism composed of information system networks, databases, internet communication, and software agents that allow tracking and tracing internally and along the entirety of the food supply chain [46]. The importance and benefits that come from these systems are several and are described in the next section.

2.2.2 Importance of Traceability

If we stop and think for a moment about our food's provenience, we might amaze ourselves. Increasing globalization led to the point where the food consumed every day might have its origin anywhere in the world. A single food item can be produced with ingredients from different countries or even different continents [43]. Simultaneously, due to FBDO, food scandals, and incidents making the news, consumers are more concerned. The demand and expectation for a higher degree of quality, safer food, and transparency have never been higher [47]. Traceability is therefore used as a way of responding to potential food safety issues, ensuring that food is safe to eat. It gives authorities or food businesses the ability to, when a risk is identified, trace it back to its origin and rapidly isolate the problem preventing contaminated food from reaching the consumer [48]. Although traceability is mainly viewed as a tool to ensure that food is safe by providing the means for a focused and fast recall if needed and to prove food authenticity, it is also an excellent tool for improving quality as it allows producers to pinpoint where faults occur, what needs to be improved and even to audit their suppliers or buyers (for example to know if the buyer uses the products in an intended way) [36].

Overall, companies have three main objectives with traceability: make traceback for food safety and quality easier; improving supply management (internal and external); marketing or food quality claims that cannot be seen by observing the product (green food, sustainability claims, and others) [43]. Some benefits of accomplishing these objectives are brand protection, improved process control; lower-cost distribution systems; reduced recall expenses; improved sales, and enhanced product quality. From a consumer standpoint, traceability assures them that their food is exactly what the producer claims. They have a better knowledge about where their food came from, who made it, what are its components, and the processing history [49][50][51].

2.3 Temperature Control

As mentioned in Chapter 1, temperature abuses are one of the most critical factors that contribute to FBD and FBDO [16][20][21]. Some examples being insufficient time and/or temperature during cooking/heating process, adequate time and/or temperature during reheating, inadequate thawing (followed by low cooking), allowing foods to remain at room or warm outdoor temperature for several hours, inadequate cold-holding temperature, insufficient time and/or temperature during hot holding and others[18]. Therefore, maintaining food temperature under control is of the utmost importance at any point of the supply chain. These controls include temperature and duration of cooking, cooling, processing, storage, and transportation and should take into consideration the nature of the food (its water activity, pH, and microorganisms), the intended shelf-life, packaging, processing methods, and intended use (further cooking/processing or ready-to-eat) [33].

2.3.1 The effect of temperature on food

Foods are sensitive to time and temperature, with the temperature being the most crucial factor regarding food safety, perishability, and freshness. Cold helps to prevent the growth and proliferation of pathogens while hot eliminates them. The effects of temperature on food are well described in the literature.

For example, considering the pathogens responsible for major FBDO mentioned in Chapter 1, Escherichia coli O104:H4, a bacteria that cause severe FBD, has its primary source in raw or undercooked ground meat products, raw milk, and faecal contamination of vegetables. It can grow at temperatures that range from 7ºC to 50ºC, with the optimum temperature being 37ºC but can be destroyed by cooking foods until all parts reach a temperature of 70ºC or higher [52]. Listeria, which causes listeriosis, although rare, is highly mortal and resistant. Listeria can be found in several different foods that include smoked fish, meat, cheeses (especially soft cheeses), and raw vegetables. To kill it is necessary to cook food above 65ºC, and unlike many other foodborne bacteria, it can multiply at cold temperatures (between 2ºC and 4ºC) [53]. Other examples are*, Clostridium perfringens*, found on raw meat, poultry, gravies, and dried and pre-cooked foods and responsible for more than 1 million FBD cases each year in the US [54]. *Clostridium perfringens* can survive high temperatures and grows during the cooling and holding of food at temperatures from 12°C to 60°C and more rapidly between 43ºC and 47ºC. Norovirus, the leading cause of FBDO in the US, remains active at freezing temperatures and until heated at 60ºC [55].

These are just a few examples, many more exist. It is essential to follow good manufacturing practices, hygiene practices, and effective temperature control throughout the food supply chain to prevent these from happening.

2.3.2 HACCP, Traceability and Temperature Control

As seen in sections 2.1 and 2.2, HACCP and Traceability systems are tools that, when correctly used, can greatly improve food safety and quality and prevent FBD and FBDO.

As mentioned in section 2.3.1, there are temperature requisites at specific points required to ensure food safety and suitability. After conducting a hazard analysis, these points are generally declared as CCPs. It is essential to keep these CCP under control as a failure in monitoring and/or at applying corrective measures can end up contaminating food since this will enable microorganisms to survive and/or proliferate and, from there, be the source of a possible FBDO [56].

Temperature abuse can happen at any point of the food supply chain, specifically in the cold food chain. The food cold supply chain requires logistic and qualitative traceability as foods are perishable and very sensitive to temperature, humidity, and others. An efficient and transparent traceability system provides a greater assurance of quality. At the same time, if something goes wrong, if the temperature is also included in these systems, it allows understanding better if the cause was due to temperature abuse and gives the ability to improve processes in the future [43]. It also allows knowing if food has been appropriately handled during transportation and storage by other food operators along the chain, giving greater assurance and confidence to whoever buys the products, from producers to consumers.

To highlight the importance of controlling temperature with efficient and reliable HACCP and traceability systems, literature has been reviewed, and several problems that originated due to the lack (or bad implementation) of such systems are presented next.

A study analyzed the temperature of meals during hot holding display in different establishments that had already implemented HACCP. In two of these establishments, *E. coli* and/or coagulase-positive staphylococci were found. In both cases, hot holding temperatures were found to be below 70ºC. The same study also reviewed other restaurants that successfully implemented HACCP systems, and before and after comparisons showed complete elimination of the pathogens [57].

Other study reported temperature abuse during transportation, retailer storage, and retailer display of food products in Iceland, Finland, Slovenia, Spain, and France [58]. This highlights the importance that a transparent traceability system can have. In this case, other food operators would have the opportunity to know that temperature had been out of the recommended bounds. Also, with proper temperature control in the first place, this would not happen.

To finish, another study analyzed what led to several FBDO and the influence of the lack, or poor implementation, of HACCP systems. One of the cases analyzed involved a salmonellosis FBDO in a HACCP-operated industry in Denmark. In this case, cured meat was produced without suffering adequate heat treatment. Another case, this time an FBDO due to *E. coli O157,* was associated with pre-cooked meat patties and affected 32 school children. The investigation reported that the meat patties were undercooked. The last one, a salmonellosis outbreak in the US, affected 224.000 people and happened due to an ice-cream manufacturer neglecting the transportation process. It would have been avoided if a comprehensive HACCP program were in place. It was highlighted by the author that there are very few FBDO reported in cases where the food industry operates with full commitment and understanding of a HACCP system [59].

All the previous examples demonstrate the negatives effects that temperature abuse can have and the importance that proper HACCP and traceability systems have when dealing with it.

2.4 Food Safety Management Systems Technology Review

In the last years, new technologies have emerged and nowadays are being adopted and used to solve the more diverse problems in a wide range of sectors. The food safety issue is no exception. To solve the addressed problem, information is critical, and IoT has proved to be a great tool to, when correctly used, gather valuable information[60]. IoT with RFID and Wireless Sensor Networks (WSN) as enablers, and more recently Blockchain, are now a constant in the literature about the topic and are already being used to tackle this challenge. These feature amongst the most researched technologies associated with FSMS with many proposed applications, either associated with HACCP, traceability systems, or both [60][61]. In the next subsections, an overview of the conventional methods used for controlling temperature will be summarized, the impact of software in FSMS discussed, and a review of literature about the role of IoT, RFID as an IoT enabler, and their applications to FSMS will be conducted.

2.4.1 Temperature Control Devices in FSMS

As mentioned in section 2.3, dedicated to Temperature Control, proper temperature control management is an asset when it comes to avoiding serious problems like FBD and food spoilage. Furthermore, it is a critical responsibility of any retail food establishment to have an implemented method that allows this control [62].

As seen, temperature control is essential in different moments in the food supply chain, namely during storage, transportation, and preparation. To measure temperature, different types of devices are used. For example, in refrigerator and freezer areas, hanging thermometers are inexpensive and often used, especially to measure temperatures in the coldest and warmest points of the refrigerated areas. For dry storage areas (including during in transport), some examples are [62]:

- Temperature loggers that allow monitoring the environmental conditions in which temperature-sensitive products are. These devices are reusable and can be linked to digital solutions for record-keeping purposes. The downside is that they do not provide real-time monitoring as the data usually needs to be downloaded from the device.

- Package indicators that enable monitoring of the temperature of packaged foods and assess product freshness and safety. The main problem is that they need to be visually checked and don't show a temperature value.
- Fixed sensors. These can be placed inside containers, in storage rooms, or inside machines like fridges, freezing units, and others. Some only display the value; others have wireless capabilities and provide real-time monitoring and enable automatic record-keeping.

When it comes to the implementation of food temperature control that requires an active measure by the user, for example, during the process of food preparation, when receiving merchandise, to control the center temperature of products in storage, and others, different devices can be used such as bi-metallic stem thermometers, digital thermometers, and temperature sticks or sensor strips [62]. Some of these are relatively inexpensive methods that generally require manual record creation, and some of them cannot show accurate measures, only show if a specific temperature is exceeded.

One study reviewed the cooling practices of 420 restaurants and found that 95% used some kind of thermometer for temperature control. Two of the most used types being thermocouple and infrared thermometers[63]:

- Thermocouple thermometers, which digitally display the results measured by two wires located at the probe's tip. These can be used to measure internal product temperature. Some can be connected to appropriate software to aid record-keeping and maintenance.
- Infrared thermometers, which are indicated to take accurate temperature readings at surface level, reason why these thermometers should not be used to control cooked food temperature. However, this equipment has the advantage of helping to avoid cross-contamination.

Wireless Sensor Networks (WSN) can be implemented by using monitoring devices such as the ones described (thermocouple sensors, infrared, infrared sensors, or others) to real-time monitor and control the temperature of the targeted products continually, remotely, and accurately[64].

All kinds of temperature control devices previously presented fit in one of two categories: fixed devices (e.g., sensors, temperature loggers, package indicators) or handheld thermometers. However, these solutions are not mutually exclusive in establishment operations. They compliment each other and are often used together.

Temperature control devices such as those presented throughout this section allow taking temperature readings independently. Still, for FSMS effects, an efficient and sustainable process must be implemented in the food establishment [65]. Therefore, some temperature control processes depend on checklists that detail all the needed actions (which translate into required temperature readings) to check the conditions of food in different critical situations: storage, preparation, and any other relevant moment along the food supply chain, including the operations at a restaurant or other food establishment. These are going to be further analyzed in the next subsection, but a modern example follows:

Taco Bell implemented digital checklists required to be completed twice per day to ensure safe food, which proved to be a laborious and timely job. The chain has implemented a WSN to help with temperature monitoring and predictive maintenance to facilitate the process. This enabled the corporation to remotely check if stores are compliant while saving significant work and time from employees and management, and contributing to taking a preventive approach instead of a reactive one to food safety and removed the guesswork from monitoring and record-keeping [32].

2.4.2 Software in FSMS

Nowadays there is a significant need for digital technology to enable comprehensive management of food safety controls. Digital solutions are already being used along the entirety of the supply chain. For example, processes and inventory management software; software to aid HACCP's practical application; information systems used to disseminate information about FBDO quickly; active surveillance networks that share information between agencies to detect FBDO and limit its spread; software for traceability purposes and many others [66]. Nevertheless, in this work's scope, the most interesting use of software in FSMS is when applied to the management of daily operations of the supply chain that include temperature monitoring and control, more specifically in the case of restaurants or other food establishments.

As mentioned previously, for food safety purposes, it is not enough to have a way of making independent temperature readings. These should preferably be integrated into a sustainable and efficient process. One of the essential parts of such a process is real time-monitoring and efficient, reliable, and secure record-keeping[67]. Although many restaurants still use paper processes, a substantial part has already transitioned or is transitioning to digital. Digital documentation, schedules, control of operations, communication, inventory management, work schedules, and others that were all carried out in the paper can now all be digital. Controlling all these processes, including the control of temperatures in different products and machines, sometimes several times a day, is a hard task to do using just paper. Paper-based checklists are difficult to maintain. They do not allow real-time monitoring; records are easily forgotten, falsified, and have limited visibility and searchability by all of the required stakeholders. With a paper checklist, it is impossible to have some kind of automatization, managers cannot be automatically warned if something is wrong, for example, if some temperature is not inside the parameters. By using a digital checklist or task system, the advantages are numerous. The information is all in one place. Instead of many different papers for each task, all the tasks are in the same place and are easier to follow. Employees can't erase or modify records, and warnings are issued if something is not in conformity or if it is forgotten. A digital checklist, when properly executed, can lead even the most inexperienced employee through the daily tasks of such an establishment and make easier the assessment of functions to monitor controls and record the outcome in food preparation processes such as: receiving food and check cold chain compliance, storage environment conditions, cooking, hot/cold holding, cooling, reheating and serving conditions. Many of these tasks require measuring the internal temperature of products by a thermometer[68].

The device options presented in the previous subsections allow these measurements. Nevertheless, most restaurants still use thermometers with no communication capabilities and depend on the manual insertion of data in tablets or others, which leads to data being manually processed or physically introduced to a digital platform, many times resulting in a complicated system [69]. This can be a problem as employees still have a high probability of committing mistakes such as inserting wrong values and measuring temperatures in the wrong place or product. Bluetooth versions that require the use of a support device during the operation to consult the checklist can be used. However, more often than not, they are not the ideal solution, as it is one more device to take care of and to learn how to use; both hands are occupied; the costs are higher; sometimes managers would prefer that employees would not carry a tablet or smartphone in-store, and integration with existing systems is not always ideal. In the reviewed literature it was not found a case where a truly independent, and efficient smart thermometer has been used.

Taking advantage of new technologies will allow implementing automated and efficient monitoring and management systems that not only aids the establishment personnel given its influence on the daily operational tasks including processes of temperature monitoring but also positively affects the establishment, the consumer, and society in general by making it easier and faster to avoid, identify and contain irregular situations [69]. In the next subsection, the impact of IoT in FSMS is going to be reviewed.

2.4.3 IoT applied to FSMS

In 1999 Kevin Ashton used the term "Internet for Things" in the title of a presentation at Proctor and Gamble. The objective was to link the idea of using RFID technology in his company supply chain to the main topic of the moment, the Internet [70]. Decades later IoT adoption is at its peak with Gartner estimating that in the end of 2020 the number of enterprise and automotive IoT endpoints in use will be of 5.8 billion, representing an increase of 21.5% compared to 2018 [71].

IoT is defined as "a global infrastructure for the information society, enabling advanced services by interconnecting (physical and virtual) things based on existing and evolving interoperable information and communication technologies" by the International Telecommunication Union (ITU)[72]. ITU also notes that IoT makes full use of things to offer services to all kinds of applications, recurring to identification, data capture processing and communication capabilities whilst ensuring security and privacy [72]. A Thing is defined as a physical object that can be identified through a unique identifier (UID) and that can make use of sensors (temperature, humidity, and others), actuators (motors, displays, and so on), might be able to run programs and logic, and has communication capabilities, either wired or wireless. Things can go from a simple mail envelope with a tag attached (RFID, NFC, barcodes, QR codes) that can be tracked up to complexly connected products, devices, or machines such as cars, supply chains, security systems, and more. Things are then connected to the internet, directly or indirectly, using communication methods such as Bluetooth, WiFi, ZigBee, Sigfox, Nb-IoT, Lora, and others, and its data or services made available to be accessed and/or processed by other applications [73]. It is also essential to take into consideration security and privacy issues. These became a big concern regarding IoT in recent times. Issues such as privacy, authentication, verification, access control, system configuration, information storage, and management are currently trending and essential topics regarding IoT [74].

RFID is seen as a fundamental technology to enable IoT [75]. Composed by two components, the transponder and the reader, it allows identifying objects that have no communication to the internet. The transponder, many times available in the form of a sticker or card, consisting of a coupling element (coil or antenna) and a microchip, contains a UID and is placed on the object that needs to be identified. The reader, as the name suggests, making use of a radio frequency module (transmitter and emitter), a control unit, and a coupling element, is used to read the information that is made available by the transponder[76][77]. RFID Is consistently on the top of technologies that are used by IoT, more specifically, when applied to FSMS (HACCP, traceability, supply chain control, and more) [60][61]. Some of which are going to be addressed in the next subsection.

IoT application examples in FSMS

Although the topic of IoT applied in food safety is relatively recent, the publication of articles on the subject has shown a growing trend [60]. This tendency leads to the conclusion that there is considerable interest in studying and applying IoT to food safety, along with the advantages that are more and more being recognized [78].

Several studies have been conducted on the application of IoT in FSMS. For example, in 2019, a literature review was made in which the authors analyzed 48 articles related to the use of IoT in food safety, and where they show that IoT using RFID as an enabler has been used in many traceability systems in order to ensure food tracking, tracing and product authenticity. Furthermore, their work showed that 60% of the studies measured temperature, followed by humidity (40%) and location (40%). This research also points that RFID, along with Internet/Ethernet and wireless sensor networks (WSN) are present in the top of the most commonly used technologies for communications between IoT devices in food safety [60]

Another study focused on identifying risks through the different steps of the food supply chain to find and suggest measures to solve the identified risks recurring to an approach based on IoT. Thus, the work described in the article described risks present throughout the whole food supply chain (production, processing, transportation, storage, and sale) and pointed out if there were (IoT) solutions already realized, under research, or if the problem could be solved through IoT and in what way. For example, labeling in all packages should present the necessary information (following regulations). Using an RFID reader, it is possible to check if the information on the labels is sufficient efficiently. Similarly, IoT applications are also valuable in transportation (and storage) operations since they can help check real time factors, such as temperature, and record shipping with the help of RFID [79].

Another study focused on an IoT infrastructure with smart-objects and RFID tags embedded on the containers to obtain data from gateways within food establishments such as restaurants, supermarkets, or food production companies. This enables tracking food ingredients and making the path from farm to fork more efficient, including detecting any issues (such as temperature) that might arise due to defective transportation conditions, for example [78].

The great amount of data provided by the different devices taking part in an IoT-enabled food supply chain can be used with blockchain technologies in order to create a safer and more transparent traceability system[67]. As mentioned in section 2.3 , this information can be useful to customers, who are increasingly preoccupied with food quality, and auditors to ensure the law is being complied with and track the source of possible food contamination. As pointed out: "in a blockchain-enabled logistics system, such tracking time can be in seconds, enabling faster containment of foodborne illnesses, increased revenue due to faster response time and selective recalls, and increased trust among the partners". All these advantages in taking preventive measures through IoT have led companies to start using IoT companies to aid them ensuring reliable and efficient traceability systems [67].

When allied with regulation, IoT applied to FSMS can foster a proactivity culture, focusing on identifying risks and emerging problems, and therefore adopting a preventive approach which can be made more sustainable and efficient in the long term by providing adequate data, training and support to all parties involved [8]. More and more IoT technologies have been applied in different sectors of the economy, and the food sector is no different. As mentioned throughout this Chapter, new technologies are being used to identify and help prevent challenges from food safety issues. This is one of the most important challenges society faces nowadays, as reflected in the ONU Sustainable Development Goal 2: End hunger, achieve food security and improved nutrition, and promote sustainable agriculture. FSMS can be a powerful tool to help mitigate this issue, especially when combined with an IoT approach by taking advantage of technologies such as Blockchain, sensors, and AI, which can contribute to creating a more robust and trustworthy system [67].

Chapter 3

Requirements

This Chapter starts by discussing the context that led to the definition of the functional and non-functional requirements and summarizes them. The requirements specification has been adapted from the IEEE guide for software requirements specification [80].

As discussed in the previous chapters, temperature control is part of restaurants and other food-related establishments' daily operations. It is a crucial part of HACCP and traceability and a critical step when looking to prevent FBDs.

Feedback obtained from an HACCP consulting company allowed to understand that a significant number of establishments use ordinary food thermometers, such as thermocouples and IR thermometers with no communication capabilities. They might also use sensors that need to be visually checked. Others, digitally more advanced, use WSN, but thermometers are also required. In both cases, establishments typically have a checklist or a task system that their employees must go by every day. The way procedures are carried out can be grouped into two main categories: paper (Figure 4 - *Common paper checklist*) or digital (Figure 5).

2 - CONTROLO DE TEMPERATURA NO LOCAL (por módulo)				
NÚMERO	EQUIPAMENTO	NORMA	TEMPERATURA	
1	CÂMARA REFRIGERADOS	0 a 5ºC		ºC
2	CÂMARA CONGELADOS	< -18ºC		ºC
3	CÂMARA CONGELADOS (PÃO)	< -18ºC		ºC
4	L.S. REFRIGERADO CHARCUTARIA	0 a 5ºC		ºC
5	L.S. REFRIGERADO TALHO	0 a 3ºC		ºC
6	L.S. REFRIGERADO PEIXARIA	0 a 2ºC		ºC
7	L.S. REFRIGERADO QUEIJARIA	0 a 5ºC		ºC
8	L.S. REFRIGERADO LÁCTEOS	0 a 5ºC		ºC
9	L.S. REFRIGERADO FV	0 a 5ºC		ºC
10	L.S. REFRIGERADO GASTRONOMIA	0 a 5ºC		ºC

Figure 4 *- Common paper checklist. Provided by an HACCP consulting company*

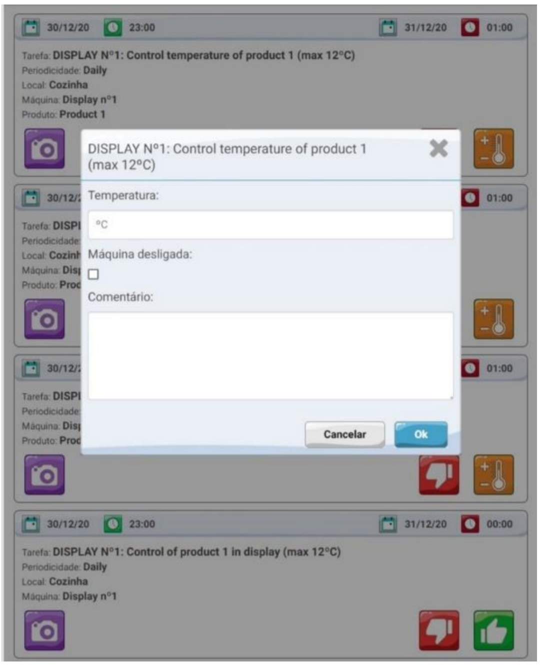

Figure 5 *- Digital checklist. Provided by an HACCP consulting company*

In the case of establishments that use paper, the common complaints were that records could be forgotten, lost, destroyed, forged, required more time and effort to do, and were unreliable. The number of controls was also lower, real-time monitoring or alarms were not possible, and management could not monitor at a distance. In more digital advanced establishments, the system was more efficient, real-time monitoring and alarmistic were possible, the number of controls was often higher, and human error less frequent. Nevertheless, records could also be mistakenly filled or forged (e.g., an employee inserting wrong values in the tablet), and complaints still exist.

In cases where digital checklists were used, when carrying measurements that required a thermometer, the used thermometer did not have any advanced capability. Users were still required to insert the values into a tablet, smartphone or to annotate values using pen and paper and, at a later stage, insert them into a database.

All the reasons above and discussed throughout this dissertation led to the conclusion that a real need for a smart thermometer exists.

Thus, the objective of the work developed in the scope of this dissertation is to create a functional smart thermometer prototype used to control temperatures more efficiently and reliably during food-related establishments' daily operations. It can be used along the entire supply chain wherever and whenever temperature readings must be performed using a thermometer. The smart thermometer shall allow users to authenticate, granting access to an integrated task system to check which tasks are in order for the day, select each one, and complete it. Furthermore, users shall also be able to take non-scheduled measurements where they make use of a list of all the available machines and products present in each establishment. The thermometer will also be able to identify machines and products, making it easier to verify that the measures are being collected at the correct location, and therefore reducing the probability of human error. Finally, the smart thermometer database is remotely updatable, and measurements are automatically submitted to a database.

To help mitigate the previously described issues and enable greater control, efficiency and reliability over the measurements that HACCP FSMS requires, the smart thermometer can either be integrated into existing systems or used as a standalone system. When an establishment already has a digital system, this solution can be integrated and complement it; when they do not have such systems, this solution can be used as a standalone solution., while also eliminates the need for using paper for this purpose. In both cases, the user no longer needs to manually insert reading results in a paper form or device. Figure 6 how with the purposed system the user can use the thermometer to identify machines

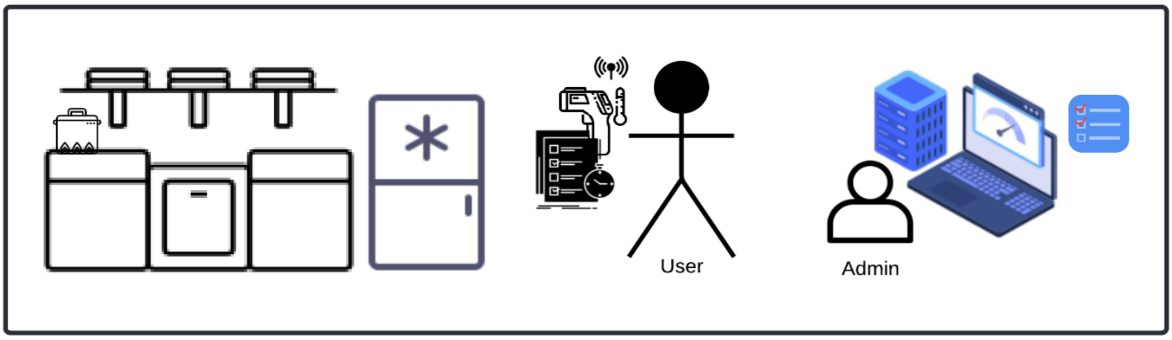

Figure 6 *– User interaction with the system*

and products, view tasks scheduled by the admin and automatically upload all measures to a remote database.

3.1 User Classes and Characteristics

Two classes have been considered: users and admins. The characteristics are the following:

- Users: users of the smart thermometer can be technically not proficient. Its use requires no particular education level or experience. Anyone that can use a smartphone shall be able to use this device. When not authenticated users shall be able to use the device as a regular thermometer. When authenticated, they shall have the possibility to take scheduled and non-scheduled measurements that are automatically uploaded to an online database.
- Admins: Must have a more advanced technical understanding. Low computer skills are needed. It is necessary to know how to use the Internet to manage the data that needs to be inserted into the database. System admins shall be able to create, read, update, and delete entities such as stores, machines, products, tasks, users, measurements, and others. An admin can also be a user.

3.2 Main Features and Functional Requirements

The functional requirements presented are divided by user class and feature from where the requirements originate. Requirements are numbered and can repeatedly appear from feature to feature. These represent the essential features that the system shall have.

3.2.1 User class: Employees

Feature: Scheduled temperature measures

Description:

This system feature allows an authenticated user to take measures remotely scheduled by an admin and submit them to a database. Each task has the date and time when it shall be completed, and the list is updated daily. The user can filter the task list by scanning a machine, retrieving all the associated tasks related to the scanned machine and products. The measured object must be verified through its identification. The user must select an available task through a list and/or by scanning a machine or product, take the corresponding measure, and submit the result.

Functional Requirements:

FR01 The system shall allow a user to take internal product temperature measures.

FR02 The system shall allow a user to take surface product temperature measures.

FR03 The system shall have an employee authentication mechanism.

FR04 The system shall allow to present a list of daily tasks.

FR05 The system shall allow authenticated users to see the available non-completed temperature tasks.

FR06 The system shall allow authenticated users to verify if the readings are being done in the right local.

FR07 The system shall have a machine identification mechanism.

FR08 The system shall have a product identification mechanism.

FR09 The system shall allow submitting measurements to a remote database.

FR10 The system temperature measurement features shall work in case of not having a wireless connection.

Feature: Non-scheduled temperature measures

Description:

This system feature allows an authenticated user to take temperature measurements that were not scheduled by the admins. After identifying a machine and/or product, the measurement can be taken and submitted.

Functional Requirements:

FR01 The smart thermometer shall allow a user to take internal product temperature measures.

FR02 The smart thermometer shall allow a user to take surface product temperature measures.

FR03 The system shall have a user authentication mechanism.

FR07 The smart thermometer shall have a machine identification mechanism.

FR08 The smart thermometer shall have a product identification mechanism.

FR09 The smart thermometer shall allow submitting measurements to a remote database.

FR10 The system temperature measurement features shall work in case of not having a wireless connection.

Feature: Normal temperature measures

Description:

This system feature allows the system to work as an ordinary thermometer. Any user can take a measurement.

Functional Requirements:

FR01 The system shall allow a user to take internal product temperature measures.

FR02 The system shall allow a user to take surface product temperature measures.

Feature: Login

Description:

This system feature allows a user to login into the system in case of being logged out.

Functional Requirements:

FR03 The system shall have a user authentication mechanism

3.2.2 User class: Admins

Feature: Managing Stores and Controlling Data

Description:

This feature shall allow an admin to remotely create, view, update and delete any entity related to the system's usage. It includes the ability to schedule and monitor measurements.

Functional Requirements:

FR11 The system shall allow admins to manage stores.

FR12 The system shall allow admins to manage machines.

FR13 The system shall allow admins to manage products.

FR14 The system shall allow admins to manage users.

FR15 The system shall allow admins to manage scheduled temperature measurement tasks.

FR16 The system shall allow admins to manage non-scheduled temperature measurements.

FR17 The system shall allow bulk creation of objects.

FR18 The system shall allow the filtering of data.

3.3 External Interface Requirements

The system will interface with users, admins, and other existing FSMS. To that effect, the needed external interfaces to make the features and requisites mentioned above possible are analyzed in the next subsections.

3.3.1 User Interfaces

Users and admins interact with the system through different interfaces:

- Users: user interaction is carried out through a mobile interface associated with the temperature measuring device. It allows users to access the features described in 3.3.1.
- Admins: admin interaction with the system is executed through a web browser. It allows admins to access the features described in 3.2.2.

3.3.2 Communication Interfaces

The system shall have wireless communication to access the remote database, communicate with other FSMS, and identify machines and products.

3.3.3 Software Interfaces

The system shall have an API that allows the communication between the smart thermometer and the backend support services. Through this API the smart thermometer shall be able to submit non-scheduled measurements to the remote database, submit task results and get data updates (machines, products, scheduled tasks).

This API shall also enable the system to be integrated into other existing systems. Through the API backend functionalities are exposed. It is possible to create stores, machines, schedule tasks and fetch previously existing data. If the establishment already has a digital HACCP system implemented, then it shall be possible to present machines and products, schedule tasks and see tasks and measurements performed. Dashboards, applications and other shall be able to fetch relevant information by consuming it.

The system shall be deployable on-premises or in the cloud.

3.4 Non-functional Requirements

3.4.1 Performance Requirements

NFR1 Measurements can not be slower than the current process.

NFR2 Measurement resolution shall be 0.1ºC.

NFR3 Physical Probe accuracy shall be 1ºC +-1% of reading.

NFR4 Physical probe range shall be -100ºC to 700ºC minimum

NFR5 System boot time shall be less than 500ms.

3.4.2 Safety Requirements

NFR6 Physical probe should be food compatible.

3.4.3 Security Requirements

NFR7 Users shall be authenticated.

NFR8 Network communications shall be secured.

NFR9 Server data shall be secured.

NFR10 Physical Device shall be secured.

Chapter 4

System Architecture

In this chapter, a high-level architecture for the proposed system is presented. It starts by giving the context in which the system will operate. Then it focuses on the system's main blocks, the smart thermometer itself, and the supporting backend, API, and database. It finishes by giving a high-level view of the smart thermometer's main components. The objective is to present an agnostic architecture that can be implemented using different types of technologies.

4.1 System Context View

In order to implement the features outlined in Chapter 3, it is useful to understand the context in which the proposed system is intended to operate. In this section, the focus will be on the system as a whole and the interactions that users and external systems have with it, as shown in Figure 7.

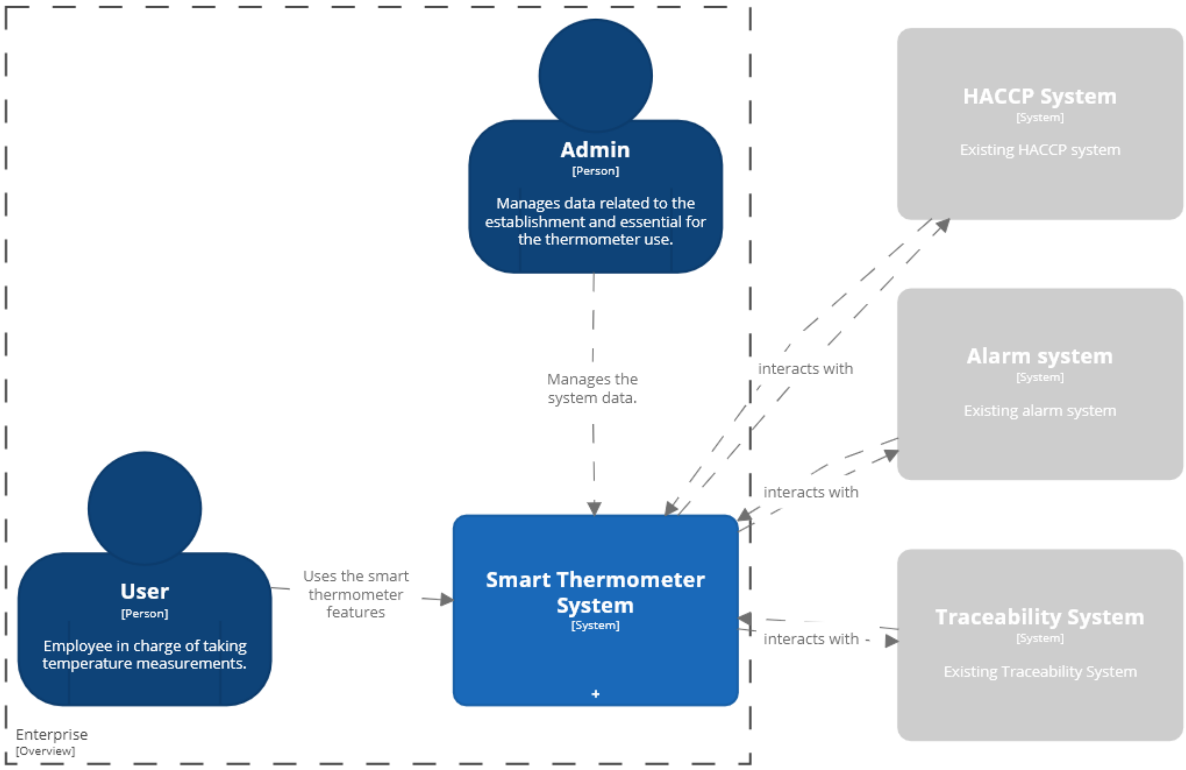

Figure 7 *- System context diagram for the smart thermometer system*

Users can be of two types (users and admins), which have already been defined in section 3.1.

External systems are systems other than the smart thermometer system that sit outside its scope but can interact with it. Three examples are given in the system context diagram present in Figure 7. These are existing HACCP, alert, or traceability systems.

For instance, consider the case where the smart thermometer system is deployed in an establishment with a digital HACCP system already implemented. The existing system might already have all the information such as users, machines, products, the daily temperature measurements that employees have to do, and others in digital support. If this is the case, then the existing HACCP system can interact with the smart thermometer system and share this information for it to be readily available instead of being inserted again in the smart thermometer system.

Another kind of interaction would be the business already having a database where all the records are stored. The smart thermometer system could simply send all the completed measurements directly to this database. Or make the data available for other systems to fetch it and make it available to be viewed in a dashboard or monitoring app.

To finish, consider a business that already has a WSN and an out-of-bounds temperature alert system in place. By making the smart thermometer temperatures readily available, these systems could detect if some machine or product temperature is not right and alert the manager.

4.2 Smart Thermometer System View

By expanding the smart thermometer system block presented, in the previous section, in Figure 7, a diagram of the system composition overview is obtained. This diagram can be checked in Figure 8.

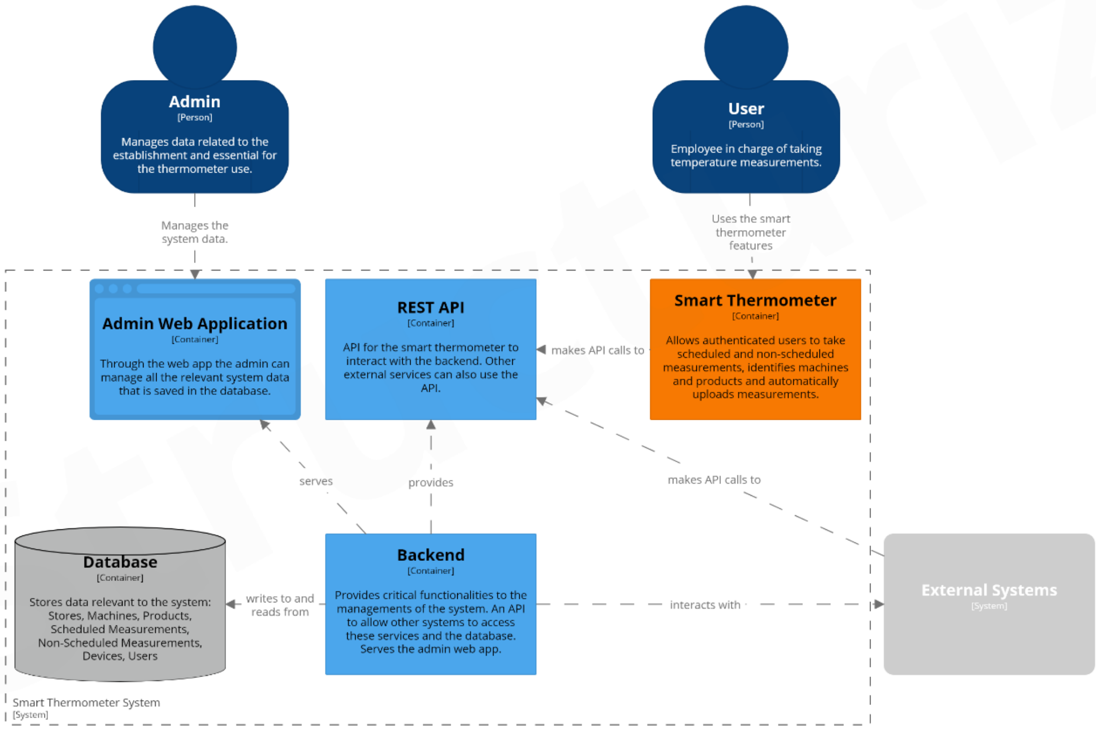

Figure 8 *- Smart Thermometer System Diagram*

As observed, the system shall be composed of the smart thermometer itself, an admin web app, an API, a backend, and a database.

The system's backend will provide a REST API that will be the primary interface that the smart thermometer and external systems have to access the backend services and the database. It will also serve the admin web application. The backend can also directly interact with external systems, for example, to send measurements to another system.

The REST API shall have endpoints that allow the smart thermometer to make API calls asking for data updates that include machines, products, users, and scheduled tasks. It shall also provide an endpoint for the smart thermometer to send the completed measurements. External systems can also consume the API, either to ask for data or to manage it.

The admin web application shall allow the admin to manage all the relevant data necessary for the system to function. Through the application, the admin shall be able to create, update or delete stores, machines, products, and users. Schedule new tasks, assigning what, where, and when should be measured. And view the existing data.

The database shall store all the essential data that has already been mentioned in the previous points.

The backend, API, and database can be deployed either on the cloud or the client premises.

4.3 Smart Thermometer

The focal point of this work is the smart thermometer itself. The backend, API, and the admin web application are just supporting services to enable the smart thermometer features.

By repeating the process from the previous section, if the smart thermometer block from Figure 8 is expanded, the diagram in Figure 9 is obtained. In this case both hardware and software are considered.

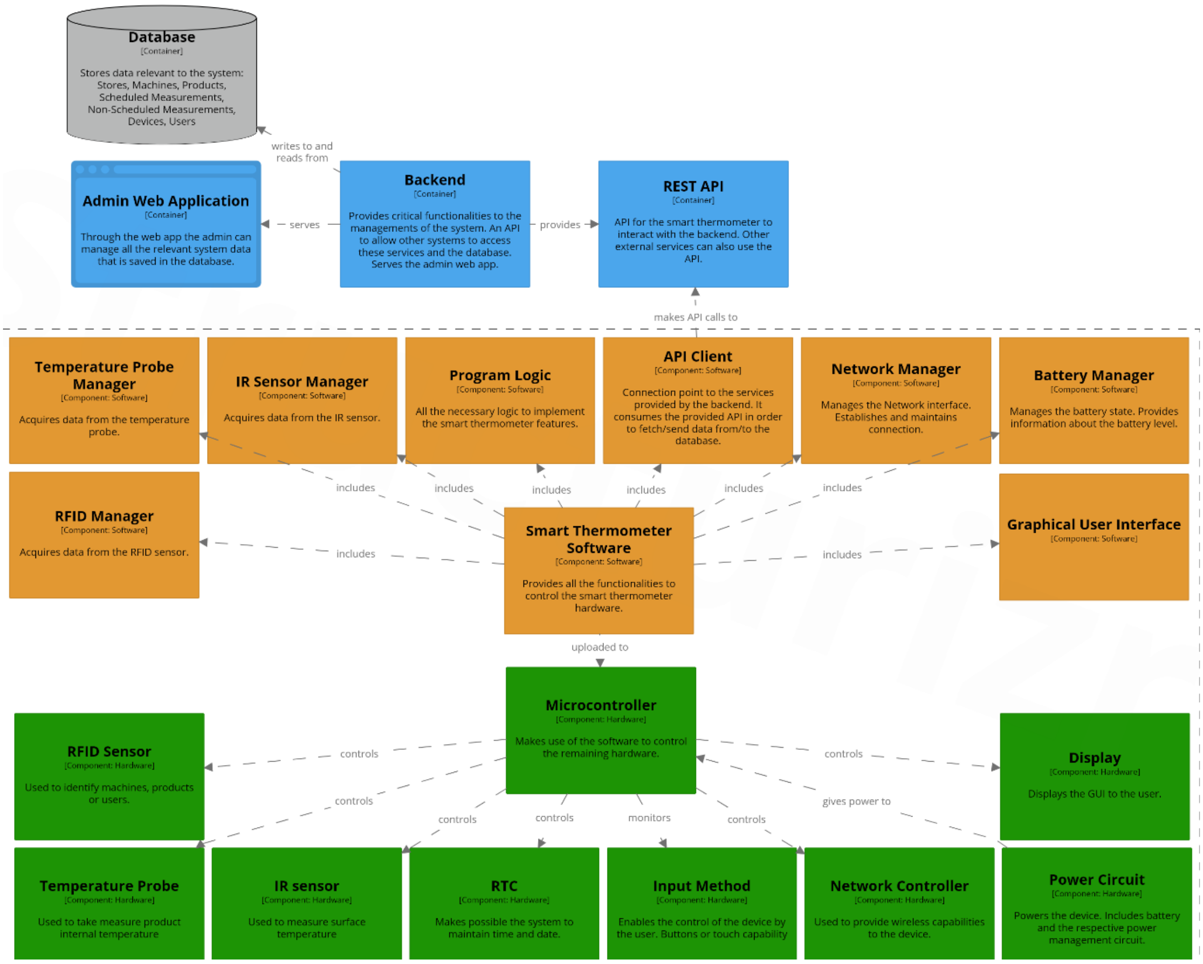

Figure 9 *-Smart Thermometer Component Diagram, with main components, hardware and software*

The components presented in this section represent the minimum necessary to implement the features proposed in Chapter 3.

The necessary hardware is the following:

- RFID sensor, necessary to identify machines, products or even users through the scanning of a tag.
- Food compatible temperature probe. To measure product internal temperature.
- IR sensor. To measure surface temperature.
- Real-time clock (RTC) module. To keep time and date accurate.
- Display. The display needs to have a size that enables all the information to be presented to the user.
- Input method. Enables the control of the device by the user. This can either be through physical buttons or through touch capabilities via the display.
- Network controller. This will provide wireless capabilities to the device.
- Battery. To power the device.
- Microcontroller. Controls the remaining hardware by making use of the system software.

The system software shall comprise all the necessary modules to control the corresponding hardware as well as the program logic necessary to implement the desired features and the API client which will consume the API provided by the backend.

In the next chapter a concretization of the suggested architecture, in the form of a prototype, will be described in greater detail. Nevertheless this represents the basis of the system and any future implementation shall have the suggested architecture as basis.

Chapter 5

Prototype Implementation

In this Chapter, the details necessary for the prototype implementation are given. The hardware used to implement the prototype is described as well as the developed software.

5.1 Smart Thermometer Prototype

To test the feasibility of the idea and to have a working device that can be shown to potential clients, a prototype has been built. The idea was to have a functional device with the necessary functionalities to be tested in an operational environment.

Although close to the final product form, the prototype has the liberty of being built using components that enable faster implementation. Nevertheless, the minimum requirements and features were considered, and the architecture suggested in chapter 4 was followed.

To achieve faster implementation, the M5Stack system [81] was chosen to be used as the system base. The system is open-source, makes use of an ESP32 microcontroller, comes in an encasement with a display and all the necessary components for its functioning, a 2.4G antenna, power management controllers, and interface components. It also allows the direct integration of components such as an RFID reader and an IR Sensor. It supports several development platforms and programming languages such as Arduino, Blockly language, and Micropython. The main factor to choose M5Stack was the ability to take advantage of the already encased hardware, which covers all the architectural needs while having the possibility to extend it if needed, along with the option to implement custom made software to control the device.

Nevertheless, the prototype could also be achieved using individual components and other development boards or by building a custom printed circuit board, PCB, and encasement. Figure 10 shows the essential components to achieve the architecture suggested in chapter 4.

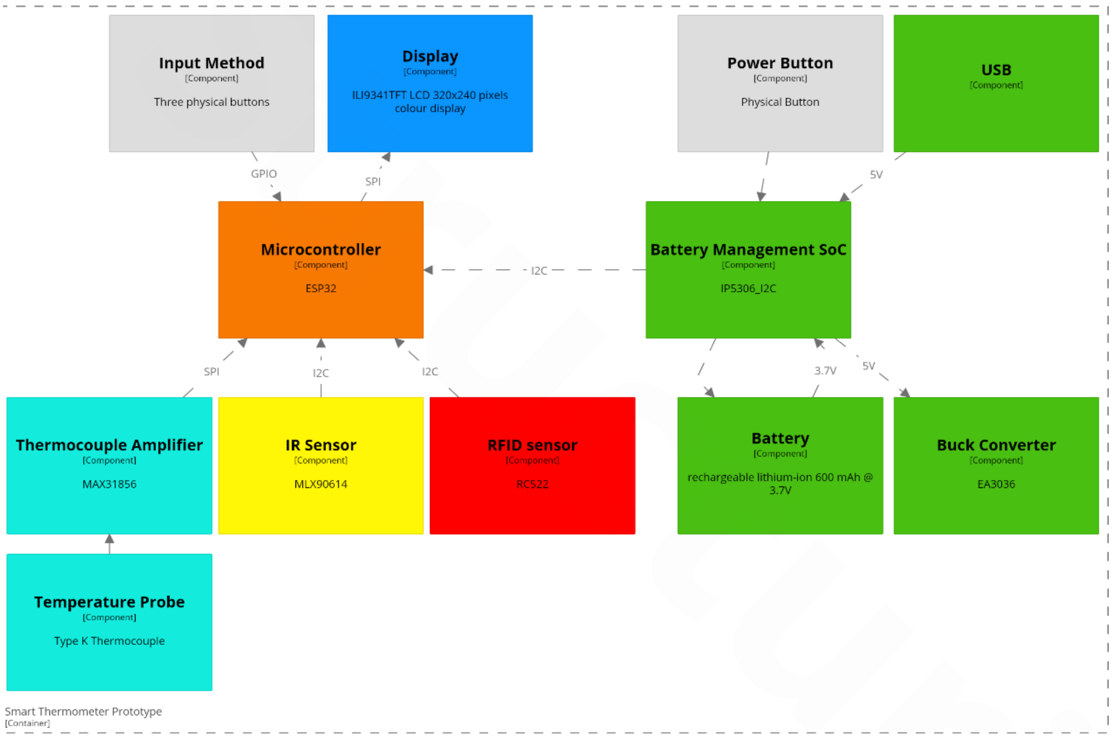

***Figure 10** – Smart Thermometer prototype essential components.*

In the next subsections, the parts vital for the smart thermometer implementation that would be necessary no matter how the prototype was developed will be analyzed.

5.1.1 Microcontroller

The used microcontroller is an ESP32 [82]. The main characteristics of the used version are:

- Integrated Wi-Fi and Bluetooth connectivity
- 240MHz Dual-Core CPU
- 16MB ROM
- 520KB SRAM + 4MB external PSRAM
- 43 GPIOs, SPI, UART, I2C, LCD interface, ADC and others
- Built-in RTC

As the ESP32 has integrated Wi-Fi, there is no need for an external network module, allowing for a smaller design and out of the box network capability.

Another version without the 4MB external PSRAM has been tried, but the 520KB SRAM proved to be insufficient to run the custom made software. Mainly due to the GUI.

The built-in analog to digital converter (ADC), however, proved to be inaccurate. It suffers from noise and linearity problems, which did not allow for accurate readings when necessary (e.g., temperature probe readings). This has been solved by using amplifiers with built-in ADC covered in the next subsection.

The built-in RTC also proved to be imprecise, showing drift over time. As recording time and date is a necessity, this represents a setback. However, the feedback received from the HACCP consulting company mentioned in section 1.3 stated that a testing version with no offline mode was more than acceptable. Allowing the user to take measurements only when Wi-Fi is available allows the transfer of the responsibility of maintaining measurements date and time from the device to the backend. In a more advanced version of the smart thermometer, an external RTC can be added and the problem easily solved.

5.1.2 Temperature Probe

Initially, the smart thermometer prototype was only intended to have an IR sensor and be tested as a non-contact thermometer, as these were readily available as a module for the M5Stack. Nevertheless, the feedback received from the HACCP consulting company resulted in the inclusion of a temperature probe used to measure internal product temperature.

As mentioned in section 2.4.1 the most common type of probes used to accomplish this objective are thermocouple probes. There are different thermocouple types, some examples being type K, J, T, and E. The main difference is the material by which they are composed, which influences temperature range and accuracy. A comparison between the most common types is made in Table 2.

__Table 2__ - Comparison of the most common thermocouple types. Source:[83]

Type	Material	Range (ºC)	Standard Limits of Error (Greater of)	Special Limits of Error (Greater of)
K	Nickel-Chromium/ Nickel-Alumel	-200 to 1250	+/- 2.2ºC or +/- .75%	+/- 1.1ºC or 0.4%
J	Iron/Constantan	0 to 750	+/- 2.2ºC or +/- .75%	+/- 1.1ºC or 0.4%
T	Copper/Constantan	-250 to 350	+/- 1.0ºC or +/- .75%	+/-0.5ºC or 0.4%
E	Nickel-Chromium/Constantan	-200 to 900	+/- 1.7ºC or +/- 0.5%	+/- 1.0ºC or 0.4%

The chosen type was a Type K thermocouple. The reasons are: being the most commonly available, inexpensive, meet temperature range and accuracy needs, and are more chemically inert than Type T and J. The other main reason was that the device available for comparison also uses a type K thermocouple.

The chosen thermocouple was an RS PRO Type K Thermocouple with 150mm length and 1.5mm diameter, which can be seen in Figure 11. The junction is insulated to reduce electrical interference. It also has a protective sheath made of 310 stainless steel to provide resistance to corrosion and oxidation. The probe has a range of -40ºC to 1100ºC. Last but not least, the probe is food compatible. The datasheet is available at [84].

***Figure 11** – The used Type K thermocouple probe*

Thermocouples consist of two wires made from different metals. The wires are welded in one end, creating a junction and, when exposed to temperature changes, a small voltage is generated in the thermocouple's electrical circuit. Figure 12 shows the thermocouple junctions.

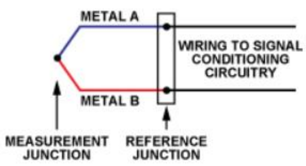

***Figure 12** – Thermocouple junctions [5]*

This voltage depends not only on the temperature at the measurement junction but also on the temperature at the reference junction, also known as the cold junction. To transform this voltage into a temperature value, it is necessary to perform a cold junction compensation (use the cold junction temperature as a reference) and digitalize the signal. To that effect, different solutions have been tried. First, an analog output amplifier, AD8495, was tested. However, as mentioned in 5.1.1 the ESP32 ADC suffers from accuracy problems, and the obtained measurements were not reliable. Therefore a digital thermocouple amplifier was used, namely the MAX31856. The datasheet is available at [85].

The MAX31856 performs cold-junction compensation and digitalizes the signal from any type of thermocouple. It also includes automatic linearization correction and a 19 bit ADC. To easily integrate this board with the existing design, it was used the Adafruit MAX31856 breakout board. This board was then placed into an M5Stack module case, and wires were soldered to the available pins. A thermocouple mini plug was attached to the module and connected to the MAX31856, allowing for the thermocouple probe to be detachable. The final result of the custom-made thermocouple module, compatible with the M5Stack is shown in Figure 13.

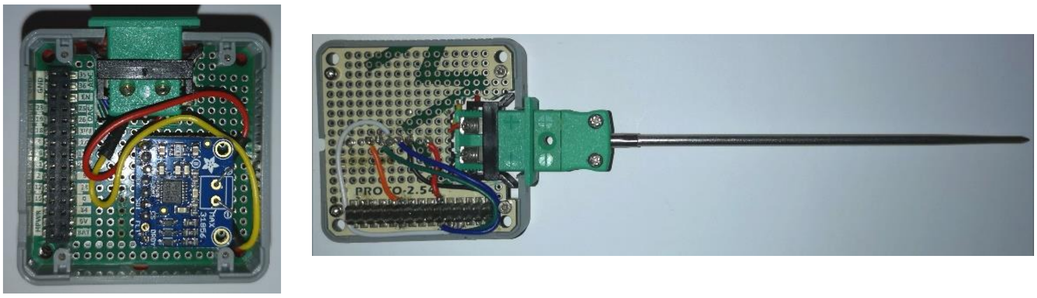

Figure 13 *– Custom-made thermocouple module*

The plug is connected to the MAX31856. In its turn, the max31856 is powered by 3.3V and uses SPI to communicate with the microcontroller. The connections being the following:

- CS – 5
- Miso – 19
- Mosi – 23
- Sck – 18

5.1.3 IR Sensor

Several establishments use IR non-contact thermometers to measure the food surface temperature. Although less accurate, these prevent cross-contamination.

One of the most commonly available IR temperature sensors is the MLX90614, which is showed in Figure 14. These are used in a wide range of applications and are easy to integrate. They already come with the necessary low noise amplifier, a 17-bit ADC, and a digital signal processor to achieve higher accuracy and resolution.

Several versions of this sensor exist, with different operating voltages, field-of-view, and operating temperatures. The used version has an operating voltage of 4.5V to 5.5V. The measuring object temperature range is from -70ºC to 380ºC, and the measuring ambient temperature range is from -40ºC to 125ºC. The reported accuracy at room temperature is +- 0.5ºC. A critical factor to have in consideration is the sensor field of view. The MLX90164 field of view is cone-shaped and, in this case, the angle is 90º, meaning that the ratio between the distance from the object and the sensing area is 1:2 (i.e., at 5 cm distance, the measured zone diameter is 10cm). The corresponding datasheet is available at [86].

M5stack already has a compatible unit that can be directly integrated into the system.

***Figure* 14 –** *MLX90614 IR temperature sensor*

The MLX90614 connects to the esp32 via I²C, is powered by 5V, and the connections are the following:

- SCL – pin 22
- SDA – pin 21
- The I²C address is 0x5A.

5.1.4 RFID Sensor

Considering that RFID will be used to identify users, machines, and products, the range necessary to scan each tag must be short. Therefore, any RFID category, ultra-high-frequency (422MHz and 860 to 960MHz), high-frequency (13,56MHz), or low-frequency (125khz and 134khz), can be used. Nevertheless, the reader shall be set up for doing short-range readings only. This will prevent reading multiple tags at once or reading tags from afar. To make the prototype development more straightforward, the chosen RFID reader was the one made available by M5Stack, Figure 15. The RFID module uses an RC522 module. It works in the 13.56MHz frequency, and the reading and writing distance is less than 20mm.

***Figure 15 –** M5Stack RFID reader module*

The RC522 connects to the ESP32 via I²C, is powered by 5V, and the connections are the following:

- SCL – pin 22
- SDA – pin 21
- The I²C address is 0x28.

5.1.5 Display

The used display, which corresponds to the M5Stack display, it is a 2.2" TFT display module with 320x240 pixels. It uses an ILI9341 driver that connects via SPI to the microcontroller.

One thing to have in consideration is the fact that the MAX31856 and the display share the SPI bus. When the display and the MAX31856 were connected at the same time a direct memory access error (DMA) happened. The error was: "spi_master: spi_device_queue_trans(620): txdata transfer > host maximum". Meaning that the data transfer was more than what the host (in this case the microcontroller) could handle. To solve this issue it was necessary to increase the factor argument of the ILI9341. By doing this the display consumes less RAM, the downside is that the refresh rate is lower. Nevertheless, for the smart thermometer case the difference is not noticeable.

The ILI9341 connects to the ESP32 via SPI, is powered by 3.3V, and the connections are the following:

- CS – 14
- Miso – 19
- Mosi – 23
- Sck – 18
- DC – 27
- RST – 33
- Backlight – 32

5.1.6 Buttons

Three physical buttons are used. They are connected to pins 37, 38, and 39 of the microcontroller. During development, it was found that there was a conflict between Button A (pin 39) and the Wi-Fi the ESP32 Wi-Fi module. Whenever the Wi-Fi was connected, the button would be affected by interferences and would be repeatedly pressed. To solve this issue, it was necessary to use the ESP32 pulse counter to count the number of rising and/or falling edges of an input signal. As the interference pulses are very short, an odd count means that the button is pressed, and an even count means that it was released.

5.1.7 Power Circuit

Although the M5Stack system comes with the powering circuit already implemented, and no work was necessary to make it function, it was analyzed to understand how it works and make it possible, in the future, to implement a similar solution in a custom board. The powering circuit, represented in green in Figure 10, includes a 3.7V rechargeable lithium-ion battery, an IP5306_I2C, and EA306 chips. The IP5306 is a multi-function power management system on chip (SoC). It has an integrated boost converter to step up battery current to 5V. It also provides battery charge management and by connecting it using I^2C to the microcontroller, it is possible to monitor the battery level. The EA306 has three buck converters and is used to regulate the 5V voltage that comes from the IP5306 down to 3.3V. This way, the system has available either 5V or 3.3V for its use.

The IP5306_I2C connects to the ESP32 using I²C protocol, and the connections are the following:

- SCL – pin 22
- SDA – pin 21
- The I²C address is 0x75.

Although out of this work scope, a power consumption analysis and optimization is necessary and will be carried in the future.

5.2 Smart Thermometer Software

Although the M5Stack comes from factory with its own software that allows programming the device by using its own version of micropython or blockly, these proved to be very basic. Documentation was scarce and it did not give the necessary freedom to customize the device. Therefore to implement the desired features, it was required to create custom software for the smart thermometer. To accomplish it, it was first necessary to choose what would be the programming language, framework, or platform used to program the ESP32. As mentioned before, the ESP32 supports micropython, Arduino and ESP-IDF. The choice was to use micropython as it is the ideal language for fast prototyping due to being high level, fast and easy to program and implement. Although micropython is not as lightweight as Arduino or ESP-IDF, it has all the required software libraries and if required it is extensible and can be used together with C or C++.

The micropython port for the ESP32 already comes with a vast set of useful modules that can be used for programming the smart thermometer. Networking, JSON encoding and decoding, garbage collector, time-related functions, power management functions, mathematical functions, and others.

However, to control the remaining hardware such as each sensor, monitor the battery management chip, make HTTP requests, and provide the GUI, open-source libraries have been adapted and used when available.

To implement the GUI the choice was to use an open-source graphic library called Light and Versatile Graphic Library (LVGL) [87]. LVGL is specially designed to work in embedded devices. Although being written in C, there are bindings that make it compatible with micropython. It is also compatible with the ILI9341 display driver.

To program the device, an event-driven programming approach was used. Two main reasons contributed to that: the device program flow being determined by user actions such as a user pressing a button and scanning an RFID card and the need to ensure a non-blocking UI.

5.2.1 Implemented features: User Point of View

In this section the different implemented features of the prototype will be described and discussed with the aid of the flowcharts (flowcharts for each feature are presented in Annex 1). Thus, to help the flowcharts interpretation, Figure 16 shows the main program flow after turning on the thermometer. To simplify the main diagram, each feature such as User Authentication, Scheduled Temperature Measurement, Non-Scheduled Temperature Measurements will have its own diagram. Also not present in the flow diagrams is the fact that at any point the user can return to main menu.

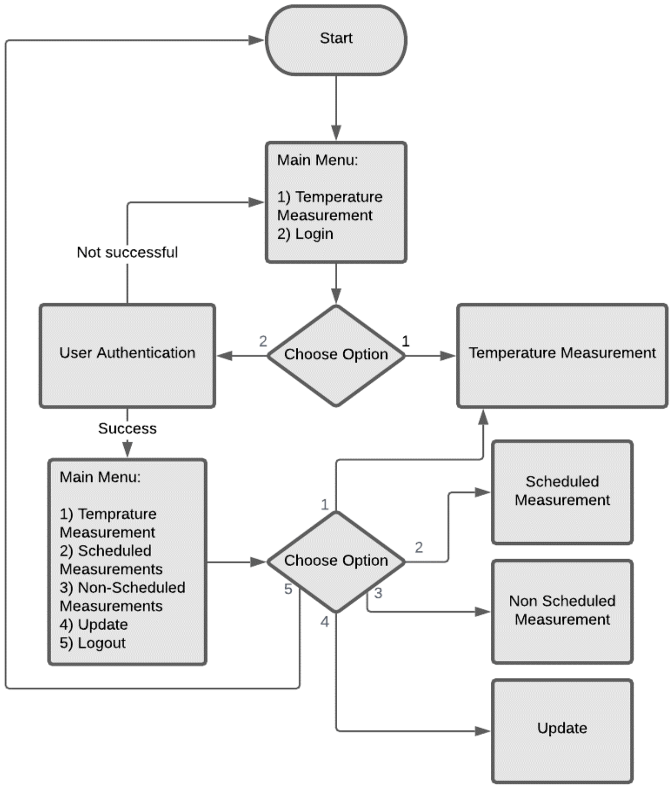

Figure 16 *– Thermometer main flowchart*

Scheduled Measurements

To use the scheduled measurements feature the user selects the option “Scheduled Measurement” when on the main menu. Once this option is selected, the user must select one of the options: “Update tasks”, “Scheduled Tasks List”, “Scheduled Tasks RFID” or “Home”.

If the user selects “Update Tasks” then the update tasks menu is shown, and the user can choose to update the scheduled tasks list. The task update process is described in subsections “Update Task List” and illustrated in Figure A.26- Update scheduled measurements/tasks process flowchart

Figure A.27.

If the user selects “Scheduled Tasks Lists”, the system will display the list of possible tasks to choose from.

If the user selects “Scheduled Tasks RFID” then the system expects an RFID (machine or product) badge to be scanned. If the identification is not successful, the system will keep asking until successful or until the user decides to cancel; once the identification is successful, the system will display the tasks associated with the machine or product identified.

At this moment, in any of the last two cases described, the user must select one of the tasks from the list presented and take the temperature measurement. Finally, the user can choose to submit the measurement to the database. After pressing submit, the system presents the main menu once again. The submission process is detailed on Figure A.20 – Scheduled Measurement (task) Submission process flowchart

Figure A.21Figure A.22.

The scheduled measurements process is graphically described in a flowchart present in Figure A.1 - Scheduled measurements flowchart

Figure A.2Figure A.3 - Scheduled measurements flowchart

Figure A.4Figure A.5 (Annex 1).

Non-Scheduled Measurements

To use the non-scheduled measurements feature the user selects the option "Non-scheduled Measurement" when on the main menu. Once this option is selected, the user must select one of the options: "Scan Machine Label", "List Machines" or "Home".

If the user selects "Scan Machine Label" then the system expects a machine RFID badge to be scanned. If the identification is not successful, the system will keep asking until successful or until the user decides to cancel; once the identification is successful, the system will display the product's list of the machine identified. Figure A.17 – Machine identification for non-scheduled measurements flowchart

Figure A.18Figure A.19 illustrates how this process is carried by the device.

Similarly, if the user selects "List Machines", the system will display the list of possible machines to choose from. Once the user selects one machine, the system will display the product's list of the machine selected.

In any of the cases, at this moment, the user must select one of the products from the list presented and take the temperature measurement (that can be repeated as many times as necessary). Finally, the user can choose to submit the measurement to the remote database. After pressing submit, the system presents the main menu once again.

The non-scheduled measurements process is graphically described in a flowchart present in Figure

A.8 - Non-scheduled measurements flowchart

Figure A.9 - Normal measurements flowchartFigure A.10 (Annex 1).

Normal Temperature Measurements

On the normal measure feature the user selects the option "Normal Temperature Measurement" when on the main menu. Once this option is selected, the user can start measurement or return to the main menu. The user repeats the measurements as many times as necessary.

The normal temperature measurements is graphically described in a flowchart present in Figure A.11 - Normal measurements flowchart

Figure A.12Figure A.13 (Annex 1).

5.2.2 Implemented Features: System Perspective

For the correct functioning of the system there are some essential underlying features that have been implemented to meet the requirements defined in Chapter 3. To better understand how the system works, some of the processes are described in the following subsections.

Authentication Mechanism

The system's process for user authentication starts when the device reads the user RFID label. Once the system scans the badge, it compares it to the user list in the filesystem. If the IDs don't match the process repeats itself until a match is found (i.e. a valid RFID badge is presented). Once this happens the user authentication is completed, and the login is confirmed.

The user authentication system process is graphically described in a flowchart present in Figure A.14 – Authentication Mechanism flowchart

Figure A.15Figure A.16 (Annex 1).

Scheduled Measurement Submission

The system's process for submitting a scheduled measurement starts by making sure that WiFi is available. If it is not available or if it is off and the HTTP request was unsuccessful, the measurement data is saved in the filesystem. When WiFi is available, a patch HTTP request with the measurement data is sent to the server (as detailed in section 5.3). If the request was successful and the data was saved in the file system, then it shall be erased.

Once the data as been saved to the file system or successfully sent to the server, the task is considered completed, and therefore erased and the user no longer have access to it.

This process is graphically described in a flowchart present in Figure A.6 (Annex 1).

RFID machine identification for scheduled measurements

The system's process for identifying tasks related to a certain machine (for a product, it would be the same) starts by reading an RFID label attached to that machine. Once the system scans the badge, it searches in the task list for tasks related to the machine. If found, all the tasks associated with the machine are fetched.

This process is graphically described in a flowchart present in Figure A.9 (Annex 1).

RFID machine identification for non-scheduled measurements

The system's process for identifying a machine and product that shall be the target of a measurement starts by reading an RFID label. Once the system scans the badge, it compares it to the machine list in the filesystem. If the IDs don't match the process repeats itself until a match is found (a valid RFID badge is presented). Once this happens the corresponding product list is fetched.

This process is graphically described in a flowchart present in Figure A.17 – Machine identification for non-scheduled measurements flowchart

Figure A.18Figure A.19 (Annex 1).

Update Smart Thermometer Machine List

In order for the smart thermometer to work when network connection is offline, it needs to save essential data made available by the server in its own filesystem. A subset of that data is the list of machines present in the store, along with the products included in each machine.

These lists do not suffer frequent changes and can be large. Therefore, in this case, a caching system is used in order to prevent the same data from being fetched once again.

The system's process for updating the machine and products lists starts by loading the ETag available from the previous update. Then if WiFi is available, an get request is submitted to the server. This request will contain the ETag present in a "if-none-match" header. If server data as changed and the request is successful, the task list is returned by the server and is written to the file system and the ETag is updated. If data has changed, nothing happens.

This process is graphically described in a flowchart present in Figure A.23 – Update smart thermometer machine and products lists

Figure A.24Figure A.25 (Annex 1).

Update Smart Thermometer Scheduled Tasks List

The other subset of that data essential for the system proper functioning is the list of scheduled measurements (tasks).

The system's process for updating the scheduled measurements tasks starts by making sure that WiFi is available. If WiFi is available, a get request is submitted to the server. If the request is successful, the task list returned by the server is written to the file system. Otherwise the user is warned.

This process is graphically described in a flowchart present in Figure A.26- Update scheduled measurements/tasks process flowchart

Figure A.27 (Annex 1).

5.3 Backend, API, Admin Web Application, and Database

To implement the backend services, the REST API, and the database, Django REST Framework (DRF) was the chosen tool [7]. DRF allows these to be implemented simply and efficiently. It has extensive documentation, and it is widely tested and used. DRF handles relational databases, object-relational mapping, can serve a native admin panel and provides a REST API.

As the framework's name indicates, communication with the API, either by the thermometer or external services, is done using HTTP requests following REST principles. A REST API is resource-based. Resources are identified in requests using unique resource identifiers (URIs) like a store, machine, or measurement ids. In this case, JSON was the chosen format to interchange data due to being lightweight, human readable and easy to use and parse. Also important is that JSON parsing is supported by micropython.

DRF allows for integration with several different database management systems, PostgreSQL, SQLite, MySQL, and others. In this case, PostgreSQL is used due to out-of-the-box compatibility with DRF and for allowing integration with cloud providers like Google App Engine or Azure. To implement the backend, API, admin web application and database, the first step was to declare the data models. Data models are the object relational-mapping between Python data objects and database models. In Figure 17 the resulting entity-relationship diagram of the defined models can be observed. The following models have been created:

- Store: Represents the establishment where the thermometer will be. The store can have multiple devices, machines, and users (employees). Several measurements, scheduled or not, can be made in a store.

- User: Who takes the measurements or complete the scheduled measurements. One user can take several measurements, or complete scheduled measurements, but
- Device: Smart thermometer used to take measurements, belongs to store.
- Machine: Contains products and is targeted by measurements.
- Product: Is in a machine and is targeted by measurements.
- Measurement: Is taken by a user and a certain device. The measurement include the machine and/or product that belong to a certain store.
- Scheduled Measurement: Inherits from the measurement model. Each task is a measurement and includes the measurement attributes.

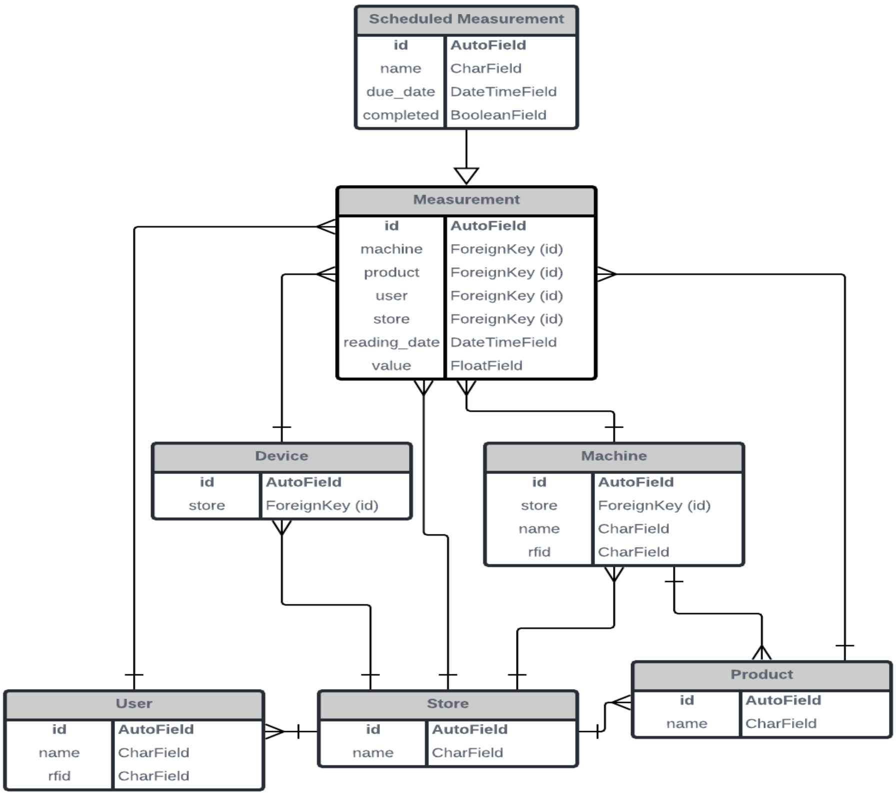

***Figure* 17** – *Entity-relationship diagram*

The second step was to declare all the serializers used to transform resource representations and send them from the server to the client and vice versa. These serializers define which fields of a data model are sent when the client asks or submits a particular resource. For example, the serializer present on Figure 18 is invoked when the API client asks for a “Task” resource. The data is serialized and a JSON representation of a task with all the corresponding fields is returned to the client.

```python
class RetrieveTaskSerializer(serializers.ModelSerializer):
    class Meta:
        model = Task
        fields = ('name','task_id','store','machine','product','due_date','completed', 'reading_date','value')

        lookup_field = 'task_id'
```

Figure 18 – *DRF serializer example*

Finally, to set endpoints that can be the target of HTTP requests, some views were created. These views define what kind of HTTP requests can be made to each endpoint. Some endpoints can only handle safe method requests like GET, others can also handle POST requests. When applicable bulk creation is available in order to make easier to external services to create large sets of data in one time. Data filtering is also possible. In the end, the following endpoints have been created:

- (…)/stores/ - allows to create stores and list all the available.
- (…)/stores/(product_id)/ - allows to retrieve, update or delete a certain store.

- (…)/machines/ - allows to create machines and list all the available.
- (…)/machines/(machine_id)/ - allows to retrieve, update or delete a certain machine.

- (…)/products/ - allows to create stores and retrieves all available.
- (…)/products/(product_id)/ - allows to retrieve, update or delete a certain product.

- (…)/scheduled_readings/ - allows to create and list all the available.
- (…)/scheduled_tasks /(task_id)/ - allows to retrieve, update or delete a certain task.

- (…)/non_scheduled_readings/ - allows to create non-scheduled readings and list all the previously done.
- (…)/non_scheduled_readings/(device_id) - allows to retrieve, update or delete a certain non-scheduled reading.

- (…)/devices/ - allows to create devices (smart thermometers) and list all the available.
- (…)/devices/(device_id)/ - allows to retrieve, update or delete a certain device.
- (…)/devices/(device_id)/tasks/ - lists all the daily tasks attributed to the corresponding device.
- (…)/devices/(device_id)/machines/ - lists all the machines, and products belonging to the machine, attributed to the corresponding device.

- (…)/users/ - allows to create users and list all the available.
- (…)/users/(user_id)/ - allows to retrieve, update or delete a certain user.

These endpoints will be consumed by the smart thermometer, either to get data updates, or to submit measurements. External services can also use them in order to create or manage data as mentioned in the previous chapters.

DRF also provides an administration web application only accessible to authorized users. Based on the metadata from the defined models a web application is served. It will allows the admin to manage stores, machines, products, users, schedule new tasks, view existing tasks and non-scheduled measures.

5.4 Security

Regarding security there are four main components that were taken into consideration. User Authentication, Device Security, Communication Security and Server Security.

To authenticate users with the device the choice was to take advantage of its RFID functionality. Each user has a personal RFID tag that must be used in order to access the smart thermometer advanced functionalities. In the future the possibility of using two-factor authentication shall be considered, as it would reduce the probability of someone accessing the device without permission by, for example, stealing the RFID card.

At the server side, the admin must be authenticated in order to access the backend services. DRF already provides security features out-of-the-box, including authentication mechanisms. The server shall be provisioned with a server certificate in order for it to be authenticated.

To further secure communications to the server, either from the smart thermometer or from external services, HTTPS shall be used to assure integrity and confidentiality of data. The ESP32 has transport layer security (TLS) support. The device shall also authenticate itself through the use of json web tokens (JWT) or even by using pre-provisioned certificates that would enable mutual TLS.

At the smart thermometer side, not only communication aspects should be taken into consideration but also physical vulnerabilities. The ESP32 already has features such as secure boot and flash encryption to prevent tampering or software copying.

Although ESP32 supports TLS, secure boot, and flash encryption, the best option that shall be considered in the future would be to use a cryptographic co-processor such as an ATECC608B which is inexpensive, works as a security safe for cryptographic keys and comes pre provisioned with certificates enabling device authentication mechanisms such as JWT while taking the processing load from the ESP32. This would lead to less memory consumption and faster performance. An added benefit of using crypto-processor chip would be that remote updates to the software would be easier as there would be no need to take special precautions about managing credentials as these would be directly loaded into the crypto-processor chip.

Chapter 6

Results

This chapter provides the results of the work conducted in the scope of this dissertation. It shows the prototype assembled hardware and GUI. It follows by presenting the results from a survey conducted to food safety managers from different types of food related establishments. The feedback from the HACCP consulting company that was consulted along this dissertation’s work is also given. Finally, it reflects on the prototype cost and provides the comparison between the prototype developed and solutions already existent in the market.

6.1 Smart Thermometer Prototype System Result

In this section, the prototype that resulted from this dissertation's work, and from which the various components and features have been discussed throughout the previous chapters, is presented.

6.1.1 Smart Thermometer Prototype

In Figure 19 the smart thermometer prototype is shown. Different views of the smart thermometer are shown. It is possible to observe the physical temperature probe, the IR sensor, USB charging port and RFID reader

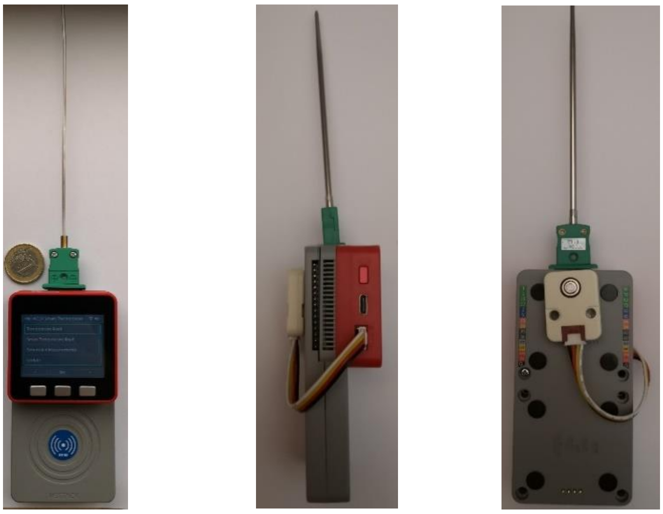

Figure 19 - *Smart thermometer prototype with probe and IR*

As it is possible to see in Figure 19, the IR sensor is external to the prototype. In future versions, the IR sensor will fully integrated in the thermometer case.

6.1.2 Smart Thermometer Prototype UI

As a result of the implementation discussed in Chapter 5, the thermometer displays the following GUI:

- Login menu, as Figure 20 represents. This menu asks the user to present their RFID tag to perform authentication. It also presents a Home button.

Figure 20 *– Login menu before and after authentication*

- Main menu with authenticated user, as Figure 21 shows. The main menu allows the user to choose the type of measure he wishes to perform: simple, scheduled or non-scheduled. It also allows to logout or to follow to the update menu.
- Main menu with a non-authenticated user, as represented in Figure 22. This menu presents the login option. It allows performing simple/normal measurements while not having access to advanced features.

Figure 21 *– Main menu with authenticated user*

Figure 22 *- Main menu with non-authenticated user*

- Update menu, which can be seen on Figure 23. The update menu allows to choose whether the user wants to update the list of machines, list of products or both.
- Menu for non-scheduled tasks, as Figure 24, presents. The list of non-schedules tasks is presented by machine (after selecting through a list or identifying a machine via RFID) with the products associated.
- List of scheduled tasks, as showed on Figure 25. The user can choose one of the tasks and perform the measurements. The list is organised by hours, with all tasks or tasks by machine if that option is selected.

Figure 23 *- Update menu and possible selections*

Figure 24 *- Steps from menu for non-scheduled tasks; Thermometer with RFID tag.*

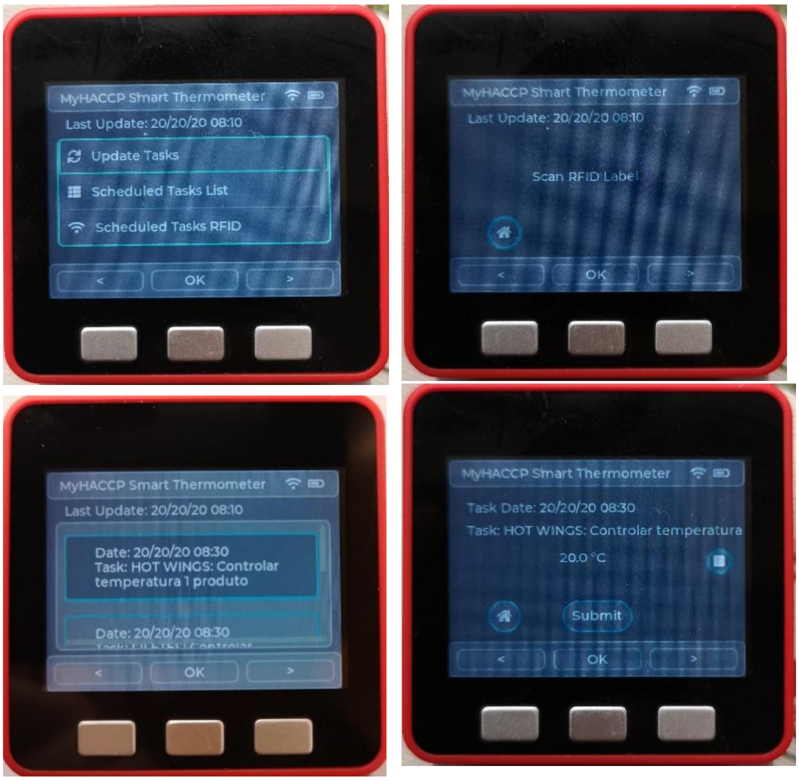

Figure 25 *- List of schedule tasks*

- Admin view, shown in Figure 26 and Figure 27. In the first figure, it is possible to see the options for the admin to manage both users (and groups) and tasks associated to machines, products, stores, and others. In Figure 27, there is an example of the fields to add new tasks associated with machines and products, once the admin selects “+Add” Task or Machine.

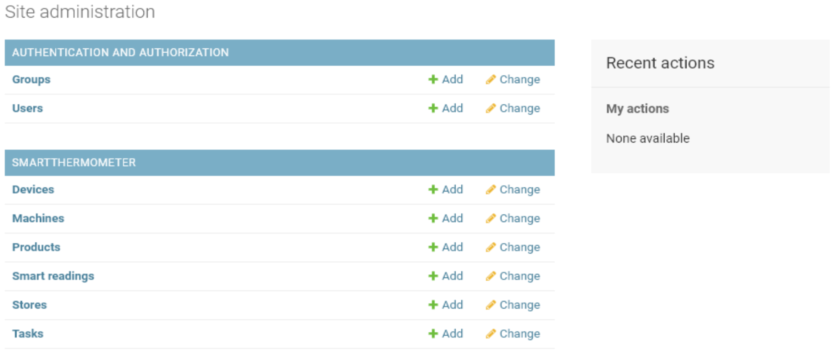

Figure 26 *- Main admin menu*

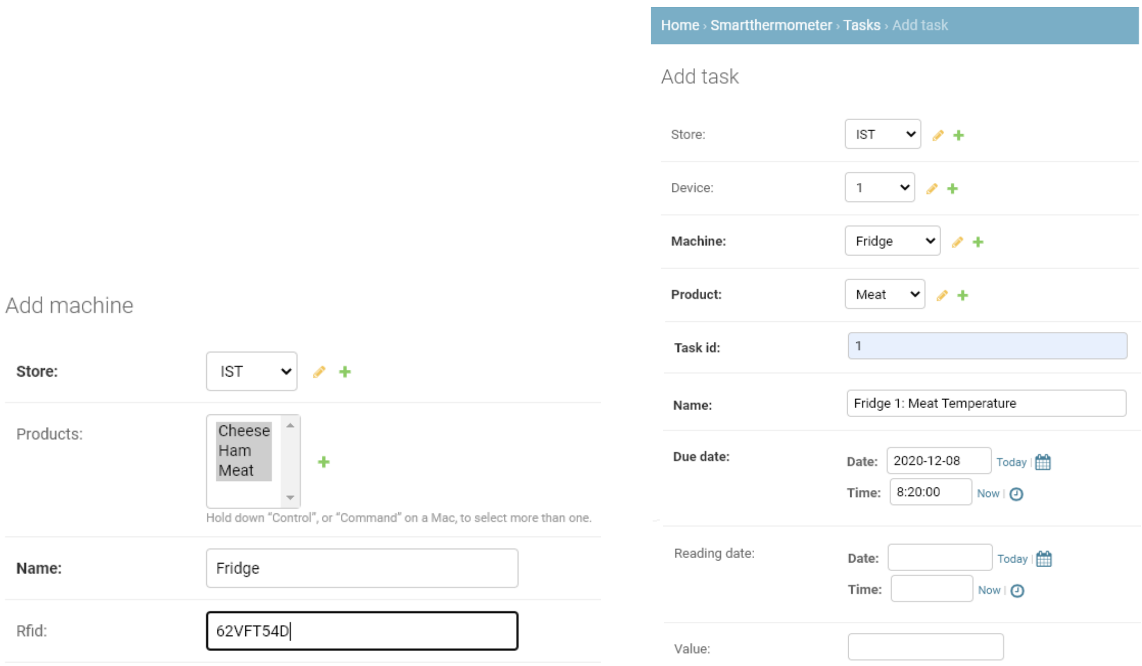

Figure 27 *- Task and machine creation examples*

6.1.3 Smart Thermometer Performance

In order to assess the thermometer performance, a practical experiment was conducted using the smart thermometer and a reference thermometer. The HACCP consulting company provided the reference thermometer, which is ThermaQ® Blue Thermocouple Alarm Thermometer[88]. This thermometer is used in different establishments for food safety purposes, carrying a factory's calibration certificate.

To conduct the practical experiment, it was first created an ice bath. In an ice bath, the water temperature shall reach 0ºC (it is not exact, since the water used is not distilled due to the presence of minerals and other substances) [89]. The water was then heated until the boiling point, where the temperature should be around 100ºC.

The following ***Table 3*** shows the regression obtained using the measures executed.

Table 3 *- Temperature measurements with reference and prototype thermometers*

	Reference Thermometer	**Thermometer Prototype**
Ice bath	0,4ºC	2,4ºC
Boiling point	99,8ºC	97,9ºC

As it can be understood from Table 3, the smart thermometer presented a variation of +/- 2ºC in both cases.

Between these two measures (which were the first and the last one, other 22 measures were taken with both thermometers. ***Figure 28*** graphically represents these measurements and shows that the values of the thermometers are quite similar and overlap in almost all the points. In red, it is represented the prototype measurements and in blue the reference thermometer's.

As can be seen in the graph, the most discrepant measures are the first and last one, which present a variation of +/- 2ºC. Taking into account the specifications of the hardware used and the results presented here, it is possible to conclude that in future versions the thermometer developed shall be able to reach the accuracy degree of the reference thermometer.

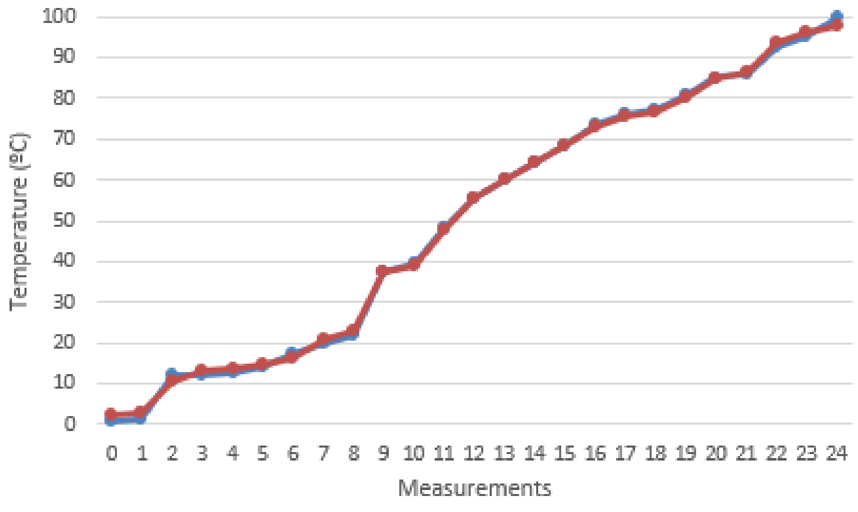

Figure 28 *- Ice bath to boiling point temperature measurements*

Although the hardware components chosen theoretically allow the thermometer to have an accuracy similar to the reference thermometer, the discrepancies observed can be due to lack of calibration or due to the hardware utilised in the prototype not being optimised for this use (extreme conditions, such as the ones encountered in a kitchen environment).

6.2 Temperature Control and Records – Market Perspective

6.2.1 HACCP Consulting Company

Along the period of this dissertation there was a constant interaction with an HACCP consulting company. The company's feedback allowed to obtain a broader view of the catering/food supply market, and gather all the requirements to develop the solution presented.

The HACCP consulting company is specialist in the digitalization and automatization of data collection, tasks and procedures through the development of custom tailormade software and the introduction of IoT technologies. Currently they are responsible for the services in more than 400 establishments.

The initial information obtained from the company is in line with the results of the questionnaires that will be discussed next: most clients with which the company works use handheld thermometers with on-screen temperature for temperature control. After the measurements, and for record taking purposes, these are input on specific Software or paper (before Software adoption).

One of the major concerns of the company as data collectors is to ensure the data is reliable: measured at the defined time, using the correct method, and that values are not forged to fit the range of pretended values. Using Software instead of a paper solution allows store and unit managers to quickly analyze the collected data and act on it guaranteeing a closer control of the operation and employees. Decision making is better informed, and problems reach the upper chains (or responsible entities) faster, allowing faster action.

Mainly, it allows managers to control at a distance and in real-time (close to real-time when offline mode is used) whether registries are being filled and if any problems are reported in a plethora of units.

When collecting temperature data, the company verified that, currently, the use of a mobile device, (such as a phone or tablet) together with a handheld thermometer (Bluetooth or manual input), is not optimal as it occupies employees' both hands and makes it take longer. When using Bluetooth thermometers, sometimes the simple synchronization between devices becomes a problem. At the moment using multiple pieces of hardware the main challenges include damages or disappearances, which are reported problems that delay the operation.

6.2.2 Food-Related Establishments

As previously mentioned, in this thesis's scope, a survey was prepared with the goal of confirming the feedback given by the HACCP consulting company and to better understand what processes are implemented in different kinds of establishments along with the current needs.

Four different entities were contacted in order to obtain feedback from different types of establishments that also differ in size:

- one entity in the business of food distribution (retail), managing more than 600 establishments;
- one industrial entity (production of frozen goods);
- one entity responsible for a restaurant chain, managing between 51 to 100 establishments;
- one small catering business, responsible for one restaurant.

In total, the survey analyzed a universe of around 700 establishments, meaning that although it was not an extensive survey it still represents a significant number of establishments with a relevant accumulated experience that cover different parts of the food supply chain.

To achieve its goal, the questionnaire tackles several topics relevant to this dissertation's work. It unveils the priorities, needs, and procedures of different establishments and approaches the possible interest in a tool such as the smart thermometer developed within this work scope.

The information gathered from the analysis of the inquiry follows next. It is important to mention that the text on the pictures is in Portuguese as that was the language used in the questionnaire distributed, but a short explanation accompanies each topic.

Importance of Temperature Control

The question of the survey that focused on the importance of temperature control, asked the respondents to select from “Not important” to “Very Important” how important is temperature control. As shown in Annex B, on Figure B.1, it was unanimous that temperature control is of very high importance in machines and equipment, stored products (refrigerated), upon receiving products from the supplier, and for quality purposes. Responses varied from very important and important for cooked products and products on display, while for traceability effects, one respondent also believed it was indifferent.

The obtained answers allow confirming the high importance of temperature control within a food establishment.

Importance of Temperature Records

One of the questions of the survey asked for the opinion of the respondents on the importance of temperature records. The results relative to temperature records' importance closely relate to those obtained on the significance of temperature control, as can be seen on Figure B.2. Responses varied mainly between very high and high importance of taking temperature records for all situations. These are temperature control in machine and equipment, stored products (refrigerated), upon receiving products from the supplier, quality purposes, cooked products, and products on display). Regarding traceability effects, there was also one answer indicating it is indifferent.

On a general note, it is possible to conclude that maintaining temperature records is of high importance, just as temperature control.

Still related to temperature record taking, 100% of the submissions indicated that the capacity to easily verify the previous temperature records is of a very high importance.

Current Temperature Control Measurements

The survey asked the respondents to indicate the temperature control measurements currently done on a regular basis. The results indicate that all the establishments within the universe analyzed have a system for taking and recording temperature measurements. The following kinds of measurement and respective temperature records are made on 100% of the food establishments: air temperature inside the various machines and/or equipment; temperature of stored products (refrigerated); temperature of cooked products; temperature of the products upon being received from the supplier; for quality purposes. Thus, these are the most critical moments, as is graphically represented in Figure B.3. For traceability effects, only 50% of the respondents (although corresponding to 85% of the total number of establishments analyzed) said it was currently done in their establishments. 75% said that temperature control was done for products on display.

Current Record Taking Methods

For each temperature measurement method (temperature probe thermometer, non-contact infrared (IR) thermometer, and fixed sensor thermometer), the survey asked the respondents how the measurements were made Figure B.4 shows the obtained results, which were dispersed: for fixed sensors temperature most records are automatic and with digital support; for IR thermometer, the temperatures are recorded using paper or digital support, sometimes using paper and then transferring the data to a digital platform or through a tablet/phone (in either case, it is not done automatically); or when using a temperature probe, methods differ the most and all of them are used when accounting for the universe analyzed.

These results show that one record taking method is not extensively established, and especially automatic submission of measurements is far from widely implemented.

The number of records taken per day per a single establishment was also inquired. The answers ranged from 10 to 500, and the time invested in the process was between less than 15 minutes to 2 hours. Especially when considering the upper limits, it is essential to consider the optimization of processes in order to save time and resources. When asked if there were any functionality that they would like to see implemented, the majority of the submissions mentioned automatic or digital records that are easy to access.

Measurement Errors Likelihood and Impact

The survey also asked the respondents to assess the probability of different possible errors happening:

- reading a wrong value from the thermometer;
- recording the wrong temperature value on the right product/machine;
- recording a measurement made on the wrong product;
- recording a measurement made in the wrong place;
- not making the measurement and making a record anyway;

- not to be registered something that should have been registered.

It is worth mentioning that there appears to exist a correlation between the number and amount of time spent per day taking temperature records and the likelihood of these errors. The respondents who take more measurements and spend more time doing them indicate a much higher chance of these problems to happen.

The next Table 4 presents the probability each type of entity indicated for each error. The results are quite dispersed, but it possible to draw the conclusion that there is a higher probability of a mistake happening in entities that involve a higher number of establishments.

Table 4 *– Probability of each error per entity, from 1 to 5 where 1 is "Rare" and 5 is "Very Likely".*

Errors	Entities			
	Food Distribution (600+ stores)	Industrial	Restaurant chain (51 – 100 stores)	Small Restaurant
Reading a wrong value from the thermometer	5	2	3	2
Recording a wrong value on the right product/machine	5	3	4	2
Recording a measurement made on the wrong product	5	2	4	1
Recording a measurement made in the wrong place	5	3	4	1
Not making the measurement and making a record anyway	5	1	2	3
Not to be registered something that should have been registered	5	1	3	3

From Figure B.5 which represents the answers to the question about the severity of each kind of mistake, it is possible to understand that, independently of each situation's probability, it is unanimous that these will have a profound or severe impact in the case of happening. Therefore, it is essential to work actively on their prevention.

Importance of the Information Associated with each Record

The respondents were also introduced to the smart thermometer and questioned about the importance they give to some of the included features.

When asked about the importance of having the automatic association of certain information to the measurement records the answers were unanimous: the identification of the machine and product were considered very important while the identification of the employee responsible for the temperature control is important, although not as important as the previous information, Figure B.6 shows.

Utility of the Smart Thermometer Features

Regarding the main smart thermometer features:

- 100% stated it Is very useful to automatically submit the temperature measurements directly from the thermometer to a digital database.
- 100% stated it is very useful to have the capacity of identifying a machine or product to mitigate the probability of the measurements being taken in the wrong location/product.
- 100% stated that it is very useful to have the list of daily tasks (daily temperature measures) to be completed presented directly in the thermometer display.

These answers help justify the research and development of a solution that includes the mentioned features.

Benefits of a Smart Thermometer

When asked if they consider that a smart thermometer system would benefit the records' reliability, the answers were positive, as there is a belief that it would reduce the human errors mentioned before.

When considering the temperature control and record taking in the different establishments, all respondents except one, who asked for more information, accepted the smart thermometer as a solution that would simplify the system due to saving resources, such as time, and mitigate errors. The respondent who asked for more information was the one responsible for the big restaurant chain's food safety quality. He stated that they would need more information to understand the system and know if they would benefit from it because they already had a WSN in place. After a brief phone interview, they acknowledged the solution's relevance and stated that it would fit and much likely improve their current practices. They also showed a particular interest in the fact that it would be able to identify machines and make the process of knowing which tasks they should complete at each place easier.

6.3 Smart Thermometer Prototype Costs

The costs of the smart thermometer solution developed in this dissertation can be divided into three parts: software and hardware development, and hardware parts.

With respect to the costs of development it is impossible at this point to estimate or evaluate it, thus only hardware parts cost is evaluated here.

When it comes to the hardware, it was necessary to purchase the eight components mentioned in the previous chapter dedicated to Implementation. Next follows Table 5 with each one's price. The components were purchased on the M5Stack and RS website (prices checked on 28^{th} December 2020).

Table 5 *- Hardware components of the Smart Thermometer and Respective Cost*

Hardware Component	Price (€)
M5Stack Fire	40,90
M5Stack Faces Bottom	6,51
M5Stack RFID RC522 Panel	6,51
2 x M5Stack Prototype Module	4,83
M5Stack NCIR Unit	16,33
Adafruit MAX31856 Breakout Board	14,33
Type K Thermocouple	19,01
Thermocouple Plug Connector	4,55
TOTAL	112,97€

As shown in Table 5, the total cost of the smart thermometer's hardware components totals around 113,00€.

If produced on a commercial level, it is most likely that the parts' price will be different since the hardware components will be bought in a higher number, possibly leading to lower costs for hardware.

6.4 Smart Thermometer vs. Current Solutions

The HACCP consulting company consulted in this dissertation's scope provided information about some of the thermometer models used the most by its clients in food temperature control procedures. Figure 29 shows the thermometers and Table 6 provides a comparison

between all of them:

Figure 29 *– Models of the thermometers described.*

From right to left: ThermaQ® Blue Thermocouple Alarm, Saf-T-Log® Paperless HACCP and Testo 735-2 Digital Multichannel, and the thermometer prototype. Source: ThermoWorks, Testo

Table 6 - *Comparison between used solutions and the smart thermometer developed. Source:* [91][92]

Thermometer	**Characteristics**					
	Connectivity	**Scheduled Tasks**	**RFID**	**Remote tasks update**	**Measurement Submissions**	**Cost**
ThermaQ® Blue Thermocouple Alarm	Bluetooth	No. No checklist either.	No	Yes, using mobile app	Yes, to the mobile app.	179,16€
Saf-T-Log® Paperless HACCP	Via USB	No, only allows regular checklists.	No	No	No	162,82€
Testo 735-2 Digital Multichannel	Via USB	No, only allows regular checklists.	No	No	No	586,73€
Smart Thermometer	Wi-Fi	Yes, tasks per day (and per machine) and respective hour	Yes (machines, products, users)	Yes, using web app	Yes, automatic to a database	112,97€ (Prototype)

According the feedback provided by the HACCP consulting company, the ThermaQ® Blue Thermocouple Alarm Thermometer is often used among the company's clients.

Through the comparison displayed on Table 6, it is possible to understand that the smart thermometer developed in the scope of this dissertation enhances the capabilities of the solutions currently in the market and tries to establish new ones, with the goal of optimizing food temperature control and record taking procedures.

Nevertheless, to understand if the prototype is well succeeded, it is important to check if the requirements defined in Chapter 3 are met. The length at which the requirements have (or not) been met is presented in Table 7 and Table 8 for functional and non-functional requirements respectively, along with the comparison with the three thermometers previously presented.

In the tables the following signs are used:

- the ✓ sign means that the requirement is met;
- the +/- means that the requirement is met at some extent, but not fully;
- the ✗ sign means the requirement is not met.

Table 7 *- Comparison of functional requirements*

Functional Requirements	Thermometer			
	ThermaQ® Blue Thermocouple Alarm	**Saf-T-Log® Paperless HACCP**	**Testo 735-2 Digital Multichannel**	**Smart Thermometer**
FR01	✓	✓	✓	✓
FR02	✓	✓	✓	✓
FR03	✗	✗	✗	✓
FR04	✗	+/-	+/-	✓
FR05	✗	✗	✗	✓
FR06	✗	✗	✗	✓
FR07	✗	✗	✗	✓
FR08	✗	✗	✗	✓
FR09	+/-	✗	✗	✓
FR10	✓	✓	✓	✓
FR11	✗	✗	✗	✓
FR12	✗	+/-	+/-	✓
FR13	✗	+/-	+/-	✓
FR14	✗	✓	✗	✓
FR15	✗	✗	✗	✓
FR16	✗	✓	✓	✓
FR17	✗	✗	✗	✓
FR18	Not enough data	Not enough data	Not enough data	✓

Table 8 - Comparison of non-functional requirements

Non-functional Requirements	Thermometer			
	ThermaQ® Blue Thermocouple Alarm	Saf-T-Log® Paperless HACCP	Testo 735-2 Digital Multichannel	Smart Thermometer
NFR1	---	---	---	Not enough data
NFR2	✓	✓	✓	✓
NFR3	✓	✓	✓	✓
NFR4	✓	✓	✓	✓
NFR5	Not enough data	Not enough data	Not enough data	✗
NFR6	✓	✓	✓	✓

As can be understood by Table 7 the smart thermometer fulfils all functional requirements defined in Chapter 3.

Nevertheless, Table 8 shows that the non-functional requirements are not entirely met, namely NFR5 (boot time less than 500ms), which can be bettered with further development.

The tables that aid the comparison of the thermometers (Table 6, Table 7 and Table 8) show that the solution proposed adds various functionalities to the thermometers currently existent in the marker, such as RFID identification of machines and products and user authentication, allowing to associate relevant information whenever data is submitted.

Thus, it is possible to conclude that the prototype developed meets the requirements established, and can serve the needs related to food safety of different establishments taking part in the food supply chain.

Chapter 7

Conclusion

This chapter provides the final conclusions of this dissertation, including main remarks, limitations of the development of the solution and recommended future work.

Temperature control procedures for food safety purposes are an essential factor for the prevention of FBD. These diseases are responsible for significant health and economic impact worldwide and every year cause millions of people to fall ill and hundreds of thousands to die. The majority of FBD are preventable through active supervision along the entire food supply chain. Therefore, food operators have an added responsibility when dealing with food safety. To that end, FSMS, such as HACCP and traceability systems, are in place and prove to be critical.

When properly implemented, FSMS significantly contribute to the improvement of food safety practices, positively impacting public health and establishments economics. However, FSMS are often poorly implemented and far from perfect, and when it happens, instead of contributing to help solve the problem, the contrary occurs.

Foods are sensitive to time and temperature, with temperature being a crucial factor when regarding food safety. Temperature abuse is, therefore, often appointed as the cause of FBDO with origin in the whole food supply chain. Hence the importance of optimizing temperature control and record taking processes is significant.

The feedback from a HACCP consulting company responsible for implementing digital FSMS in more than 400 establishments contributed to identifying and confirming the most significant issues that companies have regarding temperature control procedures. The feedback was useful for understanding temperature control procedures implemented across different types of food-related establishments. It also allowed to reflect on improvements that would benefit the establishment and FBD prevention.

It was found that in many cases the processes conducted to control and record temperature in the different machines and products are manual which makes it more complex, as it involves more tools (paper checklists, PC/phone/tablet for digital support or others) and lacks information (who made the measurement, when and where, or others). They are also susceptible to human errors such as lost, incomplete, or forged records, measurements taken in the wrong item, or forms badly fulfilled.

Thus, this dissertation's goal was to design a handheld thermometer for temperature measurements and record taking that will be used to control temperatures more efficiently and reliably, enabling greater control over the measurements that HACCP and FSMS require. This goal was achieved by developing a solution based on a smart thermometer that integrates new and improved features, such as allowing user authentication, machine and product RFID identification and association with the temperature measurement, presentation of daily tasks, and automatic remote submission to a database.

To develop the solution and before implementing the system, the main features and requirements were defined. These included the essential features, necessary external interfaces, performance, safety and security requirements, and user classes and characteristics. The system architecture was also defined. This allowed further understanding of how the system would interact with the users and other external systems, such as existing HACCP, or traceability systems. It also detailed the necessary supporting services that include a remote database, an admin web application, and an API for the smart thermometer and external systems to consume.

Finally, the system was implemented and tested through a practical experiment and compared with a reference thermometer, proving that it is able be perform its function properly as a normal thermometer while integrating all the features that make it a smart tool.

An additional survey was conducted to four food safety managers that represent different parts of the food supply chain and combined are responsible for more than 700 establishments. The survey allowed to verify that the problems described along this dissertation’s work are, in fact, present in their daily operations. The interest showed in the proposed solution was big, and it further confirmed that food safety managers find value in a smart thermometer that presents to the staff what measurements they shall take during the day identifies who is taking them, when, where, and what should be measured, automatically uploads the measurements to a remote database with all the corresponding information. It was considered that it has great potential to improve food safety operations.

This smart thermometer prototype proves that adding a solution that brings new and improved features to the market can ease temperature control and record taking tasks in a wide range of food establishments. Features such as the automatic submission of results to a database that is easy to access and verify older records are not present in thermometers now available and are of great interest to commercial establishments and the regular consumer, which is increasingly more alert and concerned about food safety issues.

Since the work here presented is a prototype and since the idea has gathered a lot of attention and has been proven that there is a great interest in a solution like the one proposed, future versions of the product shall be considered. Now that the base features and hardware are established it will be easier to further develop the idea.

References

[1] 'WHO | WHO estimates of the global burden of foodborne diseases', *WHO*. http://www.who.int/foodsafety/publications/foodborne_disease/fergreport/en/ (accessed Nov. 16, 2020).

[2] 'The burden of foodborne diseases in the WHO European Region (2017)'. https://www.euro.who.int/en/health-topics/disease-prevention/food-safety/publications/2017/the-burden-of-foodborne-diseases-in-the-who-european-region-2017 (accessed Nov. 16, 2020).

[3] FAO, *The burden of foodborne diseases and the benefits of investing in safe food*. Rome, Italy: FAO, 2018.

[4] CDC, 'Foodborne Illnesses and Germs', *Centers for Disease Control and Prevention*, Mar. 18, 2020. https://www.cdc.gov/foodsafety/foodborne-germs.html (accessed Dec. 17, 2020).

[5] D. Van Cauteren *et al.*, 'Estimated Annual Numbers of Foodborne Pathogen–Associated Illnesses, Hospitalizations, and Deaths, France, 2008–2013', *Emerg. Infect. Dis.*, vol. 23, no. 9, pp. 1486–1492, Sep. 2017, doi: 10.3201/eid2309.170081.

[6] N. Daniel, N. Casadevall, P. Sun, D. Sugden, and V. Aldin, 'The Burden of Foodborne Disease in the UK 2018', p. 95, 2018.

[7] M. K. Thomas *et al.*, 'Estimates of the Burden of Foodborne Illness in Canada for 30 Specified Pathogens and Unspecified Agents, Circa 2006', *Foodborne Pathog. Dis.*, vol. 10, May 2013, doi: 10.1089/fpd.2012.1389.

[8] S. Jaffee, S. Henson, L. Unnevehr, D. Grace, and E. Cassou, 'The Safe Food Imperative: Accelerating Progress in Low-And Middleincome Countries', p. 211.

[9] R. L. Scharff, 'Economic Burden from Health Losses Due to Foodborne Illness in the United States', *J. Food Prot.*, vol. v. 75, no. 1, pp. 123–131, Jan. 2012, doi: 10.4315/0362-028X.JFP-11-058.

[10] C. Frank *et al.*, 'Epidemic Profile of Shiga-Toxin–Producing Escherichia coli O104:H4 Outbreak in Germany', *N. Engl. J. Med.*, vol. 365, no. 19, pp. 1771–1780, Nov. 2011, doi: 10.1056/NEJMoa1106483.

[11] 'Junta de Andalucía - Salud y Familias entrevista al 79,5% de las embarazadas andaluzas en dos semanas para prevenirlas de la listeria', *Junta de Andalucía*. https://www.juntadeandalucia.es/organismos/saludyfamilias/actualidad/noticias/detalle/220344.html (accessed Nov. 26, 2020).

[12] 'WHO congratulates South Africa on the end of the world's largest listeriosis outbreak', *WHO | Regional Office for Africa*. https://www.afro.who.int/news/who-congratulates-south-africa-end-worlds-largest-listeriosis-outbreak (accessed Nov. 26, 2020).

[13] A. H. Havelaar *et al.*, 'World Health Organization Global Estimates and Regional Comparisons of the Burden of Foodborne Disease in 2010', *PLOS Med.*, vol. 12, no. 12, p. e1001923, Dec. 2015, doi: 10.1371/journal.pmed.1001923.

[14] T. F. Jones and J. Yackley, 'Foodborne Disease Outbreaks in the United States: A Historical Overview', *Foodborne Pathog. Dis.*, vol. 15, no. 1, pp. 11–15, Jan. 2018, doi: 10.1089/fpd.2017.2388.

[15] D. Gould *et al.*, 'Foodborne disease outbreaks in Australia, 1995 to 2000', *Commun. Dis. Intell. Q. Rep.*, vol. 28, no. 2, p. 211, 2004.

[16] C. C. Correia, I. C. Cunha, A. Coelho, C. Maia, and C. Pena, '_Food-borne disease outbreaks laboratory investigation: data from 2017', *Bol. Epidemiológico*, vol. 25, no. 1, p. 52, 2019.

[17] L. H. GOULD, I. ROSENBLUM, D. NICHOLAS, Q. PHAN, and T. F. JONES, ‘Contributing Factors in Restaurant-Associated Foodborne Disease Outbreaks, FoodNet Sites, 2006 and 2007’, *J. Food Prot.*, vol. 76, no. 11, pp. 1824–1828, Nov. 2013, doi: 10.4315/0362-028X.JFP-13-037.

[18] F. L. Bryan, J. J. Guzewich, and E. C. D. Todd, ‘Surveillance of Foodborne Disease III. Summary and Presentation of Data on Vehicles and Contributory Factors; Their Value and Limitations’, *J. Food Prot.*, vol. 60, no. 6, pp. 701–714, Jun. 1997, doi: 10.4315/0362-028X-60.6.701.

[19] S. M. Bartsch, L. Asti, S. Nyathi, M. L. Spiker, and B. Y. Lee, ‘Estimated Cost to a Restaurant of a Foodborne Illness Outbreak’, *Public Health Rep.*, vol. 133, no. 3, pp. 274–286, Apr. 2018, doi: 10.1177/0033354917751129.

[20] S. Kovats, S. Edwards, S. Hajat, B. Armstrong, K. Ebi, and B. Menne, ‘The effect of temperature on food poisoning: a time-series analysis of salmonellosis in ten European countries’, *Epidemiol. Infect.*, vol. 132, pp. 443–53, Jul. 2004.

[21] J. Huang, Y. Luo, and X. Nou, ‘Growth of Salmonella enterica and Listeria monocytogenes on Fresh-Cut Cantaloupe under Different Temperature Abuse Scenarios’, *J. Food Prot.*, vol. 78, no. 6, pp. 1125–1131, Jun. 2015, doi: 10.4315/0362-028X.JFP-14-468.

[22] E. Chen, S. Flint, P. Perry, M. Perry, and R. Lau, ‘Implementation of non-regulatory food safety management schemes in New Zealand: A survey of the food and beverage industry’, *Food Control*, vol. 47, pp. 569–576, Jan. 2015, doi: 10.1016/j.foodcont.2014.08.009.

[23] W. Dzwolak, ‘Assessment of HACCP plans in standardized food safety management systems – The case of small-sized Polish food businesses’, *Food Control*, vol. 106, p. 106716, Dec. 2019, doi: 10.1016/j.foodcont.2019.106716.

[24] M. Baş, M. Yüksel, and T. Çavuşoğlu, ‘Difficulties and barriers for the implementing of HACCP and food safety systems in food businesses in Turkey’, *Food Control*, vol. 18, no. 2, pp. 124–130, Feb. 2007, doi: 10.1016/j.foodcont.2005.09.002.

[25] S. S. Khandke and T. Mayes, ‘HACCP implementation: a practical guide to the implementation of the HACCP plan’, *Food Control*, vol. 9, no. 2, pp. 103–109, Apr. 1998, doi: 10.1016/S0956-7135(97)00065-0.

[26] F. Liu, H. Rhim, K. Park, J. Xu, and C. K. Y. Lo, ‘HACCP certification in food industry: Trade-offs in product safety and firm performance’, *Int. J. Prod. Econ.*, vol. 231, p. 107838, Jan. 2021, doi: 10.1016/j.ijpe.2020.107838.

[27] ‘Is HACCP mandatory? | Food Safety Research Information Office| NAL | USDA’. https://www.nal.usda.gov/fsrio/haccp-mandatory (accessed Dec. 08, 2020).

[28] ‘Regulation (EC) No 852/2004 of the european parliament and of the council of 29 April 2004 on the hygiene of foodstuffs’, *https://webarchive.nationalarchives.gov.uk/eu-exit/https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:02004R0852-20090420*. https://www.legislation.gov.uk/eur/2004/852/article/5 (accessed Dec. 08, 2020).

[29] ‘Commission Notice on the implementation of food safety management systems covering prerequisite programs (PRPs) and procedures based on the HACCP principles, including the facilitation/flexibility of the implementation in certain food businesses’, p. 32.

[30] J. Ross-Nazzal, ‘From farm to fork: How space food standards impacted the food industry and changed food safety standards.’, in *Societal impact of spaceflight*, Washinghton, DC: National Aeronautics and Space Administration, Office of ExternalRelations-History Division), 2007.

[31] H. E. Bauman, ‘The origin and concept of HACCP’, in *HACCP in Meat, Poultry, and Fish Processing*, A. M. Pearson and T. R. Dutson, Eds. Boston, MA: Springer US, 1995, pp. 1–7.

[32] C. A. Wallace, W. H. Sperber, and S. E. Mortimore, *Food Safety for the 21st Century: Managing HACCP and Food Safety Throughout the Global Supply Chain*. John Wiley & Sons, 2018.

[33] Codex Alimentarius Commission and Joint FAO WHO Food Standards Programme, Eds., *Food hygiene: basic texts ; Codex Alimentarius*, 4. ed. Rome: FAO [u.a.], 2009.

[34] K. L. Hulebak and W. Schlosser, ‘Hazard Analysis and Critical Control Point (HACCP) History and Conceptual Overview’, *Risk Anal.*, vol. 22, no. 3, pp. 547–552, Jun. 2002, doi: 10.1111/0272-4332.00038.

[35] 'Introduction-to-Codex-HACCP-and-Hazard-Analysis-for-RMP-Resource.pdf'. Accessed: Dec. 10, 2020. [Online]. Available: https://safefoodservices.co.nz/wp-content/uploads/2020/05/Introduction-to-Codex-HACCP-and-Hazard-Analysis-for-RMP-Resource.pdf.

[36] S. Mortimore and C. Wallace, *HACCP: A Practical Approach*. Springer Science & Business Media, 2013.

[37] P. M, F. Ag, P. N, and L. I, 'Implementation of the Hazard Analysis Critical Control Point (HACCP) System to a Dairy Industry: Evaluation of Benefits and Barriers', *J. Food Nutr. Diet.*, vol. 01, no. 01, Jan. 2016, doi: 10.19104/jfnd.2015.102.

[38] A. D. Karaman, F. Cobanoglu, R. Tunalioglu, and G. Ova, 'Barriers and benefits of the implementation of food safety management systems among the Turkish dairy industry: A case study', *Food Control*, vol. 25, no. 2, pp. 732–739, Jun. 2012, doi: 10.1016/j.foodcont.2011.11.041.

[39] E. S. Maldonado *et al.*, 'Cost–benefit analysis of HACCP implementation in the Mexican meat industry', *Food Control*, vol. 16, no. 4, pp. 375–381, Apr. 2005, doi: 10.1016/j.foodcont.2004.03.017.

[40] C. A. Wallace and S. E. Mortimore, 'Chapter 3 - HACCP', in *Handbook of Hygiene Control in the Food Industry (Second Edition)*, H. Lelieveld, J. Holah, and D. Gabrić, Eds. San Diego: Woodhead Publishing, 2016, pp. 25–42.

[41] V. Caporale, A. Giovannini, C. Di Francesco, and P. Calistri, 'Importance of the traceability of animals and animal products in epidemiology', *Rev. Sci. Tech. Int. Off. Epizoot.*, vol. 20, pp. 372–8, Sep. 2001, doi: 10.20506/rst.20.2.1279.

[42] 'ISO 22005:2007(en), Traceability in the feed and food chain — General principles and basic requirements for system design and implementation'. https://www.iso.org/obp/ui/#iso:std:iso:22005:ed-1:v1:en:biblref:3 (accessed Dec. 14, 2020).

[43] M. M. Aung and Y. S. Chang, 'Traceability in a food supply chain: Safety and quality perspectives', *Food Control*, vol. 39, pp. 172–184, May 2014, doi: 10.1016/j.foodcont.2013.11.007.

[44] T. Moe, 'Perspectives on traceability in food manufacture', *Trends Food Sci. Technol.*, vol. 9, no. 5, pp. 211–214, May 1998, doi: 10.1016/S0924-2244(98)00037-5.

[45] P. Olsen and M. Borit, 'The components of a food traceability system', *Trends Food Sci. Technol.*, vol. 77, pp. 143–149, Jul. 2018, doi: 10.1016/j.tifs.2018.05.004.

[46] M. Fritz and G. Schiefer, 'Tracking, tracing, and business process interests in food commodities: A multi-level decision complexity', *Int. J. Prod. Econ.*, vol. 117, no. 2, pp. 317–329, Feb. 2009, doi: 10.1016/j.ijpe.2008.10.015.

[47] A. J. M. Beulens, D.-F. Broens, P. Folstar, and G. J. Hofstede, 'Food safety and transparency in food chains and networks Relationships and challenges', *Food Control*, vol. 16, no. 6, pp. 481–486, Jul. 2005, doi: 10.1016/j.foodcont.2003.10.010.

[48] European Commission and Directorate-General for Health and Consumer Protection, *Food traceability*. 2007.

[49] J. A. Alfaro and L. A. Rábade, 'Traceability as a strategic tool to improve inventory management: A case study in the food industry', *Int. J. Prod. Econ.*, vol. 118, no. 1, pp. 104–110, Mar. 2009, doi: 10.1016/j.ijpe.2008.08.030.

[50] A. Regattieri, M. Gamberi, and R. Manzini, 'Traceability of food products: General framework and experimental evidence', *J. Food Eng.*, vol. 81, no. 2, pp. 347–356, Jul. 2007, doi: 10.1016/j.jfoodeng.2006.10.032.

[51] J. Qian *et al.*, 'Food traceability system from governmental, corporate, and consumer perspectives in the European Union and China: A comparative review', *Trends Food Sci. Technol.*, vol. 99, pp. 402–412, May 2020, doi: 10.1016/j.tifs.2020.03.025.

[52] 'E. coli'. https://www.who.int/news-room/fact-sheets/detail/e-coli (accessed Dec. 16, 2020).

[53] 'Listeria', *European Food Safety Authority*. https://www.efsa.europa.eu/en/topics/topic/listeria (accessed Dec. 16, 2020).

[54] CDC, 'Clostridium Perfringens Food Poisoning', *Centers for Disease Control and Prevention*, Oct. 02, 2018. https://www.cdc.gov/foodsafety/diseases/clostridium-perfringens.html (accessed Dec.

16, 2020).

[55] CDC, ‘CDC VitalSigns - Preventing Norovirus Outbreaks’, *Centers for Disease Control and Prevention*, Dec. 23, 2019. https://www.cdc.gov/vitalsigns/norovirus/index.html (accessed Dec. 16, 2020).

[56] C. Walsh and M. Leva, ‘A review of human factors and food safety in Ireland’, *Saf. Sci.*, vol. 119, Aug. 2018, doi: 10.1016/j.ssci.2018.07.022.

[57] J. M. Soriano, H. Rico, J. C. Moltó, and J. Mañes, ‘Effect of introduction of HACCP on the microbiological quality of some restaurant meals’, *Food Control*, vol. 13, no. 4, pp. 253–261, Jun. 2002, doi: 10.1016/S0956-7135(02)00023-3.

[58] N. Ndraha, H.-I. Hsiao, J. Vlajic, M.-F. Yang, and H.-T. V. Lin, ‘Time-temperature abuse in the food cold chain: Review of issues, challenges, and recommendations’, *Food Control*, vol. 89, pp. 12–21, Jul. 2018, doi: 10.1016/j.foodcont.2018.01.027.

[59] Y. Motarjemi and F. Käferstein, ‘Food safety, Hazard Analysis and Critical Control Point and the increase in foodborne diseases: a paradox?’, *Food Control*, vol. 10, no. 4–5, pp. 325–333, Aug. 1999, doi: 10.1016/S0956-7135(99)00008-0.

[60] Y. Bouzembrak, M. Klüche, A. Gavai, and H. J. P. Marvin, ‘Internet of Things in food safety: Literature review and a bibliometric analysis’, *Trends Food Sci. Technol.*, vol. 94, pp. 54–64, Dec. 2019, doi: 10.1016/j.tifs.2019.11.002.

[61] A. E. V. Magalhães, A. H. G. Rossi, I. C. Zattar, M. A. M. Marques, and R. Seleme, ‘Food traceability technologies and foodborne outbreak occurrences’, *Br. Food J.*, vol. 121, no. 12, pp. 3362–3379, Jan. 2019, doi: 10.1108/BFJ-02-2019-0143.

[62] *Thermometer Use in Retail Foodservice Establishments -- What Managers Need to Know*. .

[63] L. G. Brown *et al.*, ‘Restaurant Food Cooling Practices†’, *J. Food Prot.*, vol. 75, no. 12, pp. 2172–2178, Dec. 2012, doi: 10.4315/0362-028X.JFP-12-256.

[64] R. Badia-Melis, L. Ruiz-Garcia, J. Hierro, and J. Villalba, ‘Refrigerated Fruit Storage Monitoring Combining Two Different Wireless Sensing Technologies: RFID and WSN’, *Sensors*, vol. 15, pp. 4781–4795, Mar. 2015, doi: 10.3390/s150304781.

[65] M. M. Aung and Y. S. Chang, ‘Temperature management for the quality assurance of a perishable food supply chain’, *Food Control*, vol. 40, pp. 198–207, Jun. 2014, doi: 10.1016/j.foodcont.2013.11.016.

[66] T. A. McMeekin *et al.*, ‘Information systems in food safety management’, *Int. J. Food Microbiol.*, vol. 112, no. 3, pp. 181–194, Dec. 2006, doi: 10.1016/j.ijfoodmicro.2006.04.048.

[67] A. Pal and K. Kant, ‘Using Blockchain for Provenance and Traceability in Internet of Things-Integrated Food Logistics’, *Computer*, vol. 52, no. 12, pp. 94–98, Dec. 2019, doi: 10.1109/MC.2019.2942111.

[68] H. King, ‘Digital Technology to Enable Food Safety Management Systems’, 2020, pp. 121–137.

[69] X. Xiao, Q. He, Z. Fu, M. Xu, and X. Zhang, ‘Applying CS and WSN methods for improving efficiency of frozen and chilled aquatic products monitoring system in cold chain logistics’, *Food Control*, vol. 60, pp. 656–666, Feb. 2016, doi: 10.1016/j.foodcont.2015.09.012.

[70] K. Ashton, ‘That “Internet of Things” Thing’, p. 1.

[71] ‘Gartner Says 5.8 Billion Enterprise and Automotive IoT Endpoints Will Be in Use in 2020’, *Gartner*. https://www.gartner.com/en/newsroom/press-releases/2019-08-29-gartner-says-5-8-billion-enterprise-and-automotive-io (accessed Dec. 14, 2020).

[72] ‘Internet of Things Global Standards Initiative’. https://www.itu.int/en/ITU-T/gsi/iot/Pages/default.aspx (accessed Dec. 14, 2020).

[73] D. D. Guinard and V. M. Trifa, *Building the web of things: with examples in Node.js and Raspberry Pi*. Shelter Island, NY: Manning, 2016.

[74] F. A. Alaba, M. Othman, I. A. T. Hashem, and F. Alotaibi, ‘Internet of Things security: A survey’, *J. Netw. Comput. Appl.*, vol. 88, pp. 10–28, Jun. 2017, doi: 10.1016/j.jnca.2017.04.002.

[75] Lu Tan and Neng Wang, ‘Future internet: The Internet of Things’, in *2010 3rd International Conference on Advanced Computer Theory and Engineering(ICACTE)*, Aug. 2010, vol. 5, pp. V5-376-V5-380, doi: 10.1109/ICACTE.2010.5579543.

[76] K. Finkenzeller, *RFID Handbook: Fundamentals and Applications in Contactless Smart Cards, Radio Frequency Identification and Near-Field Communication*. John Wiley & Sons, 2010.

[77] J. Su, Z. Sheng, V. C. M. Leung, and Y. Chen, ‘Energy Efficient Tag Identification Algorithms For RFID: Survey, Motivation And New Design’, *IEEE Wirel. Commun.*, vol. 26, no. 3, pp. 118–124, Jun. 2019, doi: 10.1109/MWC.2019.1800249.

[78] M. Doinea, C. Boja, L. Batagan, C. Toma, and P. Marius, ‘Internet of Things Based Systems for Food Safety Management’, *Inform. Econ.*, vol. 19, pp. 87–97, Mar. 2015, doi: 10.12948/issn14531305/19.1.2015.08.

[79] Y. Gu, W. Han, L. Zheng, and B. Jin, ‘Using IoT Technologies to Resolve the Food Safety Problem – An Analysis Based on Chinese Food Standards’, Oct. 2012, pp. 380–392, doi: 10.1007/978-3-642-33469-6_50.

[80] ‘IEEE Guide for Software Requirements Specifications’, *IEEE Std 830-1984*, pp. 1–26, Feb. 1984, doi: 10.1109/IEEESTD.1984.119205.

[81] ‘M5Stack - Modular Rapid ESP32 IoT Development Board - ESP32 dev kits’, *m5stack-store*. https://m5stack.com/ (accessed Dec. 27, 2020).

[82] ‘ESP32 Wi-Fi & Bluetooth MCU I Espressif Systems’. https://www.espressif.com/en/products/socs/esp32 (accessed Dec. 27, 2020).

[83] ‘Thermocouple types’, *https://www.omega.com/en-us/*. https://www.omega.com/en-us/resources/thermocouple-types (accessed Dec. 26, 2020).

[84] ‘RS PRO Type K Thermocouple 150mm Length, 1.5mm Diameter → +1100°C | RS Components’. https://uk.rs-online.com/web/p/thermocouples/3971450/ (accessed Dec. 28, 2020).

[85] ‘MAX31856.pdf’. Accessed: Dec. 27, 2020. [Online]. Available: https://datasheets.maximintegrated.com/en/ds/MAX31856.pdf.

[86] ‘Digital plug & play infrared thermometer in a TO-can’, *Melexis*. https://www.melexis.com/en/product/MLX90614/Digital-Plug-Play-Infrared-Thermometer-TO-Can (accessed Dec. 27, 2020).

[87] L. LLC, ‘LVGL - Light and Versatile Embedded Graphics Library’, *LVGL*. https://lvgl.io/ (accessed Dec. 30, 2020).

[88] ‘ThermaQ Blue Dual Channel Thermocouple|ThermoWorks’. https://www.thermoworks.com/ThermaQ-Blue (accessed Dec. 29, 2020).

[89] ‘Creating a Properly Made Icebath’. https://www.thermoworks.com/thermapen101_creating_an_icebath (accessed Dec. 31, 2020).

[90] ‘Professional Thermometers from the Temperature Experts | ThermoWorks’. https://www.thermoworks.com/ (accessed Dec. 29, 2020).

[91] ‘Instrumentos Testo S.A. | Soluções e instrumentos de medição’. https://www.testo.com/pt-PT/ (accessed Dec. 29, 2020).

Annex A

Flowcharts of Implemented Features

This Annex presents the flowchart describing the system's implemented features discussed in section 5.2.1.

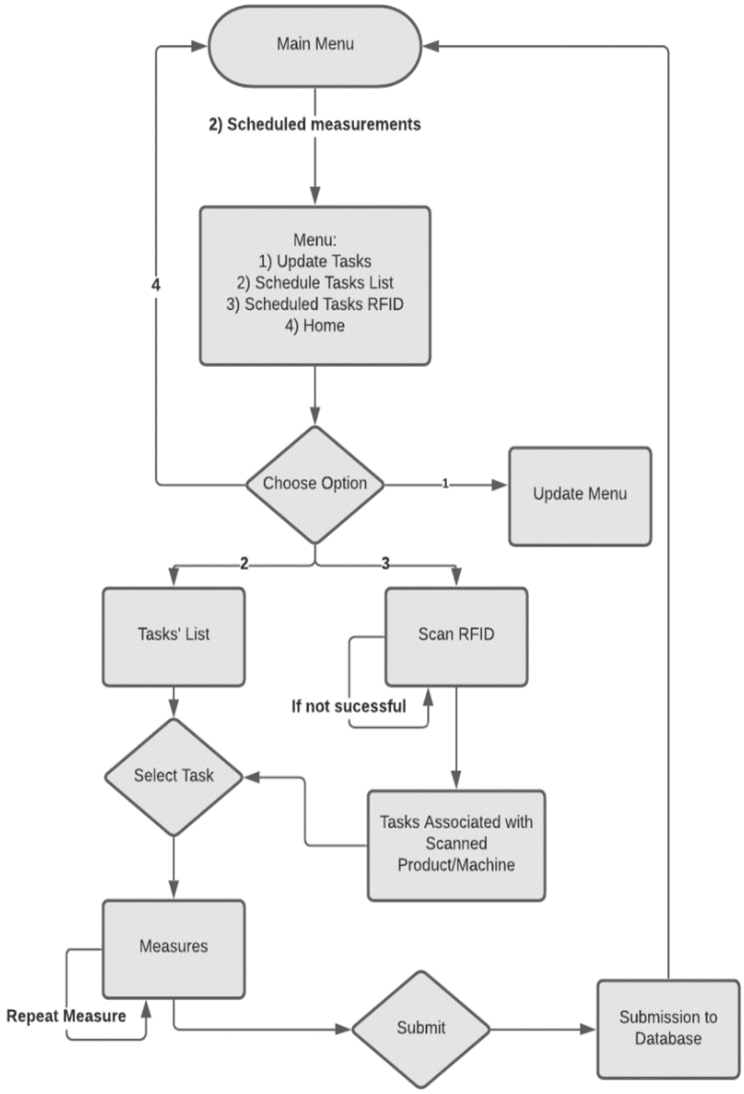

Figure A.1 - Scheduled measurements flowchart

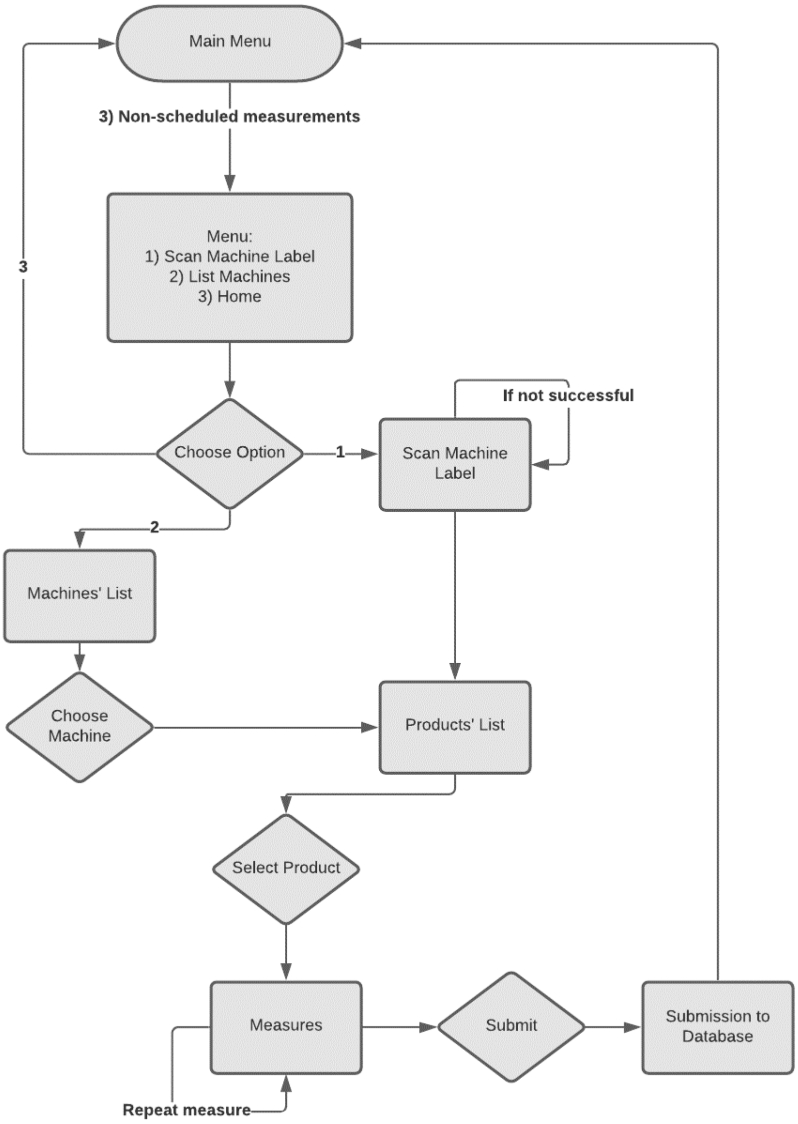

Figure A.8 - Non-scheduled measurements flowchart

Figure A.9 - Normal measurements flowchartFigure A.10 - Non-

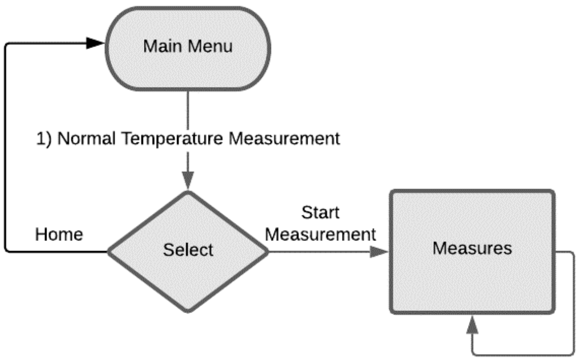

Figure A.11 - Normal measurements flowchart

ıts

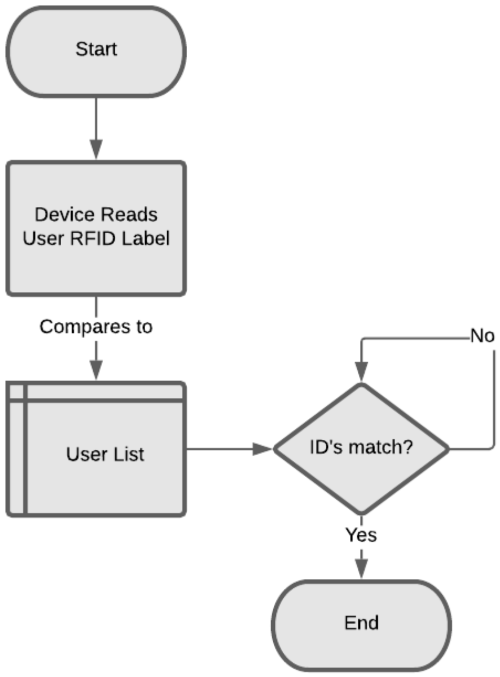

Figure A.14 – Authentication Mechanism flowchart

Figure A.15Figure A.16 – Authentication Mechanism flowchart

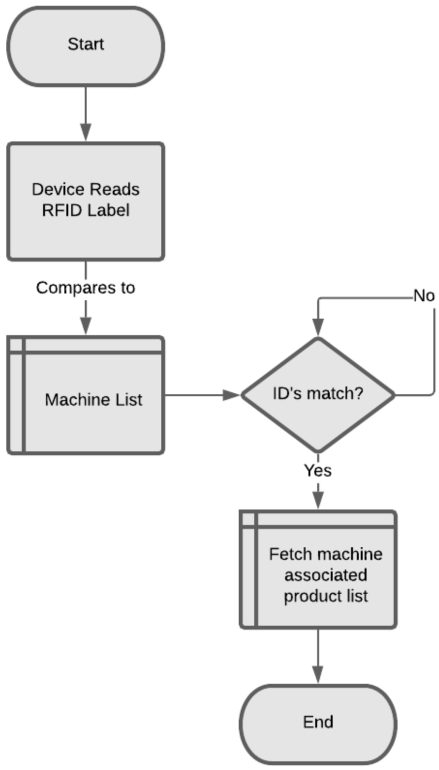

Figure A.17 – Machine identification for non-scheduled measurements flowchart

Figure A.18Figure A.19 – Machine identification for non-scheduled measurements flowchart

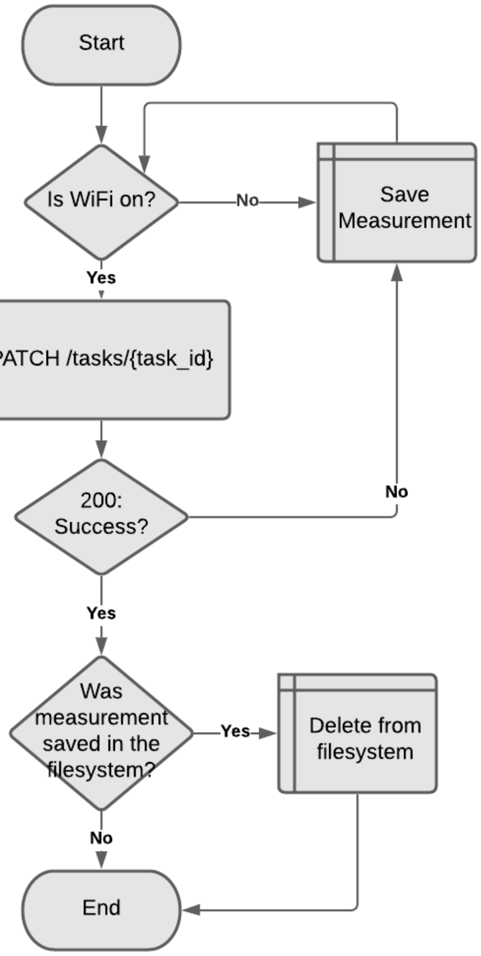

Figure A.20 – Scheduled Measurement (task) Submission process flowchart

Figure A.21Figure A.22 – Scheduled Measurement (task) Submission process flowchart

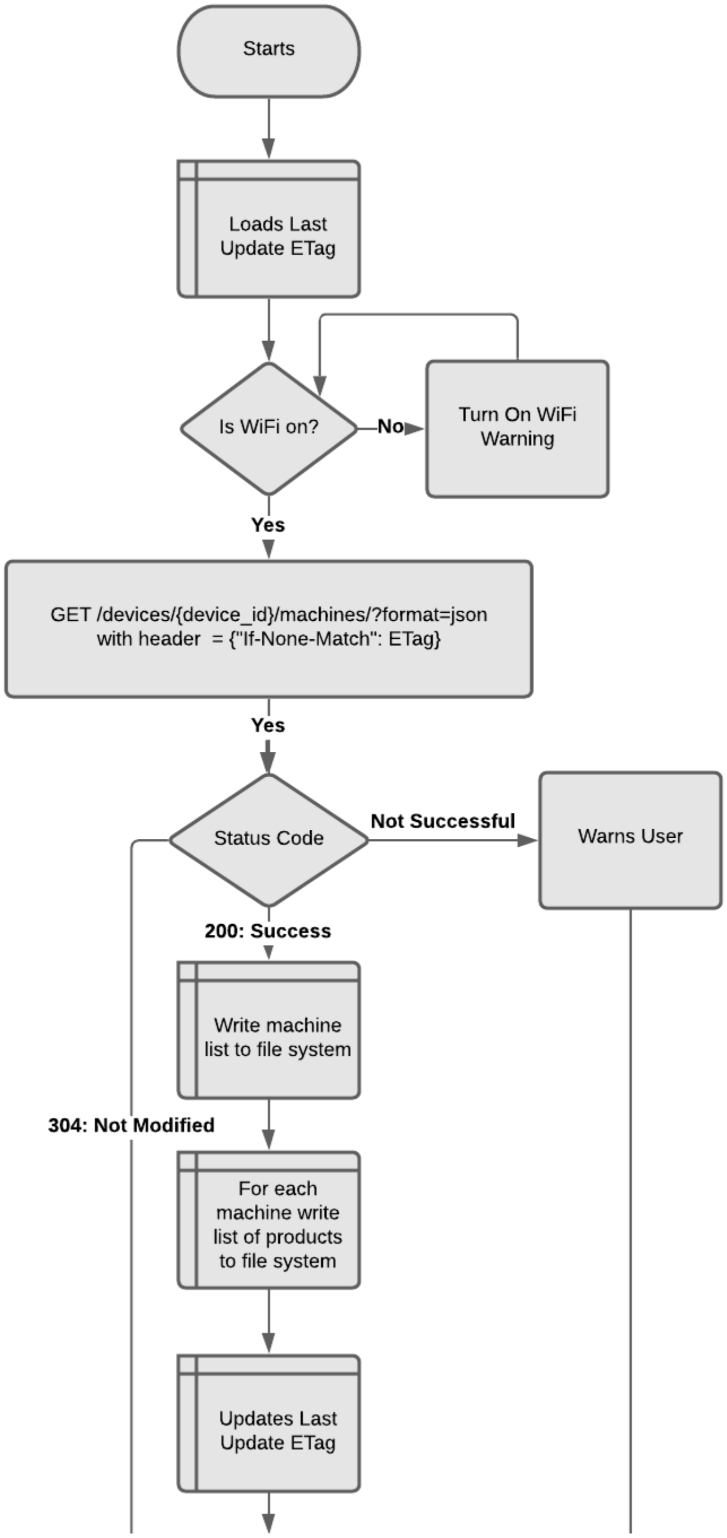

Figure A.23 – Update smart thermometer machine and products lists

Figure A.24Figure A.25 – Update smart thermometer machine and products lists

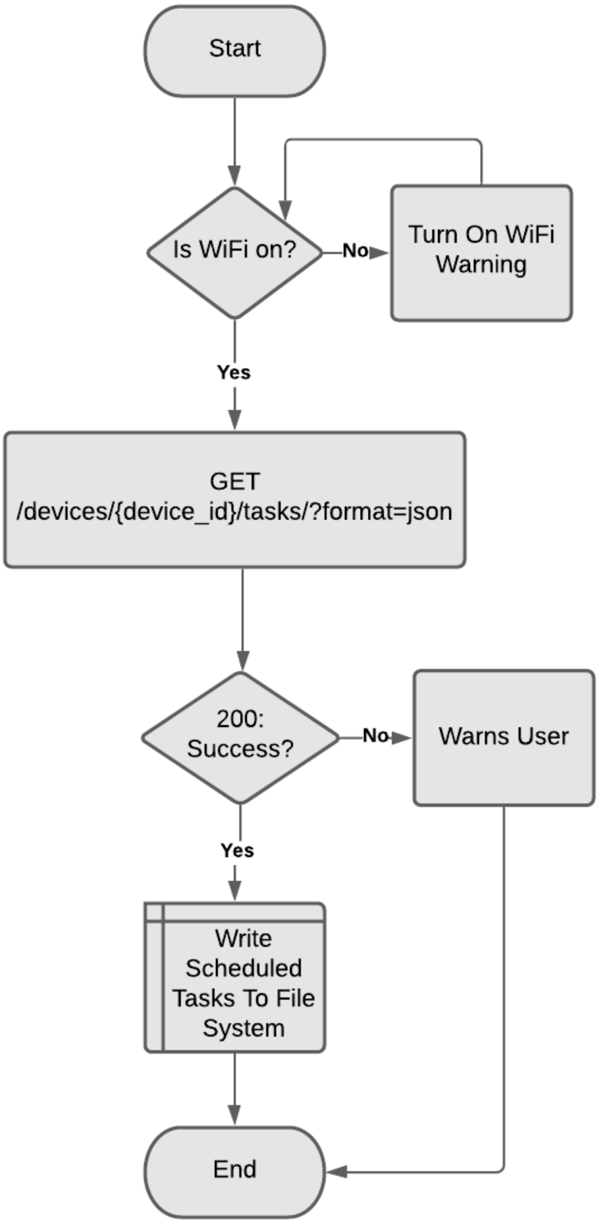

Figure A.26- Update scheduled measurements/tasks process flowchart

Figure A.27- Update scheduled measurements/tasks process flowchart

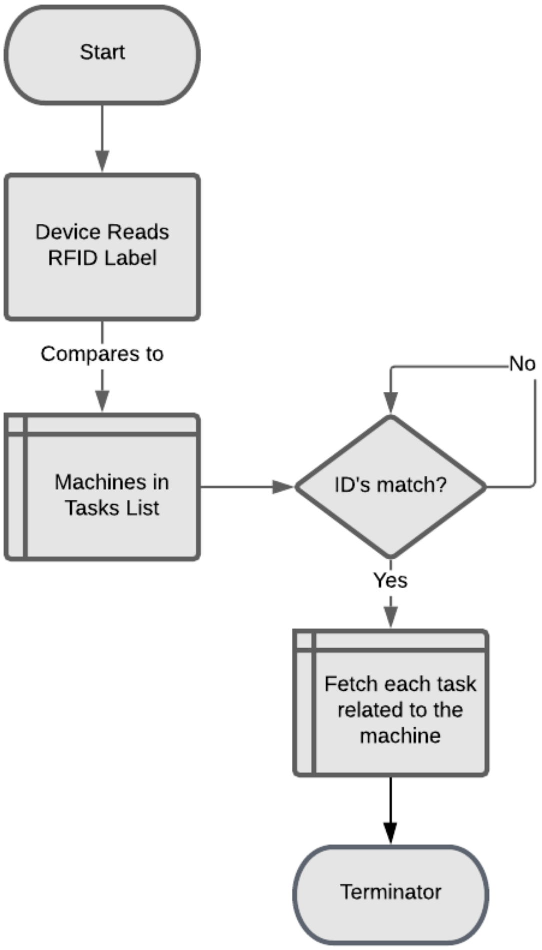

Figure A.9- Update scheduled measurements/tasks process flowchart

Figure B. 1Figure A.9- Update scheduled measurements/tasks process flowchart

Annex B

Surveys

This Annex presents the questionnaire from the surveys conducted and the analysis that complement the analysis.

Na sua opinião, quão importante é o **controlo** de temperatura de:

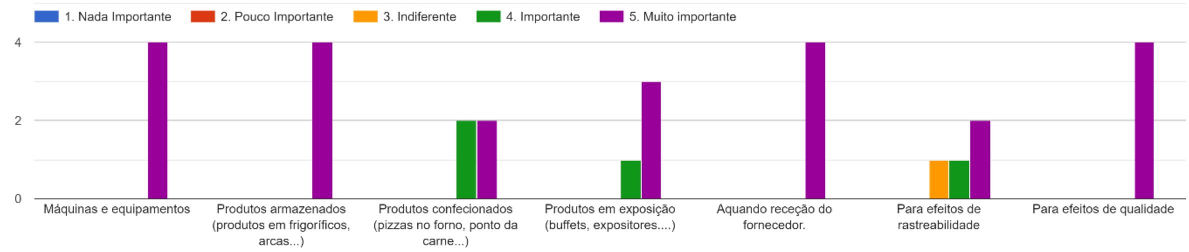

Figure B. 1 – Analysis of the importance of temperature control

Na sua opinião, quão importante é o **registo** de temperatura de:

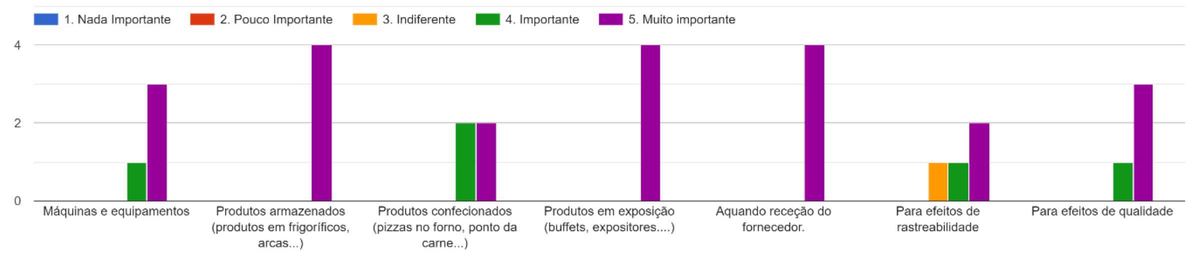

Figure B. 2 - Answers related to the importance of temperature control records

Que controlo (e registo) de temperaturas é feito atualmente? Selecione todas as opções que se aplicam.

4 respostas

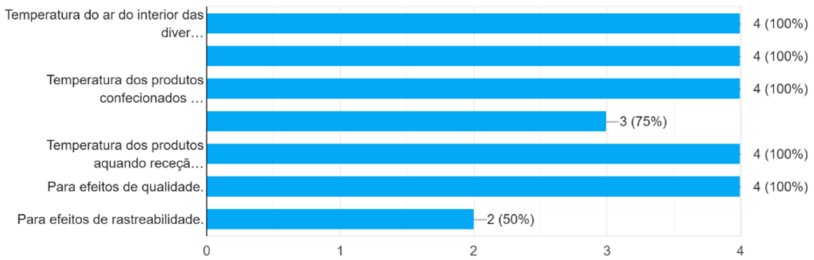

Figure B. 2 - Answers related to current temperature control measurements

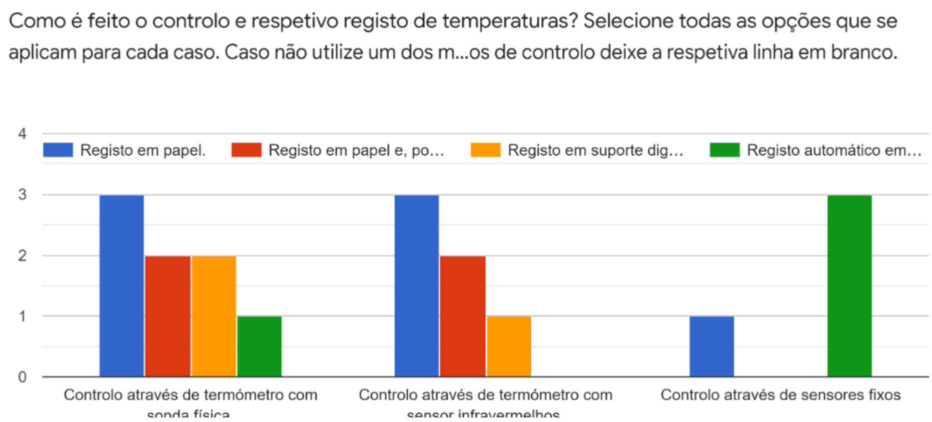

Figure B. 4 - Answers related to the current temperature record taking methods

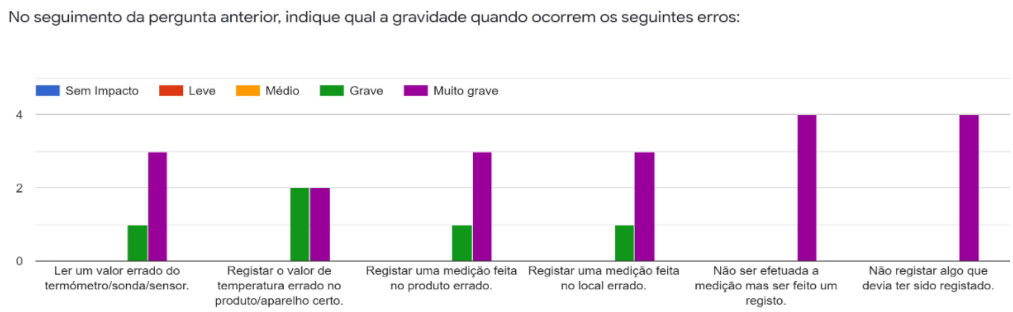

Figure B. 5 - Answers related to the impact of different possible mistakes

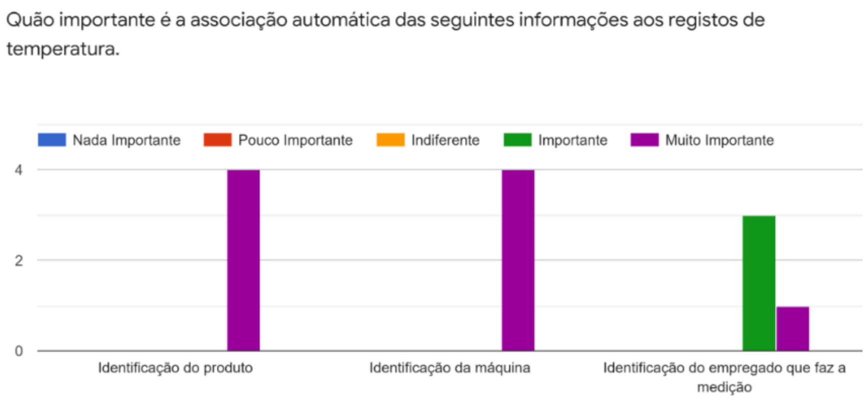

Figure B.6 - Answers related to the importance of the information associated with each record