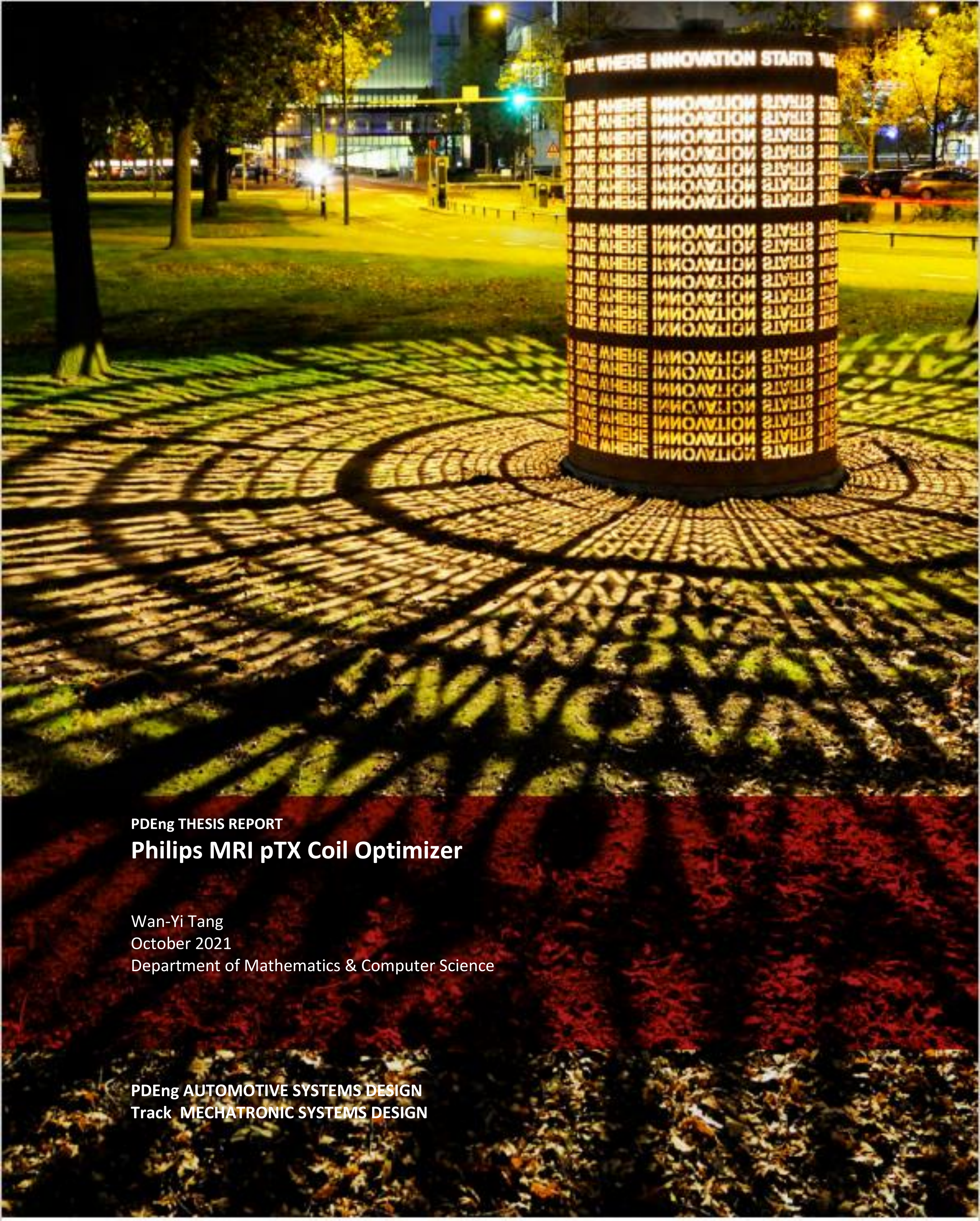
Philips MRI pTX Coil Optimizer



PDEng THESIS REPORT

Philips MRI pTX Coil Optimizer

Wan-Yi Tang
October 2021
Department of Mathematics & Computer Science

PDEng AUTOMOTIVE SYSTEMS DESIGN
Track MECHATRONIC SYSTEMS DESIGN

TU/e EINDHOVEN UNIVERSITY OF TECHNOLOGY

Philips MRI pTX Coil Optimizer

Wan-Yi Tang

October 2021

Eindhoven University of Technology
Stan Ackermans Institiute - Mechatronic Systems Design

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The design that is described in this report has been carried out in accordance with the rules of the TU/e Code of Scientific Conduct.

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Abstract	Currently, one of the research directions of magnetic resonance imaging (MRI) is to realize the safe-guaranteed high-performance ultra-high field (UHF) MRI scanner. To achieve the goal, parallel transmit coils (pTX Coil) plays an important role in overcoming the intrinsic radio frequency (RF) field inhomogeneity of the UHF MRI scanner. However, since the development process of the pTX Coil involves multiple sequential stages, and in each stage, the developers manually apply complex models and algorithms to process the data, the process is time-consuming and with limited solution space. To improve the pTX Coil development process and further improve the performance of the pTX Coil, we present the pTX Coil Optimizer. The pTX Coil Optimizer enables the developers to interact across different networks and provide functionalities to automate parts of the development process. The pTX Coil Optimizer was implemented based on the Arrowhead Framework, which is an Internet of things (IoT) framework provided by the Arrowhead Tools project. By applying the Arrowhead Framework, the pTX Coil Optimizer becomes a system of systems (SoS) realizing the concept of IoT with the following three features: interoperability, integrability, and independence. In the evaluation session, a usability study was conducted with the pTX Coil developer, the result showed that the pTX Coil Optimizer significantly improves the efficiency of the development process of the pTX Coil.

Keywords	MRI, pTX Coil, Arrowhead Framework, SoS

Foreword

Magnetic resonance imaging (MRI) scanners are getting more and more mature and applied for a diversity of clinical examinations. One of the most prominent parts of MRI systems, apart from the magnet, is the radio frequency (RF) transmit and receive system. For RF transmit systems the R&D challenge is to find the optimal configurations and control for RF transmit coils for the variety of systems and clinical applications, to achieve the best image quality, in combination with guaranteed patient safety.

In MRI the RF frequency is proportional to the magnetic field strength, so the RF energy increases and the wavelength decreases if the magnetic field is increased. Especially for higher magnetic fields, like 7 Tesla, sophisticated modeling is required to make sure that human tissue is not heated too much, and yet the RF field in the body is as large and homogeneous as possible, needed for optimal image quality. Currently, the successive steps, needed for this modeling, require time-consuming manual work for various engineers.

A tool would therefore be very helpful, if it optimizes the workflow, facilitates the exchange of data and information from various modeling tools, and automatically generates overviews with the resulting system settings.

Wan-Yi Tang successfully created a prototype of this tool, making use of the Arrowhead Toolkit, which significantly can reduce development time and increase the reliability of the results.

At the Philips MR R&D department, we are proud of the work that has been achieved and I want to take this opportunity to express our sincere thanks to Wan-Yi Tang and mentors at TU/e for this achievement.

Kind Regards,

Peter van der Meulen
Principal System Architect at Philips MR R&D

Preface

As one of the deliverables of the project, the report is formulated to explain the work that has been done during the project. The objective of the project is to improve the development process and performance of the parallel transmit coils (pTX Coil), an essential component of the Philips magnetic resonance imaging (MRI) scanner. As the project is also one of the use cases of the Arrowhead Tools project, the project also serves as an industrial demonstration of applying the Arrowhead Framework.

The project was carried out by Wan-Yi Tang as his graduation project of the Professional Doctorate in Engineering (PDEng) program in Mechatronic Systems Design (MSD). The project was carried out within Philips.

The target audience of this document is people with a technical background and interest in the pTX Coil Optimizer. Chapter 1 and 7 are recommended for the ones without technical background and would like to know the concept of the pTX Coil Optimizer and the project context. Chapters 2 to 5 are suitable for the readers who are interested in the process of defining the requirements and the architecture. Besides the architecture, Chapter 5 is also providing design and implementation detail of the pTX Coil Optimizer.

Eindhoven, September 27, 2021
Wan-Yi Tang

Acknowledgements

At the end of this project, I would like to convey my gratitude toward the people who supported and guided me in various ways during the project period.

Firstly, I would like to thank my project mentor Peter van der Meulen. The feedback and comments you provided in our weekly progress meetings were valuable. Moreover, you were supportive when I needed extra inputs, e.g., the algorithm for the simulation result analysis tool. The project would not have been possible without your guidance and support. To the project leader Frans Rosbak, I still remember at the beginning of the project, you spent your precious time to know me in person, which made me feel heartwarming. Furthermore, thank you for answering my various questions regarding the Arrowhead Tools project. To the project co-leader Jurgen Mollink, I still remember your kind welcome at the start of the project. Another incident that I will not forget is the time you spent on providing me suggestion regarding future career.

I would like to thank my TU/e supervisor Önder Babur, thank you for the valuable inputs that inspired me to dig deeper and broader toward the problems. Moreover, thank you so much for multiple times that you actively asked if I needed any help. To my TU/e colleague Mahdi Saeedi Nikoo, I would thank him for providing me with technical support in the scope of applying Arrowhead Framework.

I would like to thank my fellow PDEng trainees, the two years have been a great journey that I will not forget. Special thanks to Riske Meijer, Peter Heuberger, and Ellen van Hoof. Not only for arranging and organizing all the PDEng program-related issues, but also the guidance and support during the two years.

A word of appreciation goes to the external Thesis Evaluation Committee members Mark van den Brand and Alexander Raaijmakers. Thank you for spending time to read my thesis and grade my work.

Finally, I would like to thank my family and friends, especially my dear friend Hsiang-Wei Sung, for supporting and encouraging me throughout the project.

Eindhoven, September 27, 2021
Wan-Yi Tang

Executive Summary

As a leading health technology company, Philips is also one of the major suppliers of magnetic resonance imaging (MRI) scanners. MRI plays an important role in diagnosing by providing diagnostic images of the patient to doctors and radiologists. To further improve the performance of MRI, one of the directions is to apply a higher magnetic field, which may lead to higher spatial resolution and shorter scan time. Besides the benefits, several challenges also arise when applying a higher magnetic field. In the context of the corresponding radio frequency (RF) field applied, two challenges are related to this project: intrinsic RF field inhomogeneity and heating.

To deal with the inhomogeneity issue, the parallel transmit coils (pTX Coil) is applied. With an appropriate control setting, the synthesized RF field from the individually controlled antennas of the pTX Coil can be homogeneous on the human body. However, deriving the control setting is a challenging process. With multiple sequential development stages that require the developers to manually apply complex models and algorithms to process the data, the development process of the pTX Coil is time-consuming and with limited solution space. To improve the efficiency of the development process of the pTX Coil and to further improve the performance of the pTX Coil, the idea of the pTX Coil Optimizer was proposed.

The pTX Coil Optimizer aims to improve the development process and performance of the pTX Coil by integrating the various development stages and automating parts of the development process. To realize the pTX Coil Optimizer, the development process according to V-Model was followed. The Arrowhead Framework provided by the Arrowhead Tools project was applied. The Arrowhead Framework is an Internet of things (IoT) framework and enables the pTX Coil Optimizer to integrate the development stages by considering the various stages as different local clouds.

The implemented pTX Coil Optimizer provides the two main functionalities:

- Enable the file transfer between users across different local networks in a secured protocol.
- Automatically extract information from the simulation result raw data.

In the evaluation session, the pTX Coil Optimizer was tested by the pTX Coil developer, and a usability study was conducted by asking the developer to fill in a questionnaire and be interviewed. The result shows that the goal of improving the efficiency of the development process has been successfully achieved.

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1 Introduction

In this chapter, we start the introduction by providing the context of the project in Section 1.1, where we describe that the project is in the scope of Philips and also one of the use cases of the Arrowhead Tools project (AHT project). Then, in Section 1.2, with the basic understanding of the challenges faced by magnetic resonance imaging, we bring up the idea of the pTX Coil Optimizer. Next, in Section 1.3, we define the scope and the goal of the project. After that, we describe the project organization in Section 1.4. Finally, in Section 1.5, we provide the outline of the report.

1.1 Project context

1.1.1 Philips

As a leading health technology company, the goal of Philips [1] is to improve the lives of 2.5 billion people, including 400 million in underserved communities, by 2030. With the belief that innovation can improve people's health and healthcare outcomes, also based on the deep clinical and technological insights, Philips now focuses on three main domains. To align with the three domains, Philips is organized into three segments [2]: Personal Health, Diagnosis & Treatment, and Connected Care.

Being one of the main focuses of Philips Diagnosis & Treatment segment, precision diagnosis, the accurate and timely explanation of the patient's health problem [3], is crucial in the scope of healthcare as it leads to sustainable, precise, and personalized therapies with predictable outcomes [4]. To achieve a precision diagnosis, diagnostic imaging plays an important role since the images of a patient help the doctors and radiologists to determine the patient's condition [5]. In the field of diagnostic imaging, one major product line of the Philips Diagnosis & Treatment segment is the magnetic resonance imaging (MRI) scanner [6].

1.1.1.1 Magnetic resonance imaging

The MRI is a type of scan that can produce detailed images of the inside of the human body at any body part from various imaging directions. The MRI plays an important role in diagnosing as the produced images are good in soft-tissue contrast and can differentiate between fat, water, muscle, and other soft tissue [7].

During the MRI scanning, the MRI scanner applies both magnetic field and radio frequency (RF) field to the patient, the process of MRI is briefly described in three steps as listed below:

1. Magnetize the protons of the human body with the magnetic field, which sets the spin direction of the protons to be parallel with the direction of the magnetic field.
2. Apply RF field to excite the protons and make the spin of the proton resonate. That is to say, the protons' spin directions are the same and in phase with each other.
3. Stop the RF field, the protons return to the state which is the same as in step 1. The time needed to get to the state (relaxation time) varies in different tissues. By observing the relaxation time, the scanner can differentiate the different tissues.

Currently, most of the MRI scanners that have been installed worldwide are using 1.5 Tesla or 3 Tesla magnetic field strength [8]. However, as there are several significant advantages of applying higher magnetic field strength, such as higher spatial resolution and shorter scan time [8, 9, 10], the number of 7 Tesla MRI scanners, also known as the ultra-high field (UHF) systems, has rapidly increased.

Despite the rapid growth of installation, there are still several challenges needed to be fixed to realize the full potential of the UHF systems. In the scope of this project, we focused on two challenges. The two challenges are relevant to the fact that the speed and quality of MRI scan is highly dependent on high and homogeneous ${B_1}^+$ component of the RF field in the region of interest, the challenges are:

- **Intrinsic RF field inhomogeneity**: For the UHF systems, an RF field with a higher frequency (300 MHz) is applied. The wavelength is much shorter than the dimension of the body parts, which results in inhomogeneous RF fields applied on the body parts.
- **Heating**: The high-frequency RF field leads to heating of the human body. In the situation that the applied power is large, the heating may harm the patient. This issue is translated into the specific absorption rate (SAR) in the tissue.

1.1.1.2 Parallel transmit coils

To deal with the intrinsic RF field inhomogeneity, the parallel transmit coils (pTX Coil) plays an essential role. Unlike the traditional RF coil that is composed of only one antenna, the pTX Coil is composed of an array of antennas. There are various models of pTX Coil for applying on different human bodies and anatomies. In the scope of this project, as Figure 1 shows, the pTX Coil is composed of eight individual antennas connecting to separated RF waveform controllers and RF amplifiers. Since the eight antennas of the pTX Coil are individually controlled, by tunning the phase and amplitude of the RF field produced by each antenna, the synthesized RF field in the region of interest can be high and homogeneous.

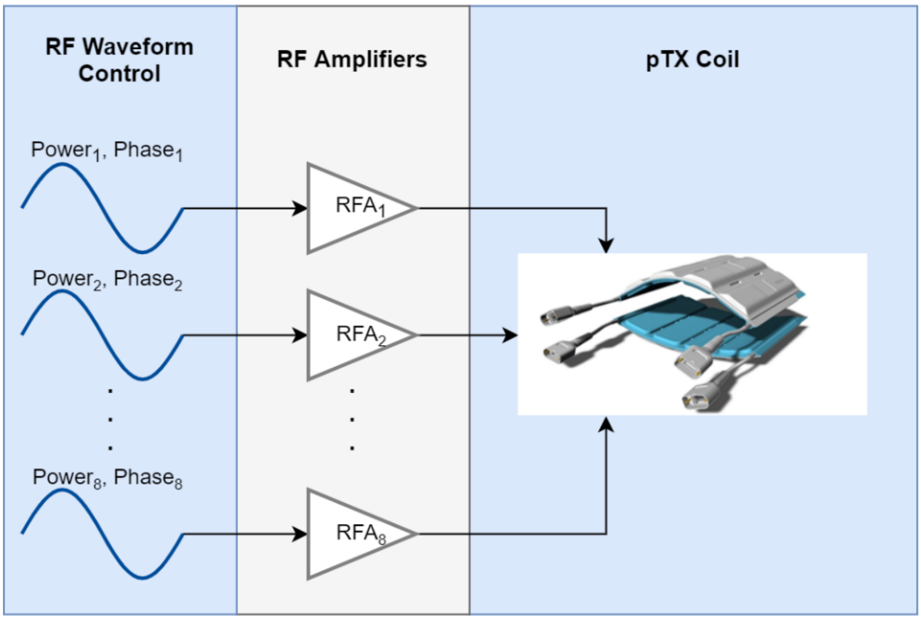

Figure 1 - pTX Coil control diagram

However, since the synthesizing result of the RF field is dependent on the patient size, anatomy, and region of interest, applying the pTX Coil gives rise to new challenges in determining the safe-guaranteed and high-performance control setting. In the following paragraph, we describe more specifically what the challenges are by showing the pTX Coil development process.

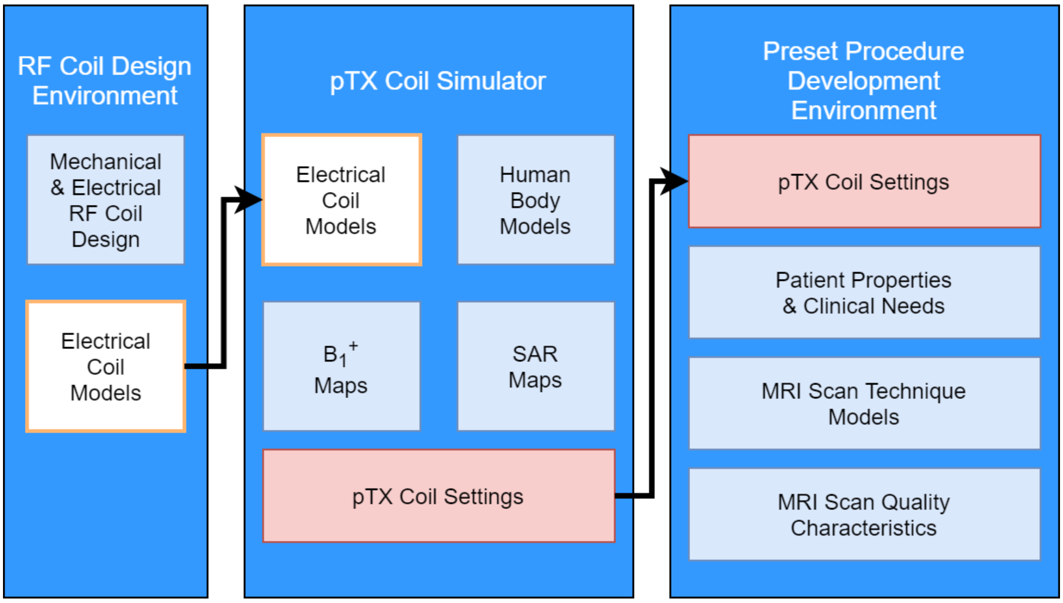

Figure 2 - pTX Coil development process diagram

As Figure 2 shows, the pTX Coil development process is differentiated into three stages:

- Design the pTX Coil electrical model. The output of this stage is the electrical coil models.
- Perform RF field simulation to get the results when different pTX Coil control settings are applied. The output of this stage is the pTX Coil settings along with the corresponding ${B_1}^+$ maps and SAR maps.
- Optimize the MRI scan technique with the derived control settings. The optimized MRI scan technique is applied by the MRI scanner.

Between different stages, the output of each stage is sequentially transferred between developers. On the other hand, during each stage, the developers manually apply complex models and algorithms to process the received data.
Overall, the sequential data flow and the manual data processing result in two problems:

- Time-consuming process.
- Limited solution space.

The two problems led to the idea of developing the pTX Coil Optimizer, which is elaborated in Section 1.2.

1.1.2 Arrowhead Tools project

Before diving into the pTX Coil Optimizer, we first introduce the AHT project, which provided the essential Internet of things (IoT) framework in the scope of the project.

The AHT project [11] is funded by ECSEL Joint Undertaking. The goal of the project is to develop digitalization and automation solutions for the industry of Europe and to remove the blocking stones on the path of IT/OT integration, where IT means information technology and OT means operational technology. To be more specific, the AHT project devoted itself to introduce new open-source technologies for the IoT and System of Systems (SoS) in both design and run-time phase. As the deliverables, the AHT project provided engineering processes, an integration platform, tools, and tool chains. The deliverables are used for the development of digitalization, connectivity, and automation system solutions.

The AHT project has a partnership with various companies and research institutions, and Philips is one of the industrial partners. The pTX Coil Optimizer project is one of the use cases to expand the field of application of the Arrowhead Framework (AHF).

1.1.2.1 Arrowhead Framework

The AHF is the IoT framework provided by the AHT project. The framework is based on the results of several larger EU projects, such as the SOCRADES project and IMC-AESOP [12].

The objective of the AHF is to enable the SoS that is realizing the IoT concept to have the following three features:

- **Interoperability:** The involving devices and stakeholders in the system of systems can connect and communicate with each other. In the AHF, interoperability is achieved by adopting the service-oriented architecture (SOA) paradigm. More details for the SOA are explained in Section 3.1.2.
- **Integrability:** The systems which are natively compliant with the AHF can interact with the legacy systems.
- **Independence:** The systems are independent of the services they provide.

1.2 pTX Coil Optimizer

As described in Section 1.1.1, the original development process of the pTX Coil is time-consuming and has limited solution space. This led to the idea of utilizing the AHF to integrate the pTX Coil development process. The concept is shown in Figure 3. Since the output of the idea is optimized pTX Coil, we call the idea pTX Coil Optimizer.

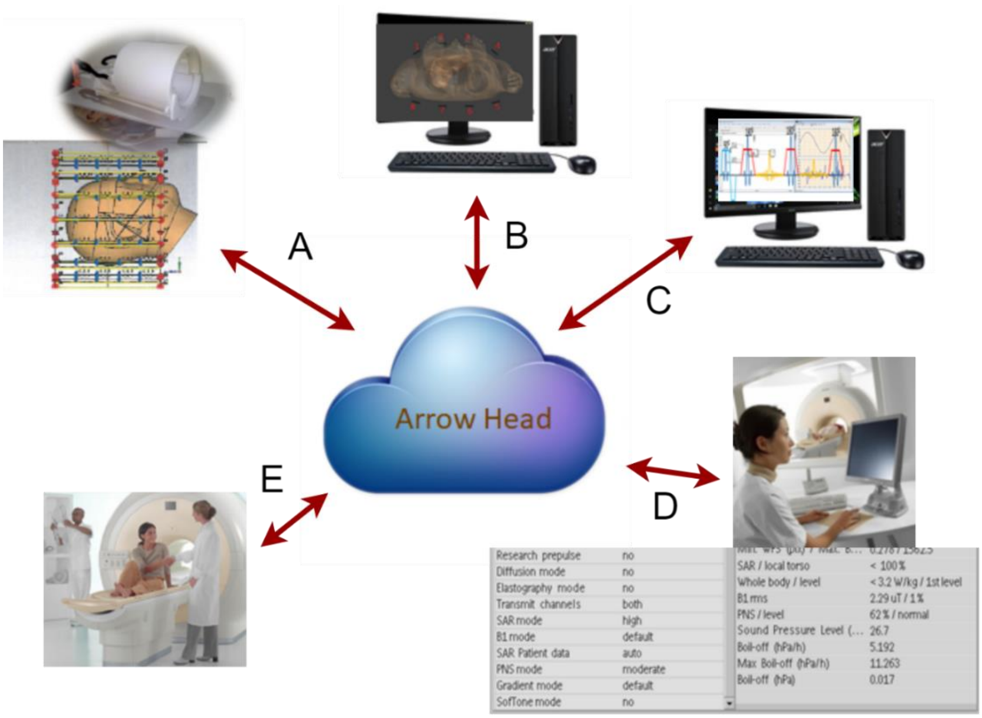

Figure 3 - pTX Coil Optimizer conceptual diagram

As Figure 3 shows, the pTX Coil Optimizer connects the developers and the end-users of the pTX Coil are connected through the AHF in the way described below:

- **A:** The RF coil engineers (coil engineer) design the coil models and share the results through AHF.

- **B:** The RF simulation engineer (simulation engineer) retrieves the coil models through AHF, performs a simulation of the RF field to derive potential control settings for the pTX Coil, and shares the results through AHF.
- **C:** The MR methods engineers retrieve the RF field simulation result of optimal pTX Coil control settings through AHF, create MR scan technique models that optimize performance, and share the results through AHF.
- **D:** The MR application engineers retrieve information of the pTX Coil and MR scan techniques through AHF, optimize the scan protocols, and share the results through AHF.
- **E:** The MR clinical users retrieve the scan protocols through AHF and use the coil with the protocols to optimally examine the patients.

In Figure 4, the benefit of realizing the pTX Coil Optimizer is described. For the developers of the department of research and development, both the productivity and the end-result quality are improved. On the other hand, For the clinical users, since optimized pTX Coil hardware and control settings can lead to better image quality and shorter scan time, the operation experience of the clinical users of the MRI scanner and the patient are both improved.

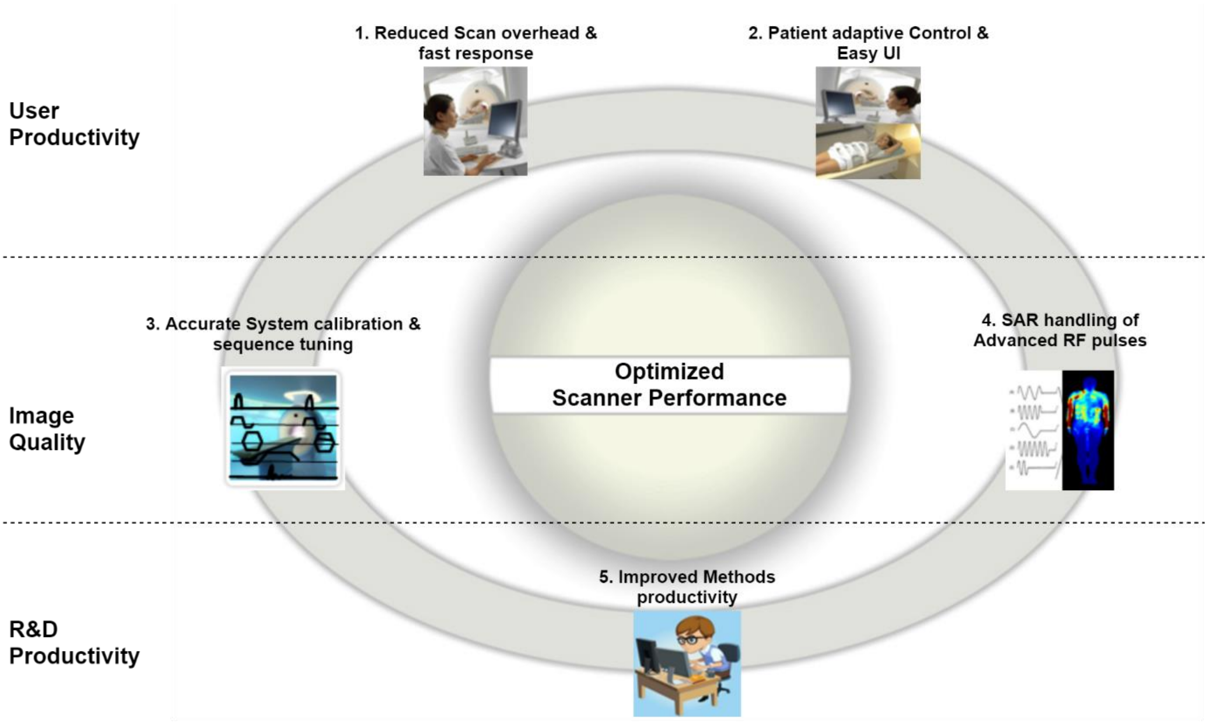

Figure 4 - Benefits of the pTX Coil Optimizer

1.3 Scope and goal

The scale of the whole pTX Coil Optimizer is large, as we have a limited number of developers and a tight time frame for the project, we focused on part of the pTX Coil Optimizer in this project. To specify the scope of the project, we look at Figure 5.

Figure 5 shows how the AHF can be integrated into the pTX Coil development process depicted in Figure 2 and realize the pTX Coil Optimizer. The AHF is integrated into the development process by having individual interfaces with each development stage. Also, there is a user interface to enable the users to interact with the pTX Coil Optimizer.

During the timeframe of this project, the scope was limited in the field indicated by the red inset, which was to have individual interfaces with the coil design stage and the simulation stage. Also, the user interface was in the scope of the project.

With the scope in mind, the problem statement of the project is stated as "Apply the Arrowhead Framework to implement the MRI pTX Coil Optimizer, which has a user interface and individual interfaces with the RF Coil Design Environment and pTX Coil Simulator." The goal of the project is to improve the efficiency of the pTX Coil development process and improve the quality of the final result.

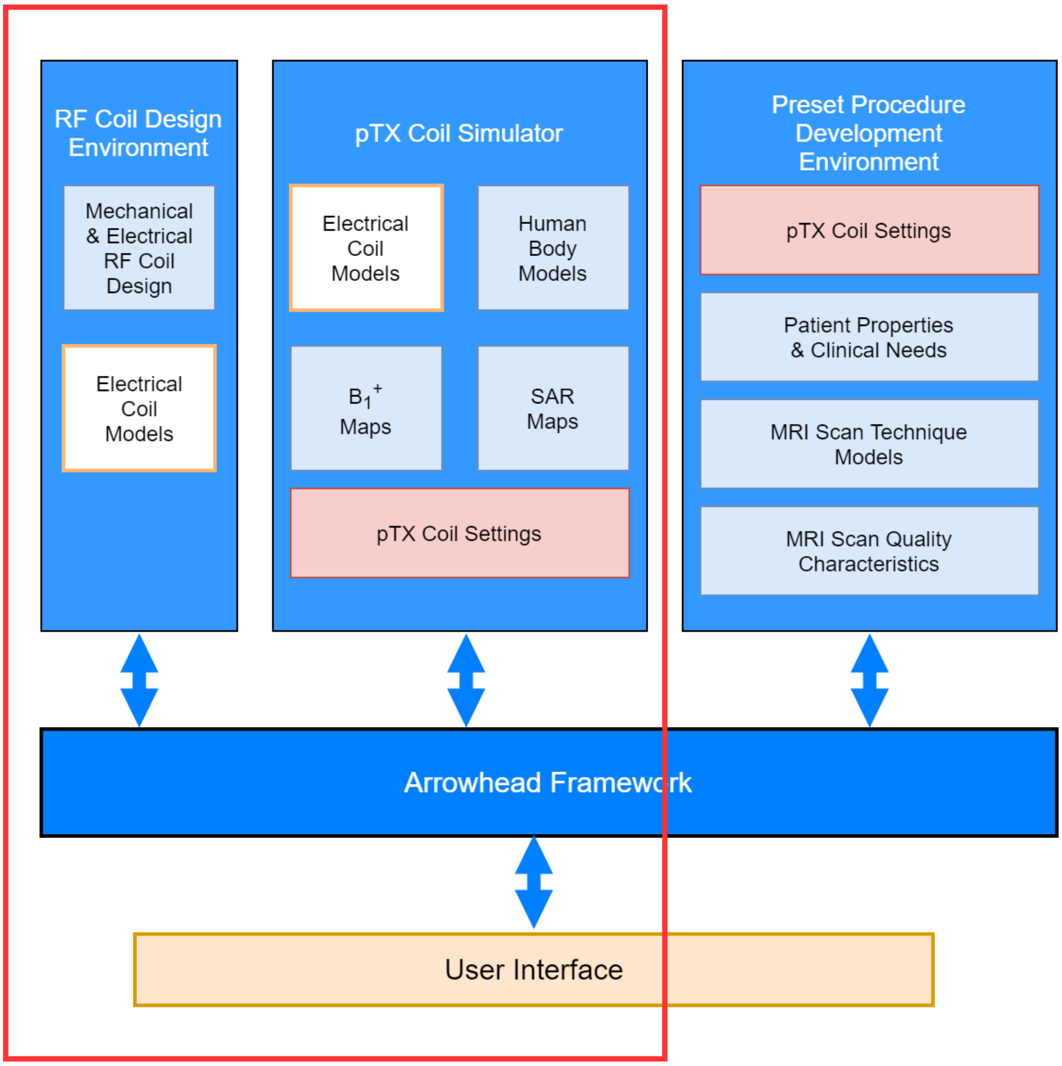

Figure 5 - pTX Coil Optimizer scope diagram

1.4 Project organization

There are three major organizations in the project:

- **Eindhoven University of Technology (TU/e):** The project is the graduation project for the Professional Doctorate in Engineering (PDEng) Trainee Wan-Yi Tang.
- **Philips:** The project is solving the problem in the scope of Philips.
- **The AHT project:** The project is one of the use cases of the AHT project.

The project organization is depicted in Figure 6. The developer is the PDEng Trainee Wan-Yi Tang. The trainee is supervised by the Supervisor Önder Babur from TU/e and the Mentor Peter van der Meulen from Philips. On the management side, From TU/e is the PDEng Program Manager Riske Meijer, and from Philips are the Project Leader Frans Rosbak and the Project Co-Leader Jurgen

Mollink. Worth noticing is that, in the scope of the AHT project, Frans Rosbak is also the work package leader and Peter van der Meulen is the use case leader.

The ones mentioned in Figure 6, excluding the trainee, form the Project Steering Group, an essential group that steers the direction of the project.

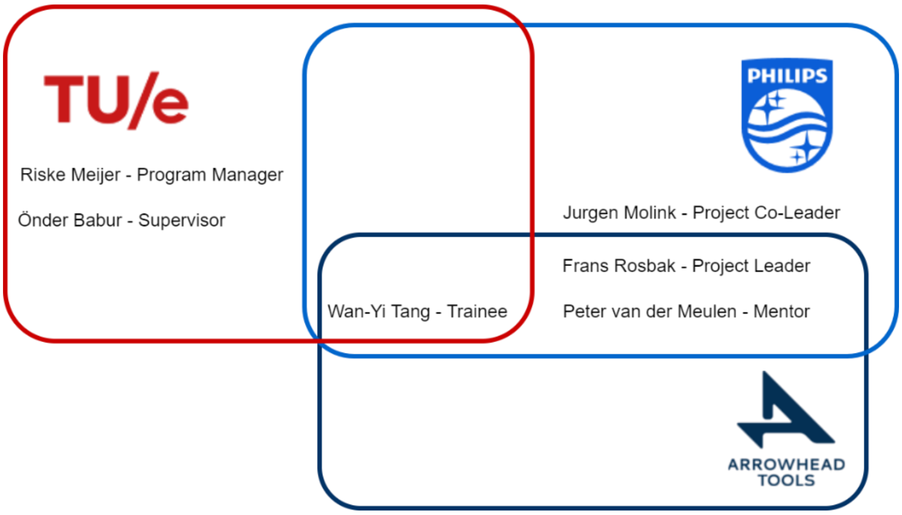

Figure 6 - Project organization diagram

1.5 Report outline

In the following chapters of this report, we first provide a thorough stakeholder analysis in Chapter 2. Then, in Chapter 3, we provide knowledge and information relevant to the project from the problem analysis. Next, we describe the process and results of requirements elicitation in Chapter 4. After that, we dive into the architecture and design of the pTX Coil Optimizer in Chapter 5. Following the architecture and design description, we then provide the process and result of the verification and validation in Chapter 6. After that, we dive into the plan and execution result of project management in Chapter 7. Then, we provide the conclusions for the project in Chapter 8. Finally, in Chapter 9, we provide the retrospective for the project.

2 Stakeholder Analysis

In this chapter, we first provide an introduction to the stakeholder analysis in Section 2.1. Then, in Section 2.2, we list the stakeholders that we identified in the project. Finally, we describe the adopted method and results of the stakeholder analysis in Section 2.3. The needs and concerns of the stakeholders are described in chapter 4.

2.1 *Introduction*

The stakeholders are the individuals or groups that are affected by the outcome of the project and/or having an impact on the success of the project [13]. During the project starting phase, the stakeholder analysis is a crucial process that enables the designer to identify who the stakeholders are, understand the stakeholders' interest in the project's outcome, and prioritize the stakeholders based on their level of interest in the project and their impact level to the success of the project.

2.2 *Stakeholder list*

The stakeholders in this project are shown in Table 1. Most of the stakeholders are from the organizations described in Section 1.4, which are from TU/e, Philips Healthcare, and the AHT Project. Two of the stakeholders are having multiple roles in this project. One is the project leader of Philips, who is also the work package (WP) leader of the AHT Project. Another is the mentor from Philips, who is also the magnetic resonance (MR) methods engineer and MR systems engineer of Philips, and use case (UC) leader of the AHT Project.

Table 1 - Stakeholder list

Organization	Position	Name
Eindhoven University of Technology	PDEng Program Manager	Riske Meijer
	PDEng Trainee	Wan-Yi Tang
	Project Supervisor	Önder Babur
Philips Health Care	Project Leader	Frans Rosbak
	Project Co-Leader	Jurgen Mollink
	Project Mentor	Peter van der Meulen
	MR Systems Engineer	Peter van der Meulen
	RF Coil Engineer	Michel Italiaander
	RF Coil Simulation Engineer	Zhiyong Zhai
	MR Methods Engineer	Peter van der Meulen
	MR Application Engineer	N/A
Arrowhead Tools Project	WP Leader	Frans Rosbak
	UC Leader	Peter van der Meulen
Hospital	Clinical MR User	N/A
	Patient	N/A

2.3 *Mendelow's Matrix*

The Mendelow's Matrix [14], also known as the power-interest grid, is a tool to categorize the stakeholders based on their power and interest into consideration. Here the power means the stakeholder's ability to impact the success of the project, while the interest means the stakeholder's level of interest in terms of the outcome of the project. With Mendelow's Matrix, the stakeholders are categorized into the following four categories, the corresponding actions that are suggested to be taken towards them are also listed:

- **High power, highly interested:** Engage and consult
- **High power, less interested:** Keep satisfied
- **Low power, highly interested:** Keep informed
- **Low power, less interested:** Monitor

The Mendelow's Matrix of this project is shown in Figure 7 below. To simplify the diagram, the stakeholders are addressed with their names if possible. The High power, highly interested category is in the up right corner and is colored in red. In contrast, the Low power, less interested category is in the bottom left corner and is colored in blue.

On the upper half of the diagram, we can find the project mentor (Peter), project supervisor (Önder), project leader (Frans), PDEng program manager (Riske), and project co-leader (Jurgen). All these stakeholders are considered to have the same level of power in the project scope, however, it is Peter and Önder are considered to have the highest interest in the project as they directly supervised the trainee along the development process. On the other hand, Frans, Riske, and Jurgen are considered to have less interest as they are in the position to manage multiple similar projects concurrently.

On the lower half of the diagram, we can find the engineers from Philips Healthcare and the stakeholders from the hospital. They are all considered to have low power in the project, however, the RF coil engineer (Michel) and RF coil simulation engineer (Zhiyong) are considered to be highly interested in the project as they have shown their interest to the trainee and Peter.

Based on Mendelow's Matrix, during the project period, the trainee has a weekly meeting with Peter and Önder to closely engage them in the development process. On the other hand, Frans, Riske, and Jurgen are having a monthly meeting with the trainee. For the remaining stakeholders, the trainee has irregular meetings with only Zhiyong to gain more insights into the simulation process.

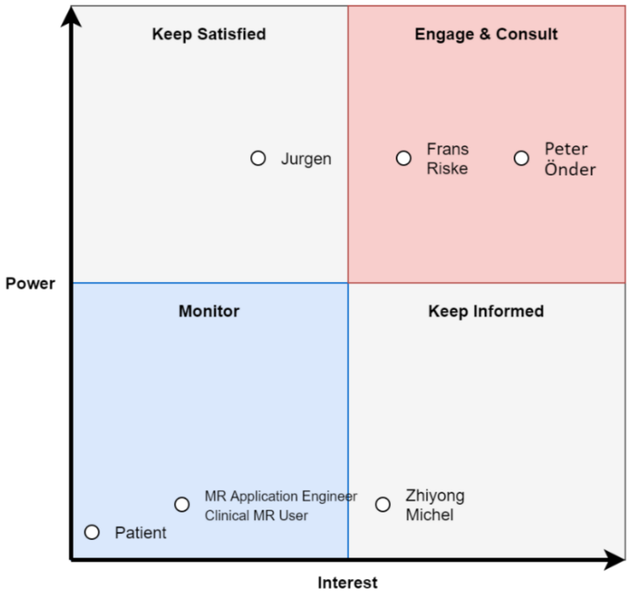

Figure 7 - Mendelow's Matrix of the project

3 Problem Analysis

In this chapter, we address the issues that are relevant to the project and provide the corresponding information. With the provided information, the readers can acquire sufficient knowledge for understanding the content of the report. In the following sections, we first thoroughly introduce the AHF. Afterward, we describe the simulation result analysis process. Finally, we describe the environment of the pTX Coil Optimizer.

3.1 Arrowhead Framework

In this section, we thoroughly introduce the AHF, the IoT framework provided by the AHT project. We first introduce the concept of the local cloud, which is the concept to be facilitated when applying the AHF. Then, we talk about the basis of the AHF, which is the service-oriented architecture (SOA). Finally, we provide the definitions of terms used in the AHF.

3.1.1 Local cloud

The AHT project introduced the concept of the local cloud in the context of digitization and automation. The concept was driven by the following main requirements [12]:

- Guarantee the latency for communication and control computations in automation.
- Provide scalability in the sense of enabling a large number of automation systems.
- Enable the agility of multi-stakeholder integration and operations.
- Guarantee security and related safety in terms of the automation systems.
- Provide ease of application engineering.

The requirements lead to the idea of local cloud depicted in Figure 8 that the systems and devices serving the desired tasks encapsulate and protect in the same local network. Furthermore, considering the existence of applications that requires multiple local clouds to realize, the local cloud concept also supports the idea of inter-cloud service exchanges.

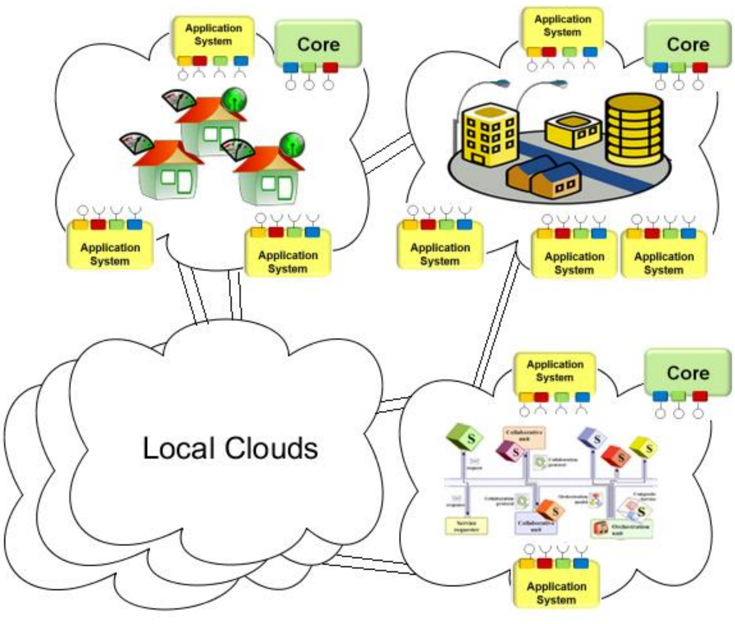

Figure 8 - Local cloud concept diagram [12]

3.1.2 Service-oriented architecture

The SOA describes how the data exchange between a service producer and a service consumer. The architecture utilizes service interfaces to enable the software components to be reusable [15]. By adopting SOA, the following properties exhibit [12]:

- **Loosely coupled:** The run-time data exchange can be achieved even if the SOA systems do not know each other during the design phase.
- **Late binding:** The interaction between two systems in the SOA is established in run-time.
- **Lookup:** The service producer can register the service and enable the consumer to find the service.

In the AHF, the systems and devices are considered as the service providers and consumers in the context of the SOA, thus the local cloud inherits the properties of SOA and addresses the requirements mentioned in Section 3.1.1.

3.1.3 Arrowhead Framework definitions

In this section, we provide the definitions for the terms used in the AHF [12].

3.1.3.1 Service

A service is an action of exchanging information from a system that provides the system to the system that consumes the system.

3.1.3.2 System

A system is what is providing and/or consuming services. Being a system, it is possible to be responsible for providing multiple services while in need of consuming multiple services. In terms of implementation, a system is a software piece executed on a device.

There are two types of systems: application systems and core systems. The application systems are developed by the users of the AHF and may provide or consume all sorts of services to realize the specific application. On the other hand, the core systems are provided by the AHF and can be further differentiated into two types:

- **Mandatory core systems:** The core systems needed to establish the minimal local cloud. There are three of them: the Service Registry system, the Authorization system, and the Orchestration system.
- **Supporting core systems:** The core systems that provide the possibility to extend the capability of the local cloud.

3.1.3.3 Device

A device may be equipment, machine, or any form of hardware as long as it can host one or multiple systems and can be deployed in the local cloud.

3.1.3.4 Local cloud

A local cloud is defined as a self-contained network with the three mandatory core systems deployed and at least one application system deployed. Figure 9 shows a general architecture of the local cloud, as the SOA is adopted, the systems have both service-providing or service-consuming endpoints to interact with each other. We can see that there may be one or multiple application systems. On the other hand, depends on the scenario, there may be multiple or no supporting core systems.

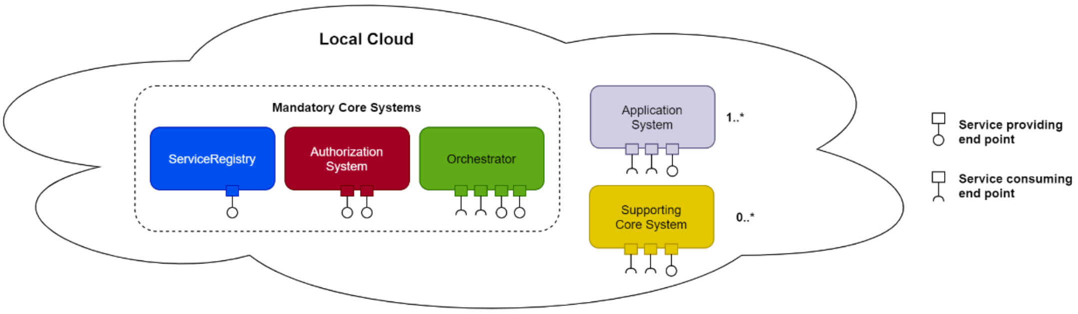

Figure 9 - Local cloud general architecture diagram

3.1.3.5 System of systems

An SoS is a set of systems that are managed by the mandatory core systems. A local cloud is an SoS in the context of the AHF. Furthermore, An SoS may be composed of multiple local clouds.

3.1.4 Processes behind the service interactions

As we can see in Figure 9, the local cloud is composed of systems that provide or consume services. In this section, we describe how the core systems interact to facilitate the service interaction between the application systems. In the following sections, we describe the service interaction inside of a local cloud.

In the scenario that both the service provider and the service consumer are in the same local cloud, the mandatory interactions between the core systems are described with the aid of Figure 10. In Figure 10, for each system represented with a block, reaching out a stick with a circular end means to provide a service, while reaching out a stick with a concave end means to consume a service.

Figure 10 provides an overview of the process when a Service Consumer request a service. As SOA is adopted, by design, the Service Consumer does not know whether the requested service exists or not. As a result, the Service Consumer asks the Orchestrator about the requested service. When receiving the request, the Orchestrator asks the Service Registry to look up if the service exists, if yes, the Orchestrator also asks Authorization to authorize the service interaction to happen. After all the processes are done, the Orchestrator responds to the Service Consumer with the information about the Service Provider, then the Service Consumer may find the Service Provider and consume the service.

On the other hand, for the Service Provider, when it is integrated into the local cloud, the services that it provides must be registered to the database of the Service Registry. Also, the rules to determine whether a service can be provided to a specific Service Consumer need to be defined and recorded on the database of the Authorization.

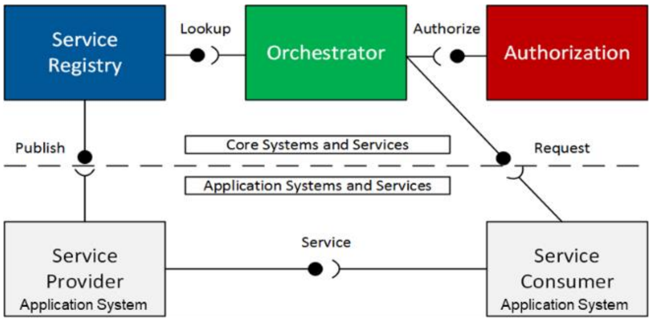

Figure 10 - High-level description of service interaction [16]

3.2 Simulation result analysis

In the pTX Coil development process shown in Figure 2, the pTX Coil settings are the output of the simulation stage. In the output, there are multiple sets of pTX Coil settings that have the potential to be the optimal set of settings. To derive the optimal set of settings, an important process is to determine the dominant parameter out of the whole body SAR, head SAR, local extremities SAR, and local torso SAR. In the following sections, we first look into the parameters we get from the simulation result, then we describe the process for determining the dominant parameter.

3.2.1 Simulation result parameters

The simulation result parameters can be classified into two categories, one is the simulation condition, another is the simulation result. Below we list the parameters:

Simulation condition

- **Human model:** The human model on which the simulation is performed. The human models are commercially available.
- **Anatomy:** The anatomy of what the region of interest is. Some examples are the heart, liver, prostate, and pelvis.
- **Control strategy:** The control strategy applied. One strategy leads to various control settings when applied to different human models and anatomy.

Simulation result

- **Average $B_1{}^+$ over specific slice (μT):** The average $B_1{}^+$ value over the slice across the region of interest. For this value, the higher the better.
- **$B_1{}^+$ standard deviation over specific slice:** The standard deviation of the $B_1{}^+$ value over the slice across the region of interest. The value indicates the homogeneity of the RF field distribution. For this value, the lower the better.
- **Whole body SAR (W/kg):** The SAR value across the whole body. The value indicates the overall heating of the whole body. For this value, the lower the better.
- **Head SAR (W/kg):** The SAR value across the head. The value indicates the overall heating of the head. For this value, the lower the better.
- **Local extremities SAR (W/kg):** The local SAR value across the extremities. The value indicates the local maximum heating of the extremities. For this value, the lower the better.
- **Local torso SAR (W/kg):** The local SAR value across the torso. The value indicates the local maximum of heating of the torso. For this value, the lower the better.

3.2.2 Simulation result analysis process

Below enlist the analysis process which determines the dominant parameter out of the whole body SAR, head SAR, local extremities SAR, and local torso SAR:

1. Extract the sets of pTX Coil settings that lead to both high enough average $B_1{}^+$ value and low $B_1{}^+$ standard deviation.
2. From the extracted sets of pTX Coil settings, further extract the sets of pTX Coil settings that lead to the maximum value of whole body SAR, head SAR, local extremities SAR, and local torso SAR. From this step, four values are derived.
3. With the four maximum SAR values derived from step 2, calculate the SAR-Power ratio, which can be calculated as SAR (W/kg) divided by the coil power (W). From this step, four values are derived.
4. With the sets of pTX Coil settings extracted from step 2, calculate the coil efficiency, which can be calculated as average $B_1{}^+$ value (μT) divided by the square root of coil power (W). From this step, four values are derived.

5. With the result from step 3 and step 4, calculate the SAR-${B_1^+}^2$ ratio, which can be calculated as SAR-Power ratio divided by the square of the coil efficiency. From this step, four values are derived.
6. With the result from step 5, calculate the maximum root mean square of B_1^+ value, which can be calculated as the square root of the result of SAR limit divided by the SAR-${B_1^+}^2$ ratio. The SAR limit is defined by the IEC standard [17]. From this step, four values are derived.

With the maximum root mean square of B_1^+ value of the four conditions, the minimum value out of the four suggests that the corresponding parameter is the most limited and considered as the dominant parameter. The parameter could be the whole body SAR, head SAR, local extremities SAR, or local torso SAR.

3.3 Development environment of the pTX Coil Optimizer

In this section, we elaborate on the development environment of the pTX Coil Optimizer. As the development environment, we refer to the collection of hardware and software tools we used to build the system. Understanding the development environment enables us to be aware of the restrictions imposed by the environment and can take actions to prevent failure due to environmental issues.

Besides the Arrowhead Framework (AHF) that we extensively introduce in the previous section, below we list the composition of the environment:

- **Java** [18]**:** Java was the coding language for the implementation of the pTX Coil Optimizer.
- **Eclipse IDE 2020-12** [19]**:** Eclipse IDE 2020-12 was the integrated design environment (IDE).
- **JDK / JRE 11** [20]**:** JDK / JRE 11 was the software development kit (SDK) and runtime environment of Java in the project.
- **Spring Boot 2.1.5** [21]**:** Spring Boot 2.1.5 was the Java framework for the development of Java applications.
- **Maven 3.6.3** [22]**:** Maven was the dependency management tool.
- **MySQL Server/Workbench 8.0.23** [23]**:** MySQL Server was adopted to store the data of the AHF.

4 Requirements Elicitation

In this chapter, first, we introduce the role of requirements in the development process in Section 4.1. Then, in Section 4.2, we thoroughly describe our procedure of gathering the requirements. Finally, we present the requirements in Section 4.3.

4.1 Introduction

A requirement is the definition of a property of a system that is either needed or wanted by a stakeholder. The requirements are essential input for the designer to effectively define, design, and create a system. There are two types of requirements:

- Functional requirement: The requirements that reflect the direct actions as it is stated with verbs, such as “do”, “provide”, “build”, etc.
- Non-functional requirement: The requirements that limit or constrain another requirement in some way, such as the quality and implementation.

As the requirements drive the development of the project, it is essential to properly define the requirements. Here we list the characteristics that a good requirement is carrying:

- The requirement must be identifiable.
- The requirement must be clear.
- The requirement should not be solution-specific.
- The requirement must be owned.
- The requirement must have an origin.
- The requirement must be able to be verified.
- The requirement must be able to be validated.
- The requirement must be prioritized.

4.2 Requirements gathering

To gather the requirements in this project, we follow the procedure listed below, note that the procedure is iterative throughout the project:

1. Perform literature review to understand the project’s context and goal.
2. Perform stakeholder analysis to identify the stakeholders, prioritize the stakeholders and understand their needs in the project.
3. Come up with use cases based on the user needs.
4. Perform risk analysis in the scope of the project and find the mitigations.
5. Based on the results of the first four steps, formulate the requirement list while keeping what good requirements are in mind.

The first step, literature review, and part of the stakeholder analysis are described in the previous chapters, in this section, we focus on the user needs, use cases, and risk analysis.

4.2.1 Collect user needs

The user needs were collected in two ways, one was to directly consult the stakeholders to express their ideas, another was to first understand the development process then extract the potential user needs from the process.

The first way was facilitated during the meetings with the stakeholders. Besides the regular meetings with the stakeholders such as the project steering group members, we also organized meetings with the stakeholders that we were not able to meet regularly to gather input from them.

The second way was facilitated by interviewing the stakeholders who were part of the segments of the development process that we were interested in. The stakeholders we interviewed were the RF coil simulation engineer and the MR systems engineer. Based on the results of the interviews, we built up our understanding of the detail of the segments of the development process, then identified the points we considered that can be improved and formulated them as user needs. The formulated was confirmed by the stakeholders.

In the following sections, we first describe our results derived from the second way, which are our understandings of the process from design to simulation and the process from simulation to control setting decision. Afterward, we provide the list of the user needs.

4.2.1.1 pTX Coil design to simulation

In Figure 11 we show the development process in the range from the design of the pTX Coil to transferring the coil model to the simulation environment. The actors involved in the process are the RF coil engineer and the RF coil simulation engineer. The process is thoroughly described as below:

1. The RF coil engineer receives design inputs and defines requirements for the pTX Coil.
2. The RF coil engineer designs the pTX Coil based on the requirements for the requirements.
3. The RF coil engineer sends the designed coil model to the RF coil simulation engineer.
4. The RF coil simulation engineer checks if the coil model is suitable for performing the simulation. If not, ask the RF coil engineer to modify the content of the coil model.

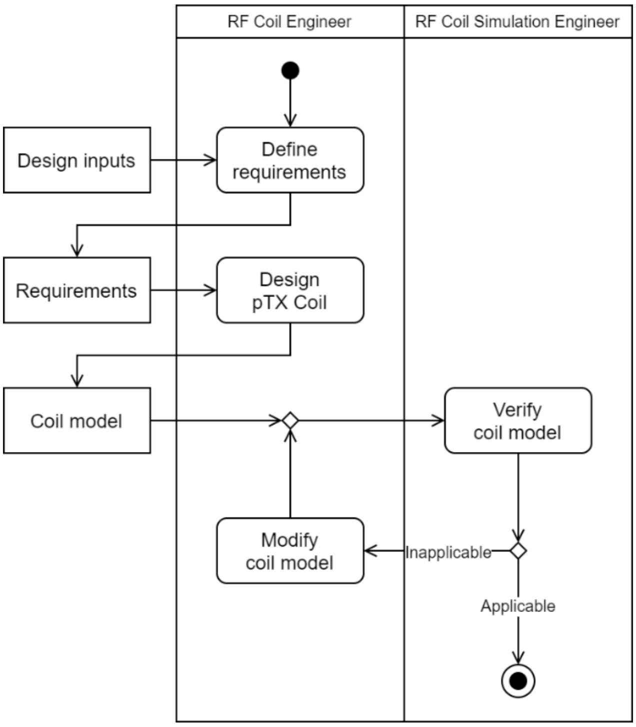

Figure 11 - pTX Coil design to simulation activity diagram

4.2.1.2 pTX Coil simulation to control setting decision

In Figure 12 we show the development process in the range from the simulation of the pTX Coil to choosing the optimal control setting for the pTX Coil. The actors involved in the process are the RF coil simulation engineer and the MR systems engineer. The process is thoroughly described as below:

1. The MR systems engineer request the RF coil simulation engineer to provide pTX Coil control settings based on the simulation results of a specific condition.

2. The RF coil simulation engineer checks if the simulation based on the requested condition has already been performed or not. If not, perform the simulation to acquire the simulation raw data, if yes, then proceed to the next step with the existing simulation raw data.
3. The RF coil simulation engineer performs post-processing to the simulation raw data. This will result to the $B_1{}^+$ maps and SAR maps and the corresponding control settings.
4. The RF coil simulation engineer formulates the post-processed simulation results into report format and sends them to the MR systems engineer.
5. The MR systems engineer interprets the simulation report and decides which control setting to proceed with.

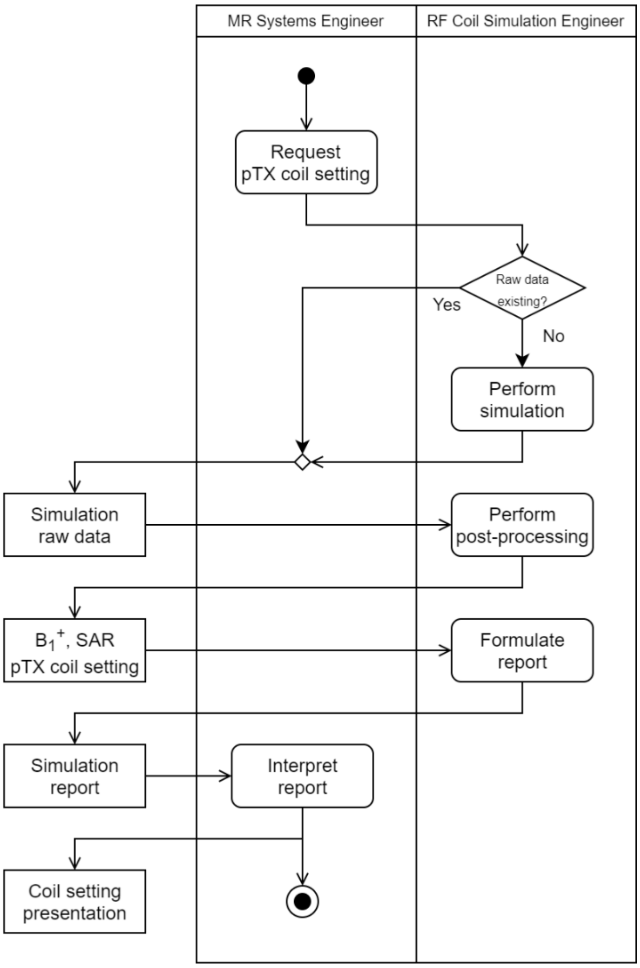

Figure 12 - pTX Coil simulation to control setting activity diagram

4.2.1.3 User needs

In this section, we list the derived user needs.

Philips Stakeholders

1. The Philips stakeholders need the confidential data from Philips to be handled securely in order to protect the intellectual property of Philips.

Arrowhead Tools Project WP Leader and UC Leader

1. The WP leader and UC leader need the system to be built based on the AHF in order to meet the objective of the AHT project.

Coil Simulation Engineer

1. The simulation engineer needs clear instructions for releasing the simulation result through the system in order to release the processed simulation results.
2. The simulation engineer needs specifications of which data types and formats are accepted by the system in order to prepare the simulation results correctly.

MR Systems Engineer

1. The MR systems engineer needs automation of the data transfer between the stakeholders in order to improve the efficiency of the engineering process.
2. The MR systems engineer needs fast feedback between stakeholders in order to improve faster and of higher quality.
3. The MR systems engineer needs the stakeholders further in the development chain to give feedback to the stakeholders earlier in the chain in order to integrate the activities of different stakeholders.
4. The MR systems engineer needs to retrieve the simulation results of various human body models and regions of interest in order to broaden the solution base for selecting optimal pTX Coil parameters.
5. The MR systems engineer needs the simulation report displayed clearly in order to improve the efficiency of interpreting the simulation report.
6. The MR systems engineer needs automated calculation of specific parameters (e.g., C: SAR - ${B_1}^2$ ratio) in order to improve the efficiency of interpreting the simulation report.

4.2.2 Use case diagrams

For the three users of the pTX Coil Optimizer in our scope: RF coil engineer, RF coil simulation engineer, and MR systems engineer, we formulated the use case diagrams, to have a clearer picture of what the functions should be provided by the pTX Coil Optimizer.

4.2.2.1 RF coil engineer

Figure 13 shows the use case diagram of the coil engineer when using the pTX Coil Optimizer. The diagram shows that when using the pTX Coil Optimizer, the pTX Coil Optimizer notifies the coil engineer that there is a request for the coil model, and the coil engineer can specify the coil model to be provided to the requester.

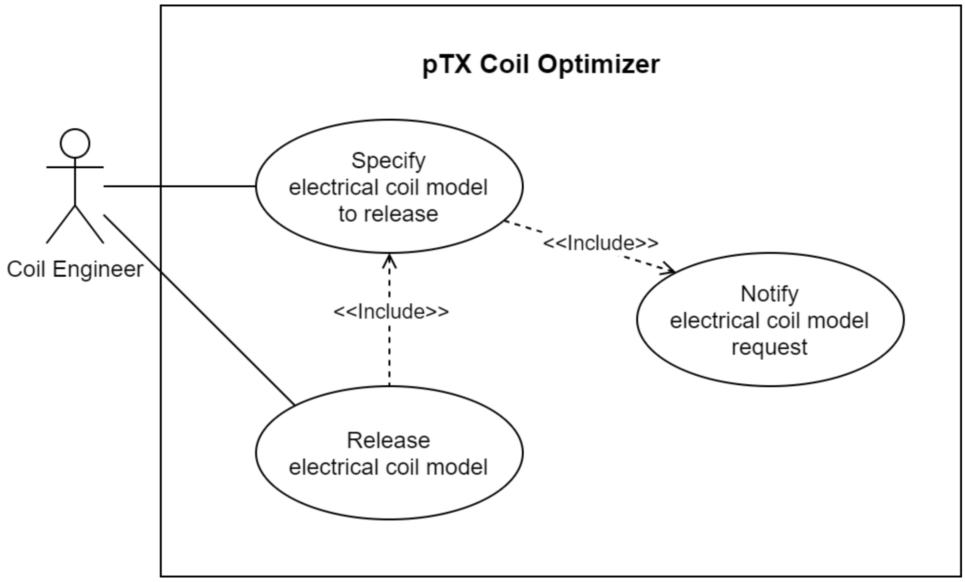

Figure 13 - RF coil engineer pTX Coil Optimizer use case diagram

4.2.2.2 RF coil simulation engineer

Figure 14 shows the use case diagram of the simulation engineer when using the pTX Coil Optimizer. The diagram shows that when using the pTX Coil Optimizer, the pTX Coil Optimizer notifies the simulation engineer that there is a request for the simulation result, and the simulation engineer can specify the simulation result to be provided to the requester.

On the other hand, the simulation engineer can also request for coil model through the pTX Coil Optimizer, and the simulation engineer can also save the received coil model in the desired directory.

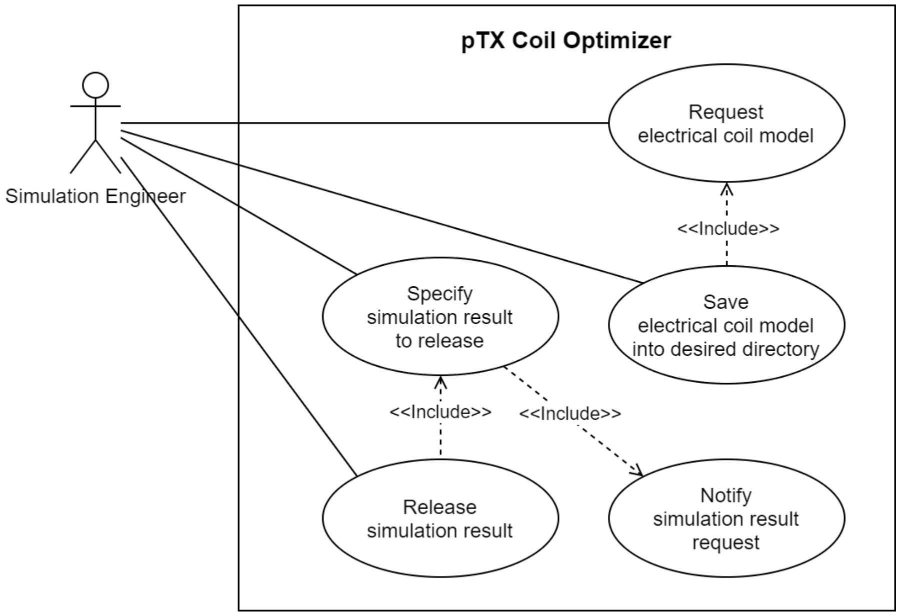

Figure 14 - RF coil simulation engineer pTX Coil Optimizer use case diagram

4.2.2.3 MR systems engineer

Figure 15 shows the use case diagram of the MR systems engineer when using the pTX Coil Optimizer. The diagram shows that when using the pTX Coil Optimizer, the MR systems engineer can request both coil model and simulation result through the pTX Coil Optimizer, and the MR systems engineer can save the received coil model or simulation result in the desired directory.

Besides requesting for coil model or simulation result, the pTX Coil Optimizer also enables the MR systems engineer to select a specific set of simulation results and extract information from the raw data of the simulation result.

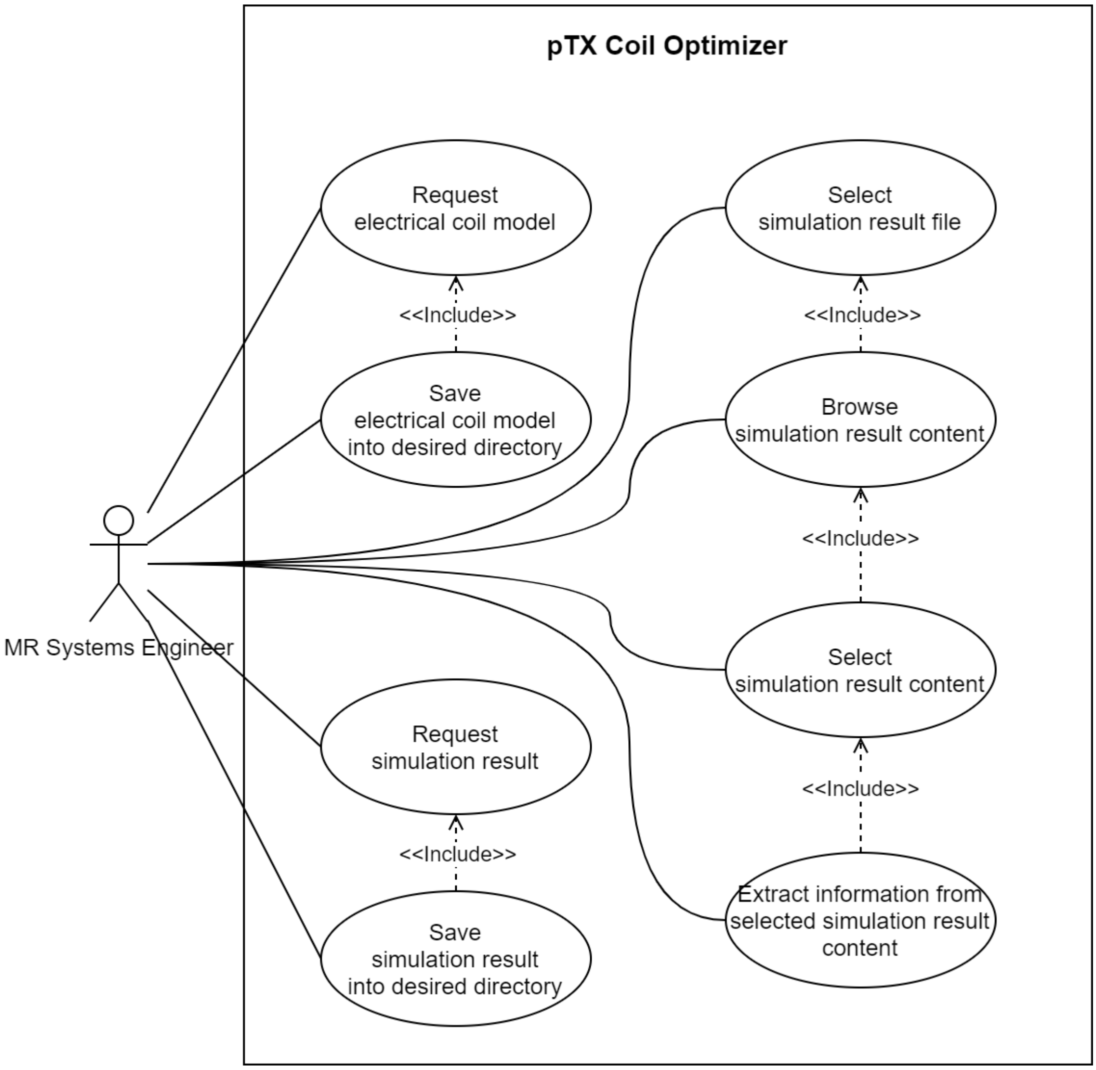

Figure 15 - MR systems engineer pTX Coil Optimizer use case diagram

4.2.3 Risk analysis

We performed risk analysis based on the user needs and the use case diagrams, the derived mitigations will be the inputs for formulating the requirements. As a result, we list the risk description, likelihood (L), impact(I), Rate, and mitigations in Table 2. For simplicity, more details such as the damage, cause, and reason for the assigned value for L and I are documented in Appendix A.

The evaluation of likelihood, impact, and rate are based on the criterion listed below:

- The likelihood (L): Very unlikely (1), Unlikely (2), Possible (3), Likely (4), Very Likely (5)
- The impact (I): Negligible (1), Minor (2), Moderate (3), Significant (4), Severe (5)
- The rate is assigned based on L*I: (High, L*I >= 15), (Moderate, 9 <= L*I < 15), (Low, L*I < 9)

Table 2 - Risk analysis

Process Risk (The risks of which the source is the development process)				
Risk	**L**	**I**	**Rate**	**Mitigation**
Lack of expertise for the trainee in terms of applying Arrowhead Framework.	4	3	Moderate	• The trainee should be aware of his expertise level when making a plan. • The trainee should use all the potential resources to speed up the learning process.

Limited stakeholder availability at the start of the project.	2	4	Low	• Form a questionnaire before the scheduled meeting with stakeholders. • A parallel approach to address other important aspects of the project while waiting for a response. • Reach out to the mentor and project leader when having difficulty in contacting specific stakeholders.
Supporting issue of Arrowhead Framework.	1	5	Low	• Use Java, which is the most mature language in the scenario of developing Arrowhead Framework systems. • Use the established core systems instead of the ones which are still developing.
Change of requirements.	3	3	Moderate	• When being asked to change the requirements, analyze if it's doable based on project status and make a clear statement to the related stakeholders regarding the feasibility.
Deliverable needs from the Arrowhead Tools project.	5	1	Low	• Keep track of the content of the deliverables and make use of them when formulating the documents for the PDEng project.
Product Risk (The risks of which the source is the end product)				
Risk	**L**	**I**	**Rate**	**Mitigation**
The software architecture of the system is not properly designed.	3	3	Moderate	• The software architecture should be aligned with the rules of the Arrowhead Framework. • The architecture shall be reviewed before being applied.
The system is not able to provide the simulation result produced by the simulation engineer.	1	5	Low	• The way of releasing simulation results and the requested result format has to be communicated with the simulation engineer.
The system is not able to successfully transfer information between the stakeholders.	2	4	Low	• The design and implementation of the communication function can be put into a higher priority.
The MR systems engineer is not able to retrieve the simulation results based on various human body models and regions of interest.	4	4	High	• Produce as many simulation results as possible. • Decrease the number of manual works needed for performing the simulation to maximize efficiency.
The simulation result is not user-friendly for the MR systems engineer.	3	4	Moderate	• Keep the stakeholder in the loop when defining the display format of the simulation result.
The file transfer needs a manual operation to accomplish.	3	4	Moderate	• Keep the stakeholder in the loop when defining the operation scenario regarding file transfer.
The file transfer process leaked the confidential data of Philips to the public network.	1	5	Low	• Store the data in a private drive and transfer the confidential data through the secured protocol.

4.3 Requirements overview

In this section, we display the functional and non-functional requirements separately.

4.3.1 Functional requirements

The functional requirements are prioritized with MoSCoW analysis, which classifies the requirements into must have, should have, could have, and won't have.

Table 3 - Functional requirement list

ID	Priority	Description
F-1	Must	The system shall transfer the coil model (file and metadata) from the RF coil engineer to the RF coil simulation engineer.
F-2	Could	The system shall transfer the coil model (file and metadata) from the RF coil engineer to the MR Systems engineer.
F-3	Could	The system shall deliver feedback from the RF coil simulation engineer to the RF coil engineer.
F-4	Could	The system shall deliver feedback from the MR Systems engineer to the RF coil engineer.
F-5	Must	The system shall transfer the simulation result report from the RF coil simulation engineer to the MR systems engineer.
F-6	Could	The system shall deliver feedback from the MR systems engineer to the RF coil simulation engineer.
F-7	Could	The system shall deliver feedback from the MR systems engineer to the RF coil engineer.
F-8	Must	The system shall display the values of the requested parameter.
F-9	Must	The system shall provide the values of parameters derived from the parameters in the simulation result report.
F-10	Must	The system shall identify the dominant parameters in the simulation result.

4.3.2 Non-functional requirements

The non-functional requirements are prioritized with MoSCoW analysis, which classifies the requirements into must have, should have, could have, and won't have. Furthermore, the requirements belong to various contexts.

Table 4 - Non-functional requirement list

ID	Priority	Context	Description
NF-1	Must	Arrowhead	The system shall be implemented based on the core systems of the Arrowhead Framework.
NF-2	Must	Arrowhead	The system shall apply the architecture that is compliant with the Arrowhead Framework.
NF-3	Must	Security	The system shall ensure data security by transferring data through a secured protocol.
NF-4	Must	Security	The system shall store the data of Philips in the scope of Philips.
NF-5	Must	Security	The system shall process the data of Philips in the scope of Philips.
NF-6	Should	Usability	The system shall improve the efficiency of the coil model (file and metadata) transfer process.
NF-7	Must	Usability	The system shall ensure usability by providing users with the document for the procedure of releasing the coil model (file and metadata).
NF-8	Must	Usability	The system shall ensure usability by providing users the document for the procedure to retrieve the coil model (file and metadata).
NF-9	Must	Usability	The system shall ensure usability by providing users with the specification of the accepted format and size of the coil model (file and metadata) being transferred.
NF-10	Should	Usability	The system shall improve the efficiency of the simulation result report transfer process.

NF-11	Must	Usability	The system shall ensure usability by providing users with the document of the procedure to release the simulation result report.
NF-12	Must	Usability	The system shall ensure usability by providing users with the document of the procedure to retrieve the simulation result report.
NF-13	Must	Usability	The system shall ensure usability by providing users with the specification of the accepted format and size of the simulation result report being transferred.
NF-14	Must	Usability	The system shall improve the efficiency of the simulation result interpretation process for the MR systems engineer.
NF-15	Must	Usability	The system shall be able to perform the service interactions across the different local networks.
NF-16	Should	Usability	The system shall be easy to use.

5 pTX Coil Optimizer Architecture And Design

In this chapter, we describe the pTX Coil Optimizer's architecture and design. The architecture and design were derived based on the functional requirements and non-functional requirements we describe in Chapter 4. To provide a clear description, first, we introduce the AHF documentation structure that we took as a guide for describing the pTX Coil Optimizer. Then, we start the description from the SoS level. Next, we go one level lower to the system level. Finally, we end up at the service level.

5.1 Arrowhead Framework documentation structure

The AHF documentation structure was defined by the Arrowhead consortium [12]. The purpose of defining the structure was to provide a common format for the developers of the Arrowhead compliant systems to document how to develop, deploy, maintain, and manage the systems. In Figure 16, we show the relationships between various types of documents in the AHF documentation structure. Each block in the diagram represents a type of document, and the connecting line between the blocks states that where the further explanation for a specific document can be found. In the following paragraphs, we briefly introduce how each type of document fits into the three levels defined in the structure.

At the SoS level:

- **System of Systems Description (SoSD):** The SoSD describes the functionalities and architecture of the SoS abstractly. The systems which serve as the building blocks of the SoS are presented.
- **System of Systems Design Description (SoSDD):** The SoSDD describes how an SoS has been implemented in a specific scenario. With this purpose, the technologies used and the set-up are described in the SoSDD.

At the System level:

- **System Description (SysD):** The SysD documents the system functionality, the hosted services, and the interfaces. As the SysD describes the system as a black box, no internal implementation is described.
- **System Design Description (SysDD):** The SysDD extends the black-box description of the SysD, shows the internal details of the system.

At the Service level:

- **Service Description (SD):** The SD describes the service from an abstract view. The main objectives and functionalities are described.
- **Interface Design Description (IDD):** The IDD describes the implementation of the service.
- **Communication Profile (CP):** The CP contains information regarding the transfer protocol, data compression, data encryption, and data encoding.
- **Semantic Profile (SP):** The SP defines the data and information semantics.

For this report, we take the AHF documentation structure as a guideline and structure the report in a way that fits our project.

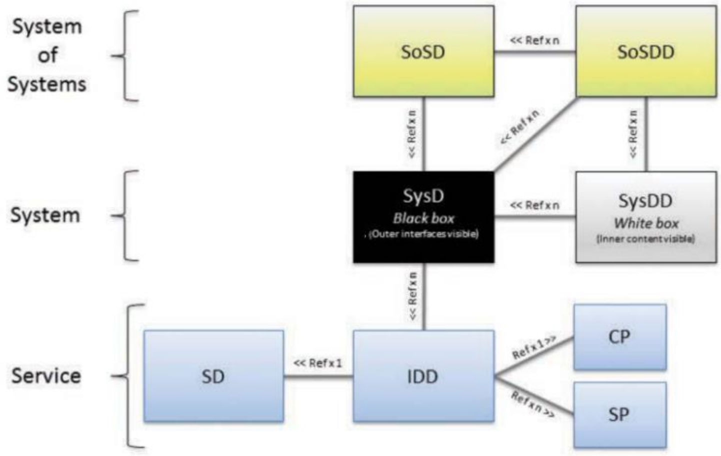

Figure 16 - Arrowhead Framework documentation structure [12]

5.2 System of systems level

5.2.1 System of systems description

The application scenario of the pTX Coil Optimizer is the development process of the pTX Coil. The three users involved are the coil engineer, the simulation engineer, and the MR systems engineer. For the three users, the pTX Coil Optimizer provides different functionalities.

For the coil engineer, the pTX Coil Optimizer transfers the coil model specified by the coil engineer to the one requested for the coil model. The functionality is aligned with the F-1 and F-2 in Table 3.

For the simulation engineer, the pTX Coil Optimizer enables the simulation engineer to request for coil model from the coil engineer, moreover, the simulation engineer can specify the directory for storing the received coil models. On the other hand, the pTX Coil Optimizer transfers the simulation result specified by the simulation engineer to the one who requested it. The functionalities are aligned with the F-1 and F-5 in Table 3.

For the MR systems engineer, the pTX Coil Optimizer enables the MR systems engineer to request for coil model from the coil engineer, also, to request for simulation result from the simulation result engineer. Moreover, the MR systems engineer can specify the directory for storing the received coil model or simulation result. Besides the functionalities related to file transfer, the pTX Coil Optimizer analyzes the simulation result for the MR systems engineer and displays the result in the desired way. The functionalities are aligned with the F-2, F-5, F-8, F-9, and F-10 in Table 3.

In the application scenario, the users of the pTX Coil Optimizer are in different geographical locations, as a result, the users are connected to different local networks. To address the scenario, the pTX Coil Optimizer can provide the file transfer functionalities across different networks, moreover, the files are transferred through a secured protocol.

To realize the pTX Coil Optimizer, the architecture shown in Figure 17 was formulated. The pTX Coil Optimizer was composed of three local clouds:

- Coil Model Provider (CMP) local cloud
- Simulation Result Provider (SRP) local cloud
- Simulation Result Consumer (SRC) local cloud

In this project, the three local clouds had the same architecture, which was based on the general local cloud architecture we described in Figure 9, all of them were composed of the following six systems:

- AH Service Registry

- AH Authorization
- AH Orchestrator
- AH Gateway
- AH Gatekeeper
- Application system

Among the six systems, the first five of them are the AH core systems. The roles and actions of the five AH core systems are thoroughly described in Section 3.1.4. On the other hand, the difference between the local clouds happened in the application systems. As shown in the white blocks in Figure 17, In CMP local cloud the application system is the CMP, in SRP local cloud the application system is the SRP, and in the SRC local cloud, the application system is the SRC. The application systems served as the interfaces for the users to interact with the pTX Coil Optimizer.

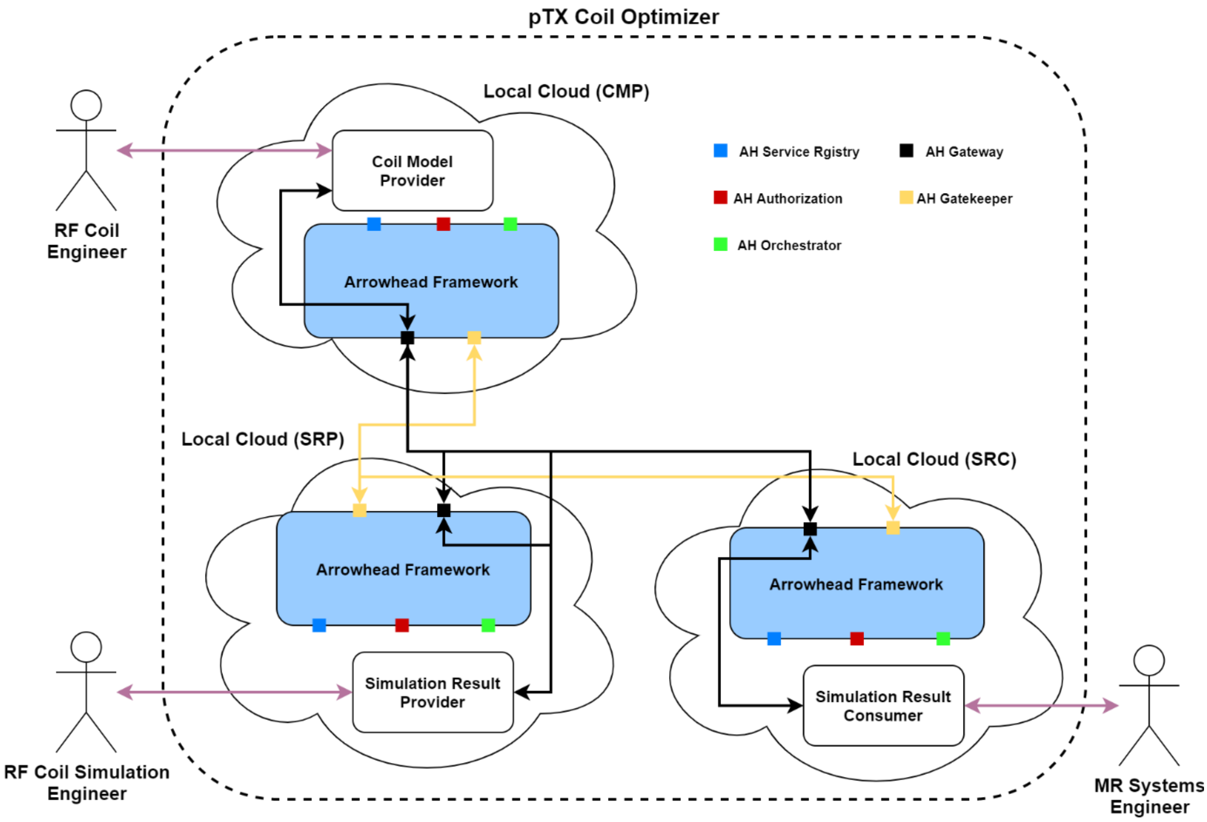

Figure 17 - pTX Coil Optimizer architecture diagram

5.2.2 System of systems design description

In this section, we describe how the SoS was implemented and deployed. To provide a clearer description, we provide the design description from two different levels. We start the description from the very top level where we can see the multiple local clouds. After that, we describe the individual local clouds.

5.2.2.1 Multiple local clouds

As depicted in Figure 18, in this project, the CMP local cloud and the message broker ActiveMQ are both executed on laptop A, while the SRP local cloud and the SRC local cloud are executed on laptop B. The setup was due to there were only two laptops available in the scope of the project. In case that more computing devices are available, all the local clouds and the message broker can be deployed on different devices.

Regarding the network environment where the local clouds were executed, the two laptops were connected to two different networks that were defined by two different modem routers. To enable the interaction between the local clouds, the message broker is needed as described in Section 3.1.4. In this project, we applied ActiveMQ to serve as the message broker.

It was necessary to enable all the local clouds to find the ActiveMQ through the internet. To make the ActiveMQ discoverable from outside of the local network where it was executed, we applied port forwarding. The idea of port forwarding is to assign one of the ports of the modem router to directly connect with one of the ports of the device in the local network. In that case, the message from outside of the local network can be sent to the assigned port on the modem router and further got transferred to the port of the local device. In this project, the ActiveMQ was listening to port 61616 of the local device, we had port 80 of the modem router as the access point to port 61616 of the local device. As a result, from the internet, the ones who know the public IP of our modem router can send a message to the modem router's port 80, the message can then be listened to by ActiveMQ.

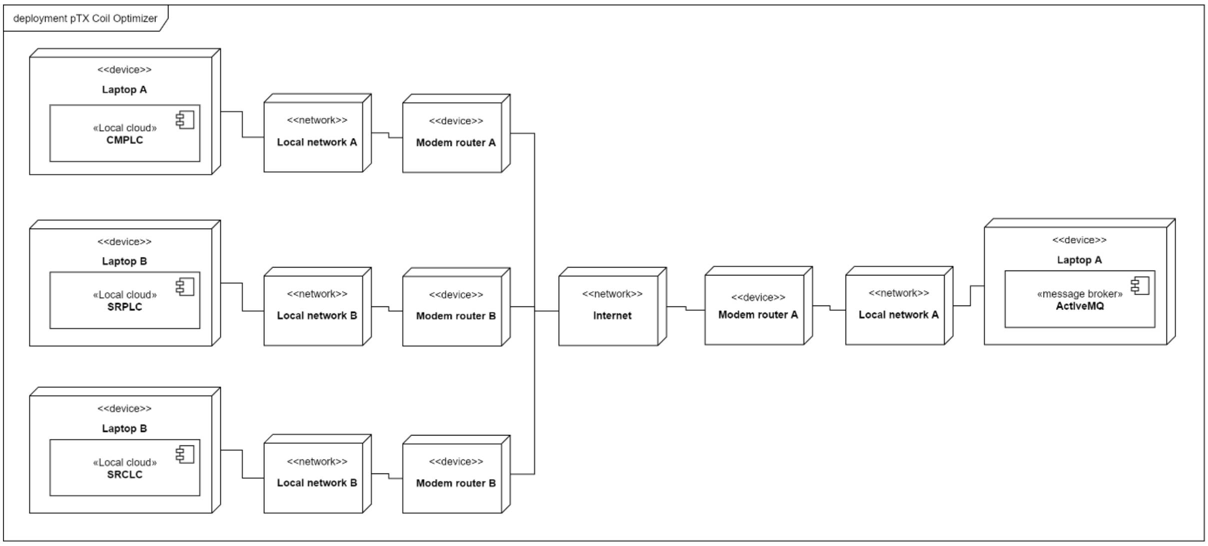

Figure 18 - pTX Coil Optimizer multiple local clouds deployment diagram

Following the execution architecture of the pTX Coil Optimizer, we dive into the process behind the inter-cloud service interaction. As Figure 19 shows, the application system in the local cloud on the left-hand side requests for a service provided by the application system in the local cloud on the right-hand side. There are three new systems needed to facilitate the interaction, they are the Gatekeeper, Gateway, and the message broker, which is named Arrowhead Relay in this situation. Worth noticing is that the Gatekeeper System and Gateway are both supporting core systems.

We can describe the process with aid of the numbers in Figure 19, the number indicates the sequence of the actions:

1. Service consumer requests Orchestration System (Orchestrator) for specific service.
2. The Orchestrator can not find the service in the local cloud, instead, the Orchestrator requests the Gatekeeper for Global Service Discovery, which is a service for finding other local clouds that are available. As another local cloud is found, the Inter Cloud Negotiation (ICN) is initiated by the Orchestrator.
3. The Gatekeeper proposes ICN to the Gatekeeper of the other local cloud.
4. The service request is sent to the Orchestrator of the other local cloud.
5. As there is a positive response from step 5, the Gateway is asked to build a connection with the service provider in the other local cloud.
6. The ICN response is sent back to the Gatekeeper in the original local cloud.
7. As there is a positive response from step 6, the Gateway is asked to build a connection with the service consumer.

8. The orchestration response for the request in step 1 is sent to the consumer.
9. The consumer sends the service call to the Gateway.
10. The Gateway sends the service call to the Arrowhead Relay.
11. The Arrowhead Relay sends the service call to the Gateway in another local cloud.
12. The service call is sent to the service provider in another local cloud.

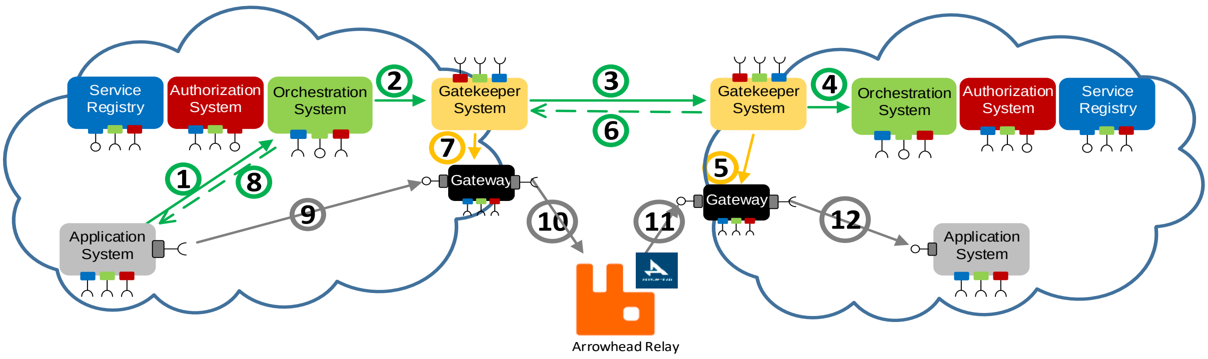

Figure 19 - Inter-cloud service interaction concept diagram [16]

5.2.2.2 Individual local cloud

As described in Section 5.2.1, the difference between the local clouds happened in the application system. This situation led to the fact that the execution environment of the different local clouds was the same. Hence, we here show only Figure 20, the deployment diagram of one local cloud to explain the physical deployment of all three local clouds.

The local cloud was composed of six systems, correspondingly, when launching local clouds, there were six jar files executed in the Java Runtime Environment (JRE). After being launched, the systems were running on the Tomcat server. To manage the data of the AHF core systems, the MySQL server was set up as the database. Inside of the database, tables were structured so that the systems may access the data in an organized way.

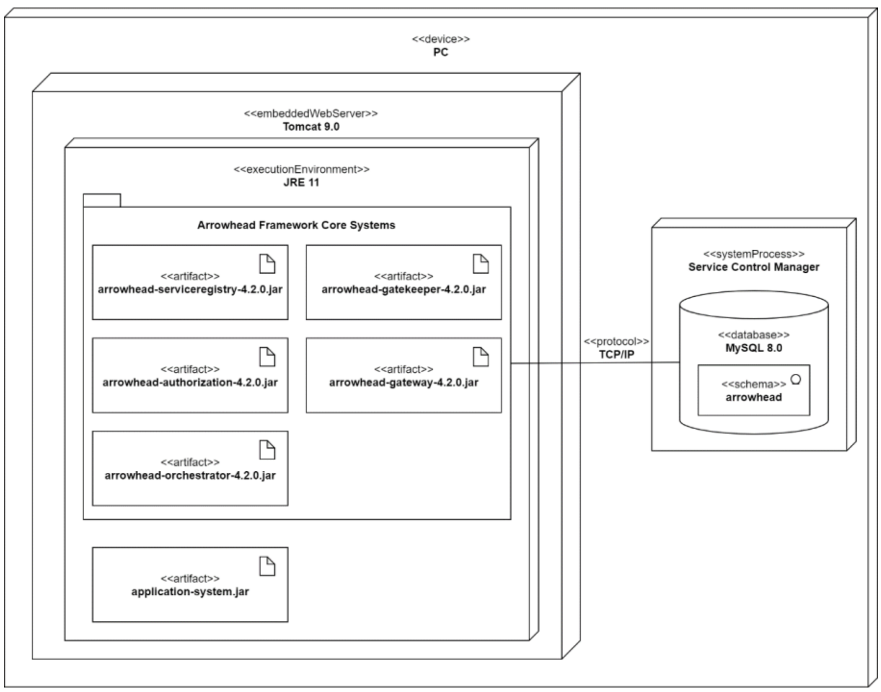

Figure 20 - Local cloud deployment diagram

For more details into the process behind the internal service interaction, we look into the sequence diagram shown in Figure 21. In this diagram, we take the service interaction between an SRC and SRP as an example. The blocks in the top row of the diagram stand for the participating systems, while the second rows mean the services provided by the specific system. We can see that the SRC sends a service request to the Orchestrator. The request initiates the Orchestrator to send service requests to two other core systems: ask Service Registry for the service provider; ask Authorization to authorize the service interaction and provide the token. With the Orchestrator response, the SRC then directly contacts the SRP and consumes service.

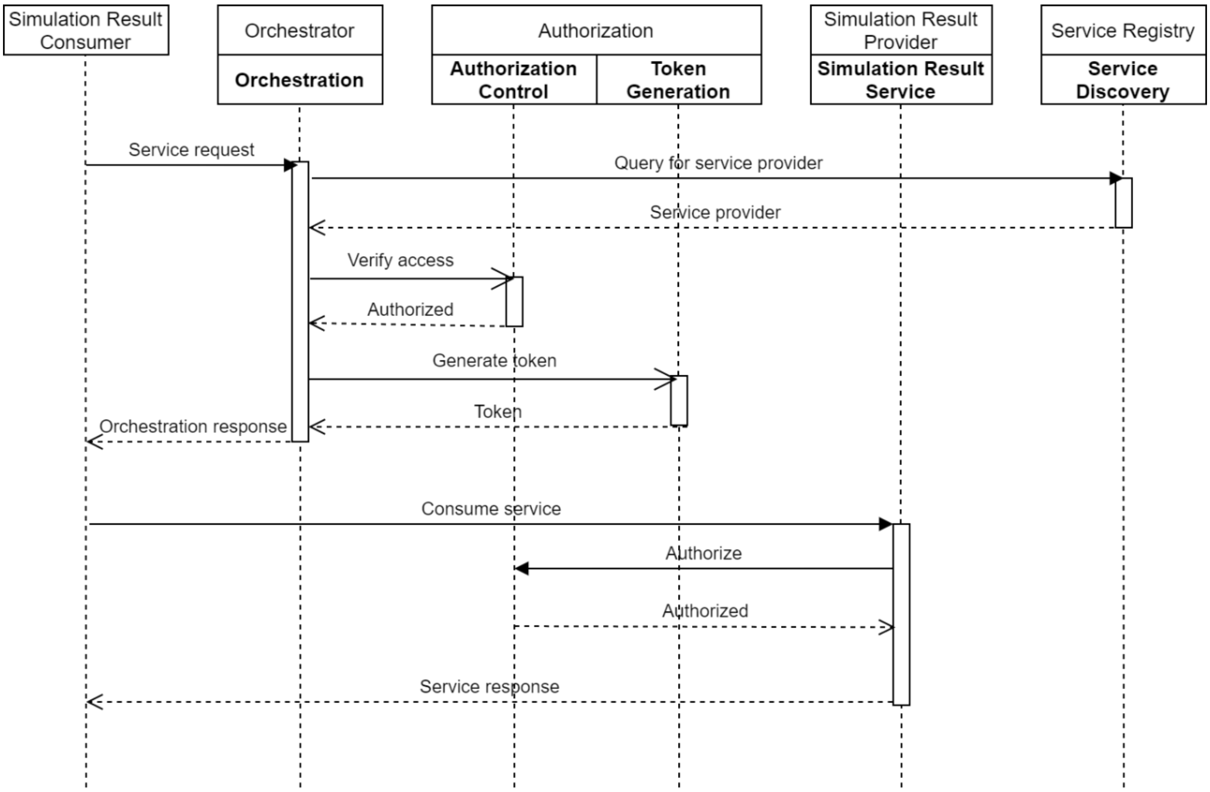

Figure 21 - Service interaction sequence diagram

5.2.3 Design alternatives and rationales

In this section, we elaborate on the existence of alternatives for the design decisions we made at the SoS level and provide the rationales behind the decisions.

5.2.3.1 Internet of things framework

As digitization is a booming trend in the industry, nowadays, numerous IoT frameworks are developed and available to be applied. Some examples of the IoT frameworks are AUTOSAR, BaSyx, FIWARE, IoTivity, LWMWM, OCF, etc.

In this project, the Arrowhead Framework was chosen to be the IoT framework that we based on for developing the pTX Coil Optimizer. Applying the AHF was one of the requirements from the stakeholders, which left us no option of working with other IoT frameworks. However, in case that applying other IoT frameworks was an option, it is a good practice to first check the general description and technical specification of the IoT framework to see if it meets the need of the project. Some issues that can be kept in mind when making such a design decision are real-time specifications, runtime features, hardware requirements, and the distribution of the systems [24].

5.2.3.2 Programming language

There is no strict requirement when it comes to the programming language for developing application systems that are compliant with the AHF.

In this project, Java was chosen to be the programming language for the implementation of the application systems of the pTX Coil Optimizer. We chose Java because the AHF was also developed based on Java and using Java led to the least chance of having compatibility issues with the AHF.

5.2.3.3 Java version

JDK / JRE 11 was chosen as the software development kit (SDK) and runtime environment of Java in the project. Version number 11 was chosen since it was one of the requirements to run AHF.

5.2.3.4 Dependency management tool

Dependency management is an important issue when it comes to the development of Java applications. Two dependency management tools that are mainly used are Maven and Gradle.

In this project, maven was chosen to be the dependency management tool. We chose Maven because the AHF was also applying Maven, we need Maven to compile and run the source code.

5.2.3.5 Database

The Arrowhead core systems need database service to manage the data such as the service definition and the authorization rules. There are plenty of options for the database service, such as PostgreSQL, MariaDB, Oracle Database, etc.

In this project, MySQL was chosen to provide database service. We chose MySQL because the AHF was also applying MySQL, we need MySQL to compile and run the source code.

5.2.3.6 Multiple local clouds or single local cloud

In this project, since performing service interaction across the different networks is one of the requirements, we applied multiple local clouds to build up the pTX Coil Optimizer.

Having multiple local clouds increased the complexity of the SoS as we had to apply two additional core systems: the Gatekeeper and the Gateway. Also, a message broker is mandatory to facilitate inter-cloud communication. Moreover, to ensure secureness, we had to generate certificates for communicating through the HTTPS protocol.

5.3 System level

In this section, we describe the application systems, as the detailed description for the core systems can be found in the web document of the Arrowhead Framework [16].

5.3.1 System description

As the SysD, we describe the functionalities of the system and the service interactions related to the systems. In this project, the term “service” refers to the exchange of information between the systems. The actions related to the end-users are addressed as “functionality”.

5.3.1.1 Coil Model Provider

The CMP is the system that the coil engineer directly interacts with. The functionalities of the CMP are listed below:

- Enables the coil engineer to transfer the electrical coil models to the one who requested.
- Enables the coil engineer to specify the electrical coil models to be transferred.

In the scope of the local cloud, the CMP provides/consumes the following services:

- Provides CoilModel Service
- Consumes ServiceDiscovery service
- Consumes AuthorizationControl service
- Consumes TokenGeneration service
- Consumes Orchestration service

5.3.1.2 Simulation Result Provider

The SRP is the system that the simulation engineer directly interacts with. The functionalities of the SRP are listed below:

- Enables the simulation engineer to request the electrical coil model from the coil engineer.
- Enables the simulation engineer to specify the directory to store the coil electrical model.
- Enables the simulation engineer to transfer the simulation result to the MR systems engineer.
- Enables the simulation engineer to specify the electrical coil models to be transferred.

In the scope of the local cloud, the SRP provides/consumes the following services:

- Provides SimulationResult Service
- Consumes CoilModel Service
- Consumes ServiceDiscovery service
- Consumes AuthorizationControl service
- Consumes TokenGeneration service
- Consumes Orchestration service

5.3.1.3 Simulation Result Consumer

The SRC is the system that the MR systems engineer directly interacts with. The functionalities of the SRC are listed below:

- Enables the MR systems engineer to request the electrical coil model from the coil engineer.
- Enables the MR systems engineer to specify the directory to store the coil electrical model.
- Enables the MR systems engineer to request the simulation result from the simulation engineer.
- Enables the MR systems engineer to specify the directory to store the simulation result.
- Provide the MR systems engineer information extracted from the simulation result in the scope specified by the MR systems engineer.

In the scope of the local cloud, the SRC provides/consumes the following services:

- Consumes CoilModel service
- Consumes SimulationResult Service
- Consumes ServiceDiscovery service
- Consumes AuthorizationControl service
- Consumes TokenGeneration service
- Consumes Orchestration service

5.3.2 System design description

In this section, we describe the internal details for the CMP and SRC. The SRP was also a service provider like CMP and had a similar design, as a result, we present only CMP. For each system, we provide the class diagrams to describe how the systems were structured, also we describe the simulation result analysis algorithm behind the SRC.

5.3.2.1 Coil Model Provider

The CMP was implemented based on the skeleton provided by the AHT project. The skeleton served as a starting point where the packages were defined and the mandatory classes relationships were built. Figure 22 shows the class diagram of the CMP.

In this project, to develop the CMP, most of the implementation were done in two packages: eu.arrowhead.client.skeleton.provider and eu.arrowhead.client.skeleton.provider.controller. The other packages were for configuration or security purposes and were not modified.

In the package eu.arrowhead.client.skeleton.provider, the class ProviderMain was the starting point of the program. In the same package, there also lied the class Constants and the class ProviderApplicationInitListener. The class ProviderApplicationInitListener was in charge of the processes such as checking the environment for CMP and registering the services provided by CMP into ServiceRegistry, as a result, we edited the class as we were adding services provided by the CMP. On the other hand, the class ProviderApplicationInitListener inherits the class ApplicationInitListener in the package eu.arrowhead.client.library.config.

In the package eu.arrowhead.client.skeleton.provider.controller, the class ProviderController contained the response of the CMP when receiving a service request. For example, we defined the response of the CMP when receiving the request for CoilModel service.

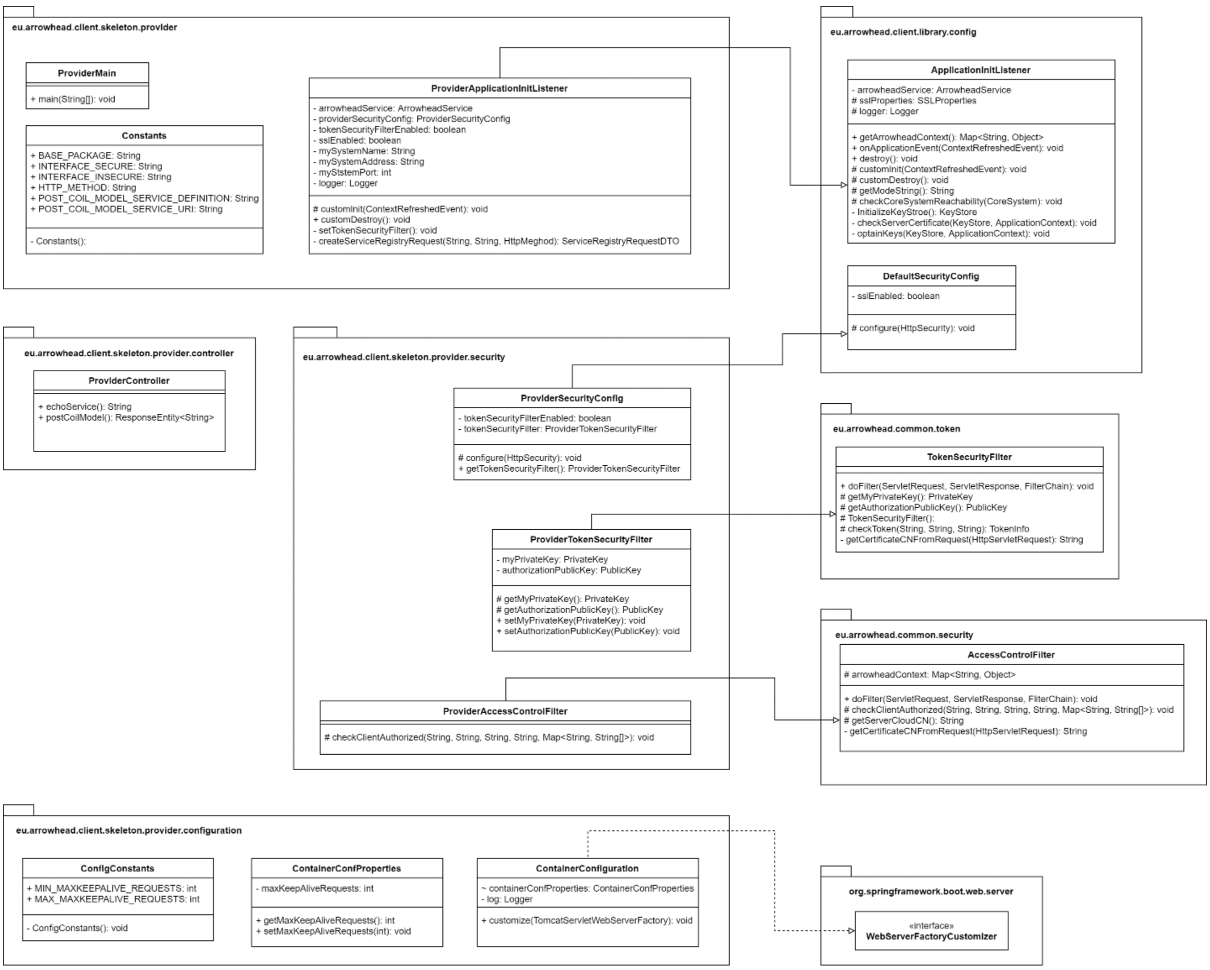

Figure 22 - Coil Model Provider class diagram

5.3.2.2 Simulation Result Consumer

The SRC was also implemented based on the skeleton provided by the AHT project, Figure 23 shows the class diagram of the SRC. In this project, to develop the SRC, the implementation was done in the package eu.arrowhead.client.skeleton.consumer. The other packages were not modified.

In the package eu.arrowhead.client.skeleton.consumer, the class ConsumerMain was the starting point of the program. As a service consumer, we implemented the service consuming logic in the class ConsumerMain, moreover, the simulation result analysis algorithm was also implemented in this class, later in this section, we describe more regarding the algorithm. The logic was implemented in the method run(), which is implemented based on the interface ApplicationRunner.

In the same package, there also lied the class Constants, Parameters, and the class ConsumerApplicationInitListener. The class Parameters was for defining the parameters used by the simulation result analysis algorithm. The class ConsumerApplicationInitListener was in charge of the processes such as checking the environment for SRC. On the other hand, the class ConsumerApplicationInitListener inherits the class ApplicationInitListener in the package eu.arrowhead.client.library.config.

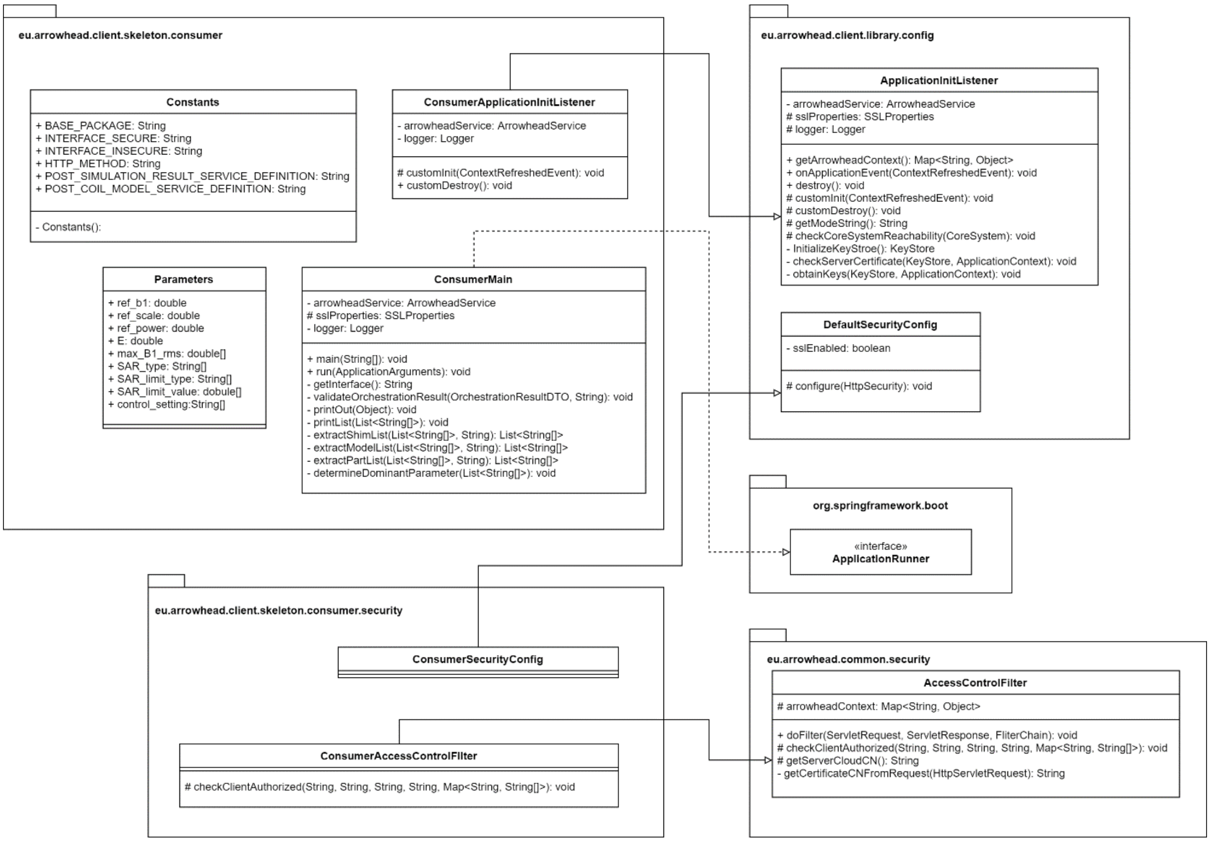

Figure 23 - Simulation Result Consumer class diagram

The automatic simulation result analysis is crucial for improving the efficiency of the MR systems engineer. The algorithm is described in Section 3.2. The automatic simulation result analysis takes the simulation result and search scope defined by the MR systems engineer as input and provides the insight that which parameter out of whole body SAR, head SAR, local extremities SAR, and local torso SAR, is the most limited one.

5.3.3 Design alternatives and rationales

In this section, we elaborate on the existence of alternatives for the design decisions we made at the system level and provide the rationales behind the decisions.

5.3.3.1 Java framework

When developing java applications, it is useful to apply the Java framework to speed up the development process. The Java framework is pre-written code that serves as a template or skeleton. The ones who apply the Java framework can focus on implementing high-level logic for specific applications and leave the lower-level configuration and setup issues to be dealt with by the Java framework. There exist many frameworks, such as Struts, Grails, Vaadin, Google Web Toolkit, etc. The developers can choose a framework based on their goal, programming skill level, and personal preference.

In this project, Spring Boot was chosen to be the Java framework that we based on when developing the pTX Coil Optimizer. The Spring Boot was chosen because of both the benefits and features of the Spring framework and embedded server. Also, the skeletons provided by the Arrowhead Tools project were developed based on Spring Boot, it was wise to apply the skeleton to speed up the development process.

5.4 Service level

In this section, we describe the CoilModel service provided by the CMP and the SimulationResult service provided by the SRP.

5.4.1 Service description

- **CoilModel service:** The CoilModel service provides coil models.
- **SimulationResult service:** The SimualtionResult service provides the simulation result report.

5.4.2 Interface design description

The CoilModel service and SimulationResult were implemented in the same way because both services were meant to transfer files.

We implemented the services in the following sequence:

1. Read the file to be transferred and save it into the byte array variable “data”.
2. Base64 encode the content of “data” and save the result into a String variable “base64String”.
3. Send the “base64String” to the service consumer.

5.4.3 Communication profile

Both the CoilModel service and the SimulationResult service were using the HTTPS protocol.

5.4.4 Semantic profile

The coil models were interpreted by the engineering drawing software. The content of simulation results was interpreted with the context of pTX Coil.

5.4.5 Design alternatives and rationales

5.4.5.1 Data type

In this project, we store the file to be sent in a byte array. In case that the file size is too big for the memory to handle, using streaming data type is an alternative.

5.4.5.2 Data encoding

Base64 served the job as we wanted to convert our byte array into String to be sent. However, as the file size increased after Base64 encoding, the measure was not recommended when the file size is large.

6 Verification & Validation

In this chapter, we first describe the evaluation process of the functional requirements in Section 6.1. Then, we describe the evaluation of non-functional requirements in Section 6.2 to Section 6.4.

6.1 Functional evaluation

The testing procedure of software can usually be divided into four stages [25]: unit, integration, system, and acceptance testing. Unit testing aims to make sure that the algorithms are correctly implemented on the individual software components. Then, in the integration test, the goal is to ensure the tested software components can properly work when integrated. After that, with the system testing the focus is to ensure all the integrated parts, including hardware can work properly together. Finally, in the acceptance test, the user uses the software system and confirms if the product meets the expectations. In this project, due to time constraints, we performed only the acceptance test with the MR systems engineer.

We carried out test sessions and have the MR systems engineer test and evaluate the implemented functions. Based on the direct hands-on experience with the pTX Coil Optimizer, the MR systems engineer verified whether the functional requirements were correctly implemented and validated whether the implementation aligned with the user's expectation.

Table 5 shows the implementation status of the functional requirements. All the requirements which were prioritized as must have were implemented, while all the requirements regarding delivering feedback were not implemented. The requirements regarding delivering feedback were not implemented due to the limited time.

Table 5 - Functional requirements implementation status

ID	Priority	Implemented	Description
F-1	Must	**Yes**	The system shall transfer the coil model (file and metadata) from the RF coil engineer to the RF coil simulation engineer.
F-2	Could	**Yes**	The system shall transfer the coil model (file and metadata) from the RF coil engineer to the MR Systems engineer.
F-3	Could	**No**	The system shall deliver feedback from the RF coil simulation engineer to the RF coil engineer.
F-4	Could	**No**	The system shall deliver feedback from the MR Systems engineer to the RF coil engineer.
F-5	Must	**Yes**	The system shall transfer the simulation result report from the RF coil simulation engineer to the MR systems engineer.
F-6	Could	**No**	The system shall deliver feedback from the MR systems engineer to the RF coil simulation engineer.
F-7	Could	**No**	The system shall deliver feedback from the MR systems engineer to the RF coil engineer.
F-8	Must	**Yes**	The system shall display the values of the requested parameter.
F-9	Must	**Yes**	The system shall provide the values of parameters derived from the parameters in the simulation result report.
F-10	Must	**Yes**	The system shall identify the dominant parameters in the simulation result.

6.2 Usability

In the context of usability, we defined eleven non-functional requirements as described in Section 4.3.2. In this project, considering the accessibility of the stakeholder, we evaluated the requirements that the tests can be performed with the MR systems engineer. As a result, in this section, we focus on evaluating the following two requirements:

"The system shall improve the efficiency of the simulation result interpretation process for the MR systems engineer."
"The system shall be easy to use."

To assess the two requirements, we performed a usability study to justify our results. We performed the usability study described in the following sections.

6.2.1 Usability study preparation

To justify the non-functional requirements in the context of usability, our usability study started with deciding which research method to adopt. After that, we decided on the data collections techniques for our study.

6.2.1.1 Research method

A research method is a set of principles that the researcher can follow when organizing the data collected. To decide which method to adopt for the research [26], the potential concerns including the theoretical stance of the researcher, the researcher's access to the resources, and whether the method is aligned with the goal of the researcher.

During the decision process, the following five methods were considered:

- Controlled experiments
- Case studies
- Survey research
- Ethnographies
- Action research

Considering that we have limited time to perform the study, also considering that we planned to have the MR systems engineer be our only user to justify the usability of the system. We decided to adopt case study as our research method.

6.2.1.2 Data collection techniques

The next step after deciding the research method was to choose the data collection techniques. Below we list the potential techniques, which are classified into direct techniques, indirect techniques, and independent techniques:

- **Direct techniques:**
    - Brainstorming and focus groups
    - Interviews and questionnaires
    - Conceptual modeling
    - Work diaries
    - Think-aloud sessions
    - Shadowing and observation
    - Participant observation
- **Indirect techniques:**
    - Instrumenting systems
    - Fly on the wall
- **Independent techniques:**
    - Analysis of work database
    - Analysis of tool use logs
    - Documentation analysis

- Static and dynamic analysis

When deciding the data collection techniques, the main concern is whether the techniques are suitable for the study's unit of analysis, which is the MR systems engineer in our study. Based on our condition, we decided to adopt interviews and questionnaires as our data collection techniques.

6.2.2 Usability study

In this section, we first describe the modified Technology Acceptance Model (mTAM) that we adopted for formulating the questionnaire. Then, we elaborate on the data collection process that we performed with the MR systems engineer.

6.2.2.1 Modified Technology Acceptance Model

To evaluate the usability of a system, besides the objective components such as efficiency and effectiveness, one important factor is the perceived usability [27]. To assess the perceived usability formally, standardized questionnaires were proposed, some examples are the Technology Acceptance Model [28] (TAM), System Usability Scale [29] (SUS), and Usability Metric for User Experience [30] (UMUX). Among the mentioned standard questionnaires, TAM evaluates both perceived usefulness (PU) and perceived ease of use (PEU), the definitions for PU and PEU are listed below:

- **PU:** "The degree to which a person believes that using a particular system would enhance his or her job performance."
- **PEU:** "The degree to which a person believes that using a particular system would be free of effort."

As the TAM is formulated to predict the likelihood of use, in order to evaluate the experience after using the pTX Coil Optimizer, we adopted the modified Technology Acceptance Model [27] (mTAM). The mTAM was formulated with the questions shown in Table 6. For each question, the user grades in the range 1 to 7 as 1 means extremely disagree and 7 means extremely agree.

Table 6 - Questions of the mTAM

Perceived Usefulness	Perceived Ease-of-Use
Using pTX Coil Optimizer in my job enables me to accomplish tasks more quickly than without using the pTX Coil Optimizer.	Learning to operate the pTX Coil Optimizer was easy for me.
Using pTX Coil Optimizer improves my job performance.	I found it easy to get the pTX Coil Optimizer to do what I want it to do.
Using pTX Coil Optimizer in my job increases my productivity.	My interaction with pTX Coil Optimizer has been clear and understandable.
Using pTX Coil Optimizer enhances my effectiveness on the job.	I found the pTX Coil Optimizer to be flexible to interact with.
Using pTX Coil Optimizer makes it easier to do my job.	It was easy for me to become skillful at using the pTX Coil Optimizer.
I have found the pTX Coil Optimizer useful in my job.	I found the pTX Coil Optimizer easy to use.

6.2.2.2 Test session

During the test session, the following procedure was followed:

1. An introduction of the pTX Coil Optimizer was provided to the MR systems engineer.
2. The MR systems engineer operated the pTX Coil Optimizer.
3. The MR systems engineer filled in the mTAM questionnaire.
4. The MR systems engineer was interviewed regarding the experience of using the pTX Coil Optimizer.

In this project, the test was performed twice.

6.2.3 Results

We performed the test twice, the test performed earlier is addressed as test A, while the latter one is addressed as test B. In this section, the results of the two tests are both provided. The test results were in two categories, one was the quantitative result based on the mTAM questionnaire, another was the qualitative results based on the interpretation of the questionnaire results and the interview.

6.2.3.1 Quantitative Results

The result of the mTAM questionnaire is shown in Table 7. The results of test A are addressed in red crosses, while the results of test B are addressed in blue crosses.

Table 7 - Result of the mTAM questionnaire

	1	2	3	4	5	6	7
Using pTX Coil Optimizer in my job enables me to accomplish tasks more quickly than without using the pTX Coil Optimizer.				X		X	
Using pTX Coil Optimizer improves my job performance.				X		X	
Using pTX Coil Optimizer in my job increases my productivity.				X		X	
Using pTX Coil Optimizer enhances my effectiveness on the job.				X		X	
Using pTX Coil Optimizer makes it easier to do my job.			X			X	
I have found the pTX Coil Optimizer useful in my job.				X		X	
Learning to operate the pTX Coil Optimizer was easy for me.		X			X		
I found it easy to get the pTX Coil Optimizer to do what I want it to do.			X		X		
My interaction with pTX Coil Optimizer has been clear and understand-able.			X			X	
I found the pTX Coil Optimizer to be flexible to interact with.		X			X		
It was easy for me to become skillful at using the pTX Coil Optimizer.		X			X		
I found the pTX Coil Optimizer easy to use.			X		X		

6.2.3.2 Qualitative Results

To further interpret the mTAM result descriptively, we first separately convert the score of PU and PEU into the range from 0 to 100. The converting process can be done as described below [27]:

1. Compute the mean of the item scores.
2. Subtract one from the mean.

3. Multiply by 100/6.

The converted scores are shown in Table 8:

Table 8 - mTAM questionnaire results in the range of 0 to 100

	Test A	Test B
PU	47.2	83.3
PEU	25	69.4

There was no benchmark for mTAM to describe the meaning of the score. However, as the SUS was designed similarly to mTAM, we adopted the benchmark of SUS as shown in Figure 24.

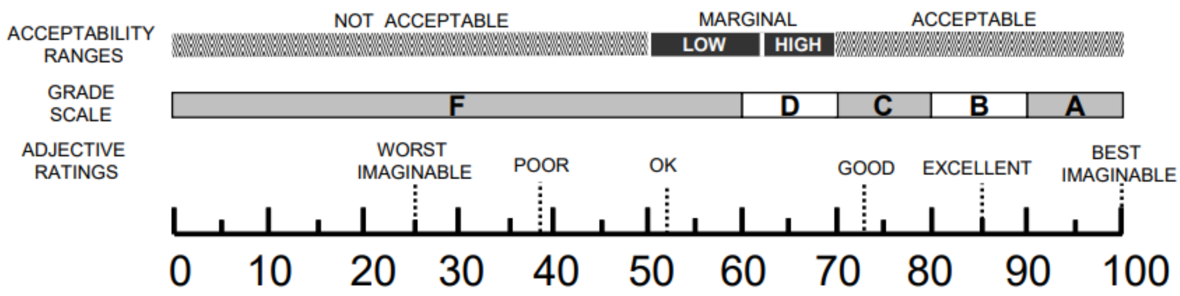

Figure 24 - Comparison of the SUS score and the adjective ratings, grade scale, and acceptability ranges [31]

We adopt the adjective ratings in Figure 24 to describe our results shown in Table 8. The results are shown in Table 9.

Table 9 - Adjective ratings for the results of the mTAM questionnaire

	Test A	Test B
PU	Between poor and ok, prone to ok	Between good and excellent, prone to excellent
PEU	Worst imaginable	Between ok and good, prone to good

On the other hand, during the interview, the MR systems engineer provided comments and feedback on the pTX Coil Optimizer, the list of the tips and tops from the MR systems engineer, also the questions and transcript of the interview, can be found in Appendix B.

Table 10 - Tips and tops from MR systems engineer after Test A

	Test A
Tips	• It is complicated and old-fashioned that you need to copy and execute several instructions in the command line to start the system. • The system is not flexible in the sense that when choosing a human model and anatomy, the user can only decide out of the provided options. • The system shall consider more anatomies, e.g., head. • The algorithm of the simulation result interpretation shall be adjusted. • The document regarding the launching process of the system is too cryptical.
Tops	• After the system has been launched, the system seems good in that the experience of navigating to the extracted data of specific human models and anatomies feels fine. • The interface to extract information for different body models and different anatomies. • The way to display the extracted data looks quite good. • Based on the current status, using the system may save 30% of development time comparing to not using the system. • The system automatically extracts the information that is otherwise done manually.

Table 11 - Tips and tops from MR systems engineer after Test B

	Test B
Tips	• The UI is slightly primitive, but it doesn't matter, it was clear enough. • The inter-cloud service interaction was not completely in place in the Philips environment, but that is due to the IT limitations. • The MR systems engineer wants to know how to modify the analysis logic if needed. • The complete flow, from core design to core simulation to core data is missing.
Tops	• The good analysis provides the information that the MR systems engineer desires. • The system provides the flexibility to select what the MR systems engineer wants. • Easy to do the selection and analysis. • The instruction of how to use the system was clear, a very clear presentation about how it works and how it is organized. • The system decreases the simulation result analysis time from a few hours to less than 15 minutes. • The information is displayed clearly.

6.2.4 Discussion and conclusion

In this section, we first describe the improvement of the pTX Coil Optimizer between Test A and Test B. Then, we describe how the questionnaire results and interview results are aligned. Finally, we describe the verification and validation results of the two usability requirements.

6.2.4.1 Improvement between tests

As we can see from Table 8 and Table 9, the pTX Coil Optimizer improved significantly in the two tests, to put it descriptively, the PU improved from almost ok to almost excellent, while the PEU improved from worst imaginable to almost good.

The improvement was because of the modifications toward two directions, user experience, and simulation result analysis algorithm. In terms of user experience, the launching procedure of the pTX Coil Optimizer was simplified from executing several instructions on the command line interface to double-clicking on two icons; also, the flexibility when using the pTX Coil Optimizer was improved, e.g., when making decisions, the user could actively describe the desired option instead of merely choosing from the provided options. In terms of the simulation result analysis algorithm, the improved algorithm is as described in Section 3.2. As a result of the improvement, one of the Tips in Test A was "The algorithm of the simulation result interpretation shall be adjusted." After thoroughly modified the algorithm, one of the Tops in Test B was "The good analysis provides the information that the MR systems engineer desires."

6.2.4.2 Verification and validation result

Looking back into the initial goal of the usability study, to assess the following two non-functional requirements:

"The system shall improve the efficiency of the simulation result interpretation process for the MR systems engineer."
"The system shall be easy to use."

The pTX Coil Optimizer did improve the efficiency. As shown in Table 11, the MR systems engineer stated that the pTX Coil Optimizer decreases the time needed for simulation result analysis from a few hours to less than 15 minutes. The good result was achieved by multiple discussions with the MR systems engineer for defining the simulation result analysis algorithm, which led to the algorithm that was aligned with the MR systems engineer's need.

On the other hand, in terms of being easy to use, the pTX Coil Optimizer was considered as almost good. On the good side, the simple launching procedure, flexibility of making selections, the clear way of displaying information, together with the clear instruction of how to use the pTX Coil Optimizer, made the system easy to use. However, as the user interface of the pTX Coil Optimizer was in the command line, it was considered slightly primitive.

6.3 Security

In the context of Security, three non-functional requirements that were prioritized as must have were defined as described in Section 0:

"The system shall ensure data security by transferring data through a secured protocol."
"The system shall store the data of Philips in the scope of Philips."
"The system shall process the data of Philips in the scope of Philips."

The "data" that shall be protected in both the design phase and runtime is the data regarding the design of the pTX Coil and the data regarding the simulation result. In the design phase, we strictly keep all the data of pTX Coil not to be transferred outside the device of Philips. On the other hand, in runtime, the system that retrieves the data of pTX Coil was executed only on the device of Philips. Also in runtime, when the data needs to be transferred, across the internet, the data were transferred through HTTPS, which is a secured protocol [32]. As a result, the three non-functional requirements in the context of security were addressed.

6.4 Arrowhead

In the context of Arrowhead, two non-functional requirements that were prioritized as must have were defined as described in Section 0:

"The system shall be implemented based on the core systems of the Arrowhead Framework."
"The system shall apply the architecture that is compliant with the Arrowhead Framework."

As described in Chapter 5, the architecture of the pTX Coil Optimizer is based on the local cloud concept of the Arrowhead Framework; also, the core systems of the Arrowhead Framework were applied to realize the service interaction between the systems in the scope of the pTX Coil Optimizer. As a result, the two non-functional requirements in the context of Arrowhead were addressed.

7 Project Management

To maximize the chance to complete the project goals in the limited time frame, we introduced project management into our project since the beginning of the project. A project management plan (PMP) was formulated. The PMP was reviewed and approved by the project mentor.

In this chapter, we first introduce the original PMP, then we talk about major changes in terms of project management during the project period. Afterward, we provide an overview of how the development process actually went and what the result was.

7.1 The original plan

The original PMP was formulated one month after the start of the project, right after the preliminary study of the project context. The structure of the PMP was based on the ISO 16326. The ISO 16326 is an ISO standard that provides a complete guideline for managing projects which are concerning software-intensive systems.

Based on the purpose and scope of the project, also considering the assumptions and constraints we had, the deliverables of the project were the following items:

- **Project management plan:** The document that covers the project overview, context, planning, assessment, and supporting plans.
- **Demo sessions:** The sessions that show how the implemented system works.
- **Final presentation:** The presentation takes place at the end of the project that concisely shows the process of development and the final product.
- **Final report:** The document that elaborates on the methods used, design decisions made, and evaluation of the final product.
- **Source code:** The source code of the final product is provided with supporting documents.
- **Intermediate presentations:** The intermediate status presentations for the Arrowhead Tools project.

To timely deliver the deliverables at the end of the project, as shown in Figure 25, we break down the development of the pTX Coil Optimizer into four major work activities shown in the blue boxes. In the blue boxes, the work activities are shown on the upper part, the deliverables are shown on the bottom part with bold fonts, and the factors to be tested or reviewed are shown in the white box in the middle. On top of the blue boxes, it shows that the V-model will be applied for each activity. Between the blue boxes, the arrows show the information flow between activities.

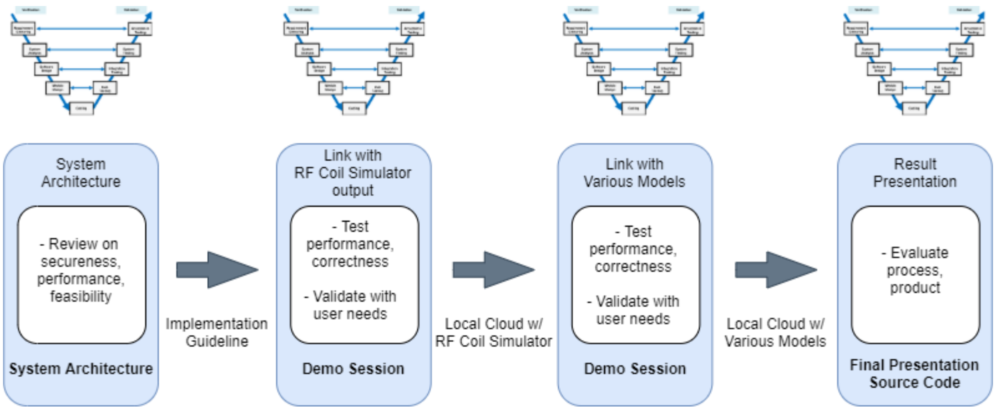

Figure 25 - Process model diagram

Furthermore, the Kanban method was used to manage the works in the project. We used both the Kanban board and the Roadmap, both were implemented on the Jira Software. On the Kanban board, the tasks were categorized into five categories, which were To do, In Progress, Today, In Review, and Done. On top of the Kanban board, the Roadmap is formulated to show the overall progress of the project.

To have an overview of what activities are involved in the project scope, we formulated the work breakdown structure diagram (WBS) as shown in Figure 26. The top-level activities are the ones in the light blue blocks, and the activities in the white blocks are assumed based on the technical knowledge and experience of the developer.

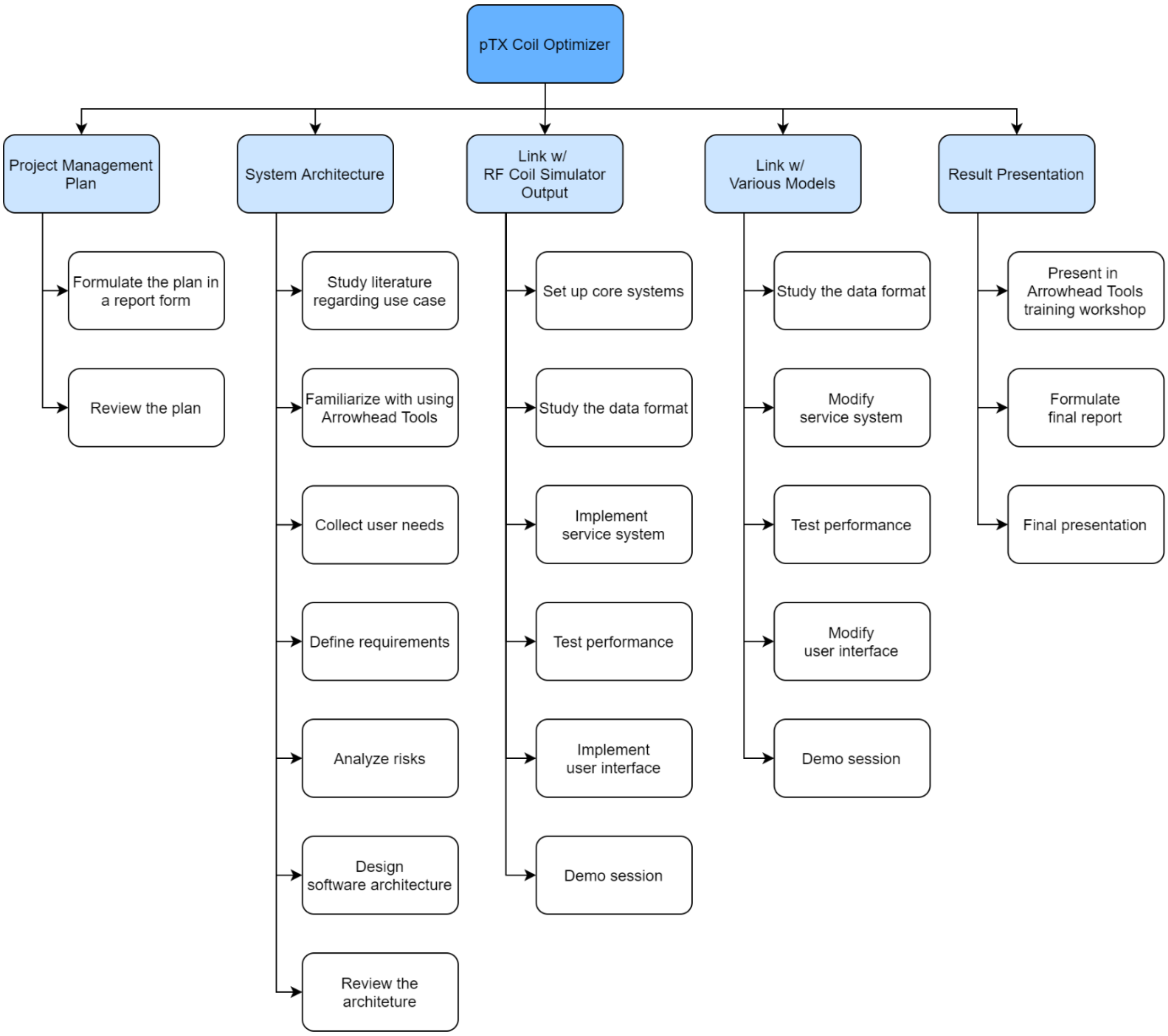

Figure 26 - Work breakdown structure diagram

Figure 27 shows the first version of the project schedule. The detailed activities listed in the schedule were based on the formulated work breakdown structure diagram.

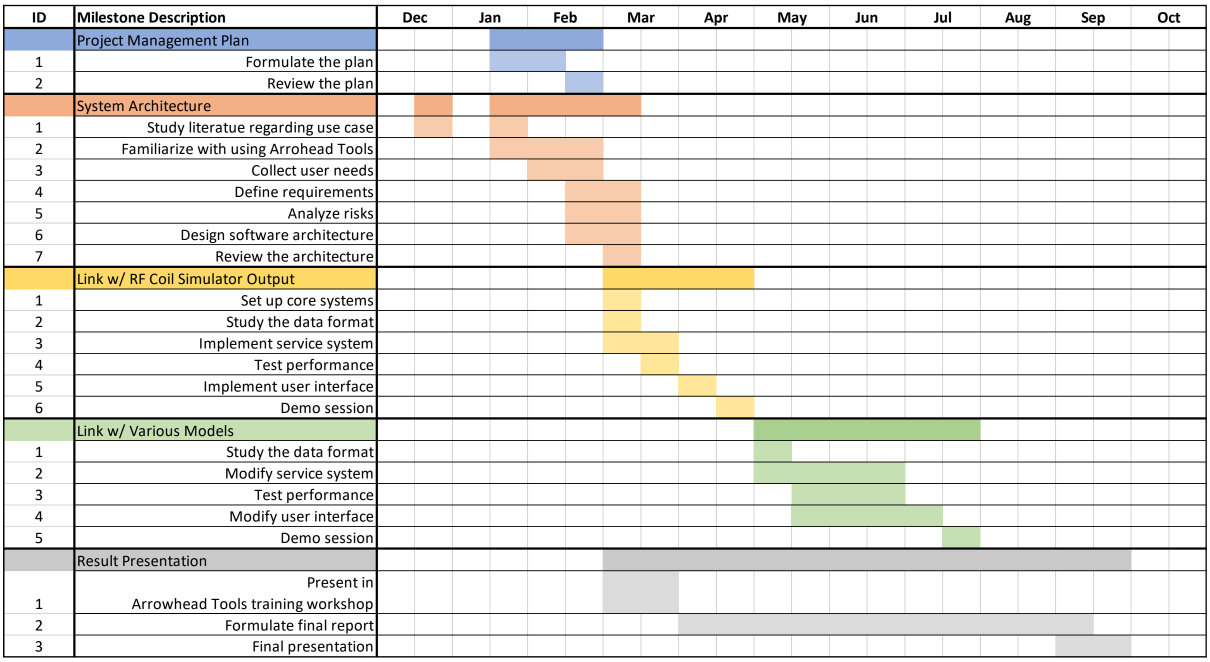

Figure 27 - Project schedule

At the starting phase of the project, we also performed risk analysis. However, as we had limited knowledge of the project context and user needs, the risk analysis focused on the process risks instead of the product risks. The identified risks are shown in Section 4.2.3.

The whole project management plan for the project can be found in Appendix D.

7.2 Major changes

Right before the middle of the project, at the end of April, as we gain more understanding of the Arrowhead Framework, we realized that the architecture of the pTX Coil Optimizer had to be changed from a single local cloud to multiple local clouds to meet the requirement of enabling cross-network service interaction. Since the significant change of the architecture may lead to a delay in the project progress, we took time to again assess the development process. The assessment led to the following major changes in the scope of project management.

7.2.1 WBS modification

The first version of WBS is shown in Figure 28. The top-level activities were the different stages that we planned to go through, however, this way to formulate the WBS was not appropriate since the development didn't go through the stages that we planned. As a result, we formulated the WBS again by assigning the deliverables as the top-level activities.

As shown in Figure 28, the top-level activities were modified to be the deliverables, i.e., the PMP, System modeling, Intermediate Presentation, Demo, Final Presentation, Final Report, and Source Code. The modification enabled us to have a clearer view of what activities are ahead of us towards accomplishing the deliverables. Moreover, the diagram served as a great reference when formulating the Roadmap.

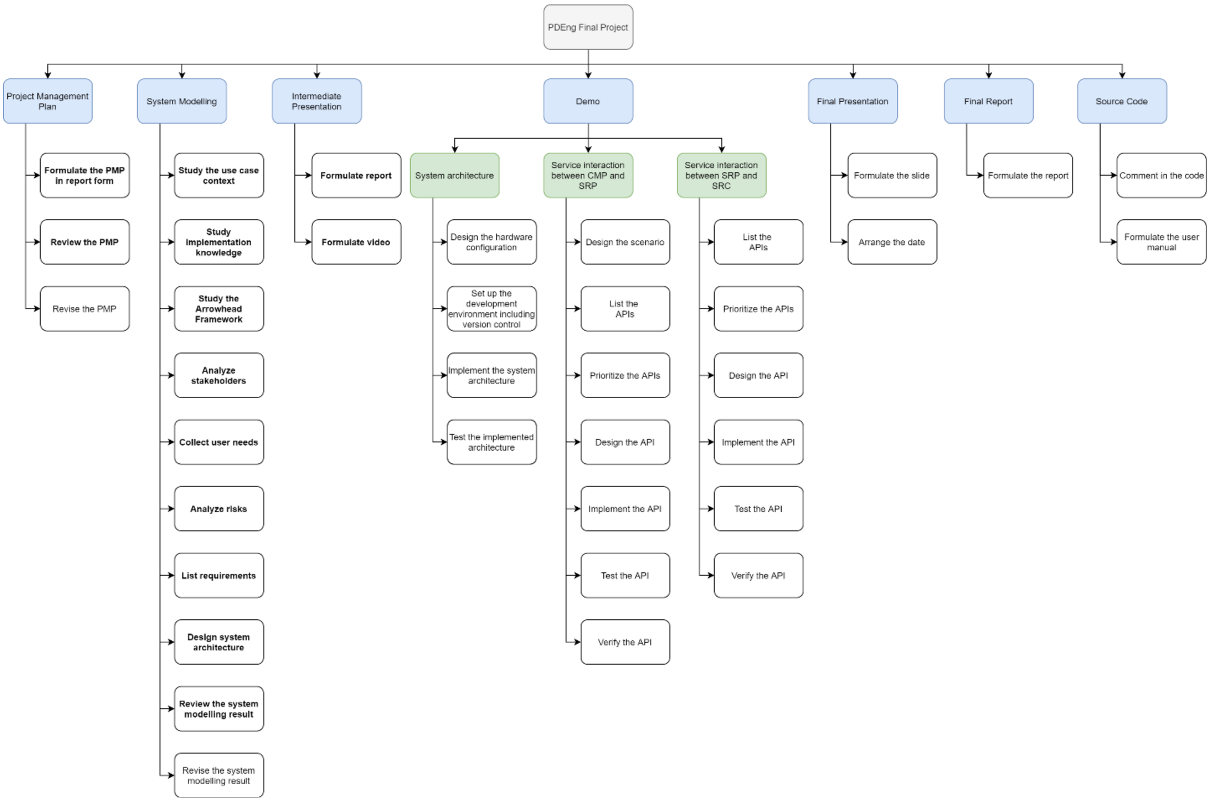

Figure 28 - Modified work breakdown structure diagram

7.2.2 Kanban to Scrum

At the beginning of the project, we adopted the Kanban method as we expected the method could bring us continuous flow. However, after four months of using the Kanban method, we realized two issues that were not ideal for us:

- In the early stage of the project, we were not familiar with the background knowledge for the project, as a result, we were not able to define work items into enough granularity. Together with the nature of no time restriction for work items in Kanban. The lead time for work items became too long.
- As more and more work items piled up in the To-Do category, we felt stressed and found it difficult to prioritize which work item should be taken care of.

Noticing the two issues, we decided to change our strategy from Kanban to Scrum. By adopting Scrum, the concept of focusing on the assigned tasks in one sprint fixed the two issues. For the first issue, the time restriction imposed by the sprint concept motivated us to accomplish our tasks timely. For the second issue, as we only had to focus on the assigned tasks, we avoided being stressed by looking at a pile of tasks stuck in the To-Do category of Kanban.

Besides adopting Scrum, we were still using Roadmap, hence, we were able to keep track of the over-all progress by looking at the Roadmap and focusing on the assigned tasks in one sprint.

7.2.3 Stop using the Jira software

In the original project management plan, we decided to adopt the Jira software as the tool to keep track of the Kanban board and the Roadmap. After using the Jira software for more than two months, we were still not used to the software since the software provided too many features that were not needed for us, oppositely, made the user interface too complicated. Noticing this issue, we decided to use Microsoft Excel to formulate the Roadmap and the table to keep track of the sprints by ourselves.

7.3 The actual progress

A table that tracks the progress of the project is shown in Appendix C.. The table shows the time spent for tasks using the week as a unit. The tasks are categorized into six major categories:

- Administrative
- System Modelling
- Project Management Plan
- Presentation
- Demo
- Final Report

The table shows that before February, most of the time spent was for literature review and formulating the project management plan. Then, from March to April, we identified the requirements, designed the first version of system architecture, and had a workshop on the Arrowhead Tools project, where we had to present our status. Next, from May to July, the second version of the system architecture was designed and further system design and implementation were performed. After two weeks of holidays in July, we then started testing and formulating the final report.

8 Conclusions

In this chapter, we first describe the results of the development of the pTX Coil Optimizer in section 8.1. Then, we provide recommendations of directions to improve the pTX Coil Optimizer and our thoughts on the Arrowhead Framework.

8.1 Results

In this project, we presented the pTX Coil Optimizer, a tool that was developed with the following two goals:

- Improve the efficiency of the development process of the pTX Coil.
- Improve the performance of the pTX Coil.

The first goal was addressed with the two functionalities provided by the pTX Coil Optimizer:

- Enable the file transfer between users across different local networks in a secured protocol.
- Automatically extract information from the simulation result raw data.

The second goal was addressed as the simulation result analysis tool prevents the user from overlooking information due to the manual data extraction process.

The pTX Coil Optimizer was implemented based on the Arrowhead Framework. Three local clouds were configured to realize the cross-network service interactions. The communications between the different local clouds were facilitated by the core systems Gatekeeper and Gateway. In each local cloud, an application system that serves as the user interface was implemented. One of the application systems was embedded with the simulation result analysis tool. The tool was implemented based on the experience and knowledge of the MR systems engineer.

8.2 Recommendations and future work

In the project, the infrastructure for service interactions across different networks has been implemented. To further improve the pTX Coil Optimizer, we propose two directions to head to:

- **Integration with the legacy systems:** Currently, the pTX Coil Optimizer and the legacy systems such as the coil design environment and the RF field simulator are not integrated, having the legacy systems integrated into the pTX Coil Optimizer may improve the file transfer functionality, as the user can make use of the functionality in the environment that they are already working in, instead of launching a separated user interface.
- **Graphical user interface:** Currently, the users of the pTX Coil Optimizer are using the system through the command-line interface, which significantly limits the level of ease-of-use of the pTX Coil Optimizer. To implement the graphical user interface, the developer shall first consult with the users regarding the desired user experience.

Regarding applying the Arrowhead Framework to develop the pTX Coil Optimizer, the framework provides an access to connect various systems across different networks securely, which is a significant adding value. However, we would suggest that the framework may provide more adding values when the systems which are connected are automated. In our case, the coil design process and the RF field simulation process are both highly dependent on human knowledge and operation.

8.3 Works to be done in near future

In this section, we list the works that we didn't manage to finalize before submitting the report to the exam committee members. These works are planned to be done by the end of the PDEng study of the PDEng Trainee Wan-Yi.

- Unit testing of the software units for simulation result analysis.
- Documentation regarding the source code of the simulation result analysis.
- Documentation for deploying the pTX Coil Optimizer.
- Deploy the pTX Coil Optimizer on the devices of the MR system engineer and the RF coil simulation engineer.

9 Project Retrospective

In this chapter, we first take a look back into the risk analysis and see if the risks identified happened or not. After that, we talk about the lessons learned by the PDEng Trainee Wan-Yi.

9.1 Revisit risk analysis

In Table 12 we list the risks identified at the beginning of the project and describe if the risk happened and what the impact was. For the process risk, three out of the five risks did happen and two of the risks that happened led to delay in the project progress. On the other hand, for the product risk, two of the seven identified risks happened and the happened all led to a delay of the implementation phase.

Table 12 - Actual impact of the risks identified

Process Risk (The risks of which the source is the development process)				
Risk	**L**	**I**	**Rate**	**Actual impact**
Lack of expertise for the trainee in terms of applying Arrowhead Framework.	4	3	Moderate	The risk did happen, which led to the impact that the developer got the confidence and knowledge to implement various functions and scenarios at the later stage of the project period.
Limited stakeholder availability at the start of the project.	2	4	Low	This risk did not happen.
Supporting issue of Arrowhead Framework.	1	5	Low	This risk did not happen.
Change of requirements.	3	3	Moderate	This risk did happen. The change of functional requirements led to a longer implementation period.
Deliverable needs from the Arrowhead Tools project.	5	1	Low	This risk did happen. The impact was low as the developer was properly informed of the deadline of submitting the deliverables and could make plans accordingly.
Product Risk (The risks of which the source is the end product)				
Risk	**L**	**I**	**Rate**	**Actual impact**
The software architecture of the system is not properly designed.	3	3	Moderate	This risk did happen. The first version of the software architecture designed in February was not addressing the need for cross-network communication. The version that addressed the cross-network communication was designed at the beginning of April. The impact was the delay of implementation.
The system is not able to provide the simulation result produced by the simulation engineer.	1	5	Low	This risk did not happen.
The system is not able to successfully transfer information between the stakeholders.	2	4	Low	This risk did not happen.

The MR methods engineer is not able to retrieve the simulation results based on various human body models and regions of interest.	4	4	High	This risk did not happen.
The simulation result is not user-friendly for the MR methods engineer.	3	4	Moderate	This risk did happen in the first version of the pTX Coil Optimizer, which led to the modification of the pTX Coil Optimizer. The impact was the elongation of the implementation.
The file transfer needs a manual operation to accomplish.	3	4	Moderate	This risk did not happen.
The file transfer process leaked the confidential data of Philips to the public network.	1	5	Low	This risk did not happen.

9.2 Challenges and lessons learned

During the one-year project, there were multiple challenges emerged. By overcoming the challenges, the PDEng trainee gained experiences and learned lessons that enable him to become a better developer/engineer.

The main source of the challenges was the fact that the trainee was lack of background knowledge in the scope of the project. Most of the technical fields related to the implementation of the pTX Coil Optimizer were new to the trainee, including the coding language, the database management system, the internet application, etc.

The situation led to the challenge that the trainee had to pick up the knowledge as soon as possible to be able to come up with a reasonable design and even actually implement the design. At the same time, stakeholder management was an issue since the trainee had to make the stakeholder believe that the development process was on track.

After went through the challenges, the trainee built up his method of picking up knowledge, which applies to various learning scenarios. On the other hand, in terms of stakeholder management, the major learning point is that fast and transparent communication is the key to enabling the stakeholders to have faith in your development process.

Glossary

AHT project	Arrowhead Tools project
MRI	Magnetic Resonance Imaging
RF	Radio Frequency
UHF	Ultra-High Field
SAR	Specific Absorption Rate
pTX Coil	parallel transmit coils
IoT	Internet of Things
IT	Information Technology
OT	Operational Technology
SoS	System of Systems
AHF	Arrowhead Framework
coil engineer	RF Coil Engineer
simulation engineer	RF Simulation Engineer
TU/e	Eindhoven University of Technology
PDEng	Professional Doctorate in Engineering
WP	Work Package
UC	Use Case
MR	Magnetic Resonance
SOA	Service-Oriented Architecture
CMP	Coil Model Provider
SRP	Service Result Provider
SRC	Service Result Consumer
SoSD	System of Systems Description
SoSDD	System of Systems Design Description
SysD	System Description
SysDD	System Design Description
SD	Service Description
IDD	Interface Design Description
CP	Communication Profile
SP	Semantic Profile
ICN	Inter Cloud Negotiation
JRE	Java Runtime Environment
SDK	Software Development Kit
mTAM	modified Technology Acceptance Model
SUS	System Usability Scale
UMUX	Usability Metric for User Experience
PU	Perceived Usefulness
PEU	Perceived Ease of Use
PMP	Project Management Plan
WBS	Work Breakdown Structure

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Appendix A.

Two tables are shown, one for the process risks, another for the product risks.

Process (The risks of which the source is the development process)				
No.	**Risk**	**Damage**	**Cause**	**Notes** **(Reason for assigned values)**
1	Lack of expertise for the trainee in terms of applying Arrowhead Framework.	Delay in project timeline due to longer study phase.	It is recommanded to use Java when applying Arrowhead Framework, which is a programming language that the trainee has no experience with. Also, the Arrowhead Framework involves knowledge domain of web application, database, and SOA, these are also new domains for the trainee.	**L:** Likely to happen due to the lack of experience in various software development domain of the trainee. **I:** Significant impact because the core of the final product is implemented by applying the Arrowhead Framework.
2	Limited stakeholder availability at the start of the project.	Lack of instant feedback from the stakeholders may lead to delay of critical design decisions and technical progress.	The stakeholders are working from home due to the pandemic. There are other major tasks for the stakeholders. The stakeholders take holidays.	**L:** Unlikely to happen because the stakeholders are actively providing support and feedback. **I:** Significant impact because the content of the project is new for the trainee.
3	Supporting issue of Arrowhead Framework.	Delay in project timeline. Or even failure of the project due to certain function is not feasible in the project period.	The Arrowhead Framework is still in development process.	**L:** Very unlikely to happen due to the mandatory core systems of Arrowhead Tools are developed. **I:** Significant impact because it may lead to failure of the project.
4	Change of requirements.	Delay in project timeline.	The stakeholders may come up with new user needs as they got inspired by the latest development result.	**L:** Possible to happen due to that this project is building a platform that is scalable in terms of feature. **I:** Moderate impact because that when the new user need rises, the trainee may also be equipped with the ability to add more features.
5	Deliverable needs from the Arrowhead Tools project.	Delay in project timeline due to working hours occupied by the deliverable work.	The project is an EU subsidy project and there are requests of deliverables.	**L:** Very likely to happen due to there are workshop planned during the project period. **I:** Minor impact because the deliverables are align with the PDEng project work.

Product (The risks of which the source is the product)				
No.	**Risk**	**Damage**	**Cause**	**Notes** **(Reason for assigned values)**
1	The software architecture of the system is not properly design.	Limit the performance and scalability of the system.	The trainee is lack of experience in software development in the Arrowhead Framework domain.	**L:** Possible to happen due to the lack of background knowledge in software architecture of the trainee. **I:** Moderate impact because the pTX Coil Optimizer may still be functional.
2	The system is not able to provide the simulation result produced by the simulation engineer.	The later stage of development will not be able to proceed with using the system, which may lead to project failure.	1. The requested way of releasing simulation result is not feasible for the simulation engineer. 2. The simulation engineer is not able to produce the simulation result in the requested format.	**L:** Very unlikely to happen because the simulation engineer is counsulted by the trainee. **I:** Severe impact as descrbed in damage part.
3	The system is not able to successfully transfer information between the stakeholders.	The MR systems engineer's user need is not satisfied.	1. The communication channel is not properly facilitated. 2. The project time is not enough for implementing the function.	**L:** Unlikely to happen because the function shall be properly designed. **I:** Significant impact as the communication between the stakeholders is part of the WP objectives.
4	The MR methods engineer is not able to retrieve the simulation results based on various human body models and regions of interest.	The MR methods engineer's user need is not satisfied.	The requested simulation result does not exist.	**L:** Likely to happen because the simulation process for one type of human body model takes at least two weeks and there are only two human body models available. **I:** Significant impact as this is one essential adding value from the project.
5	The simulation report is not user-friendly for the MR methods engineer.	The MR methods engineer's user need is not satisfied.	The display format of the simulation result does not align with the MR methods engineer's expectation.	**L:** Possible to happen due to the challenging nature of understanding user's expectation. **I:** Significant impact since the user can evaluate the successfulness of the project.
6	The file transfer needs manual operation to accomplish.	The MR systems engineer's user need is not satisfied.	The file transfer functionality needs more user operations than the MR systems engineer expected.	**L:** Possible to happen due to the nature of the files to be transferred. **I:** Significant impact since the user can evalue the successfulness of the project.
7	The file transer process leaked the confidential	The confidential agreement is violated.	The file transfer protocol is not secured.	**L:** Unlikely to happen since the file transfer protocol is properly chosen. **I:** Severe impact as described in damage part.

Appendix B.

Here we show the questions asked during the interview and the transcript of the two interviews.

The list of the questions:

1. Overall, how was your experience with the pTX Coil Optimizer?
2. Which things did you like the best about the pTX Coil Optimizer? Why?
3. Which things did you like the least about the pTX Coil Optimizer? Why?
4. If you could change something about the pTX Coil Optimizer, what would it be? Why?
5. What do you think is still missing in the pTX Coil Optimizer? Why?
6. What do you think about the pTX Coil Optimizer's documentation?
7. How much time do you think you saved by using the pTX Coil Optimizer, comparing to without using the pTX Coil Optimizer?
8. In your experience, how did the pTX Coil Optimizer save your time?
9. Is the pTX Coil Optimizer displaying the requested result in a clear way?
10. Why would you or would you not recommend pTX Coil Optimizer to a friend or colleague?

<u>Transcript from Test A:</u>
Parts of the conversation that were not related to the interview questions were removed.

Interviewer	This will be the interview for Peter regarding the pTX Coil Optimizer system. And the first question will be, overall, how was your experience with the pTX Coil optimizer?
Interviewee	Well, though it has been demonstrated to me, but **how this system was started looked complicated was a bit old-fashioned in a command line. And you had to copy several instructions to get started.** Yeah, that was not I would probably be able to reproduce that part. Oh, after having it started. It was good. And then the interface that we had at the end, where you can select the different body models and anatomies. Looks fine.
Interviewer	Yeah, okay.
Interviewee	So point two, which things that **I like the best, are the interface at the end, where you could extract information for different body models and different anatomies.** Okay. **The least was the starting of the whole simulator.**
Interviewer	I see. Okay. So that would be question three. And then for question four, if you could change something about the pTX Coil Optimizer? What would they be?
Interviewee	If there would be just an icon that directly clicks then the whole thing starts would be obviously much easier. Instead of copying things from a script file to a command prompt. **And I haven't seen yet but you said that they're supposed to be different reports with different anatomies and different models? I don't know. So if there is an interface that makes it easy to modify, or automatically.**
Interviewer	I can add a feature just to say if you want to, I mean, there will be another question popping up saying, which model Do you want to check? For now, I'm kind of like hardcode as Duke and Ella. I can also make it flexible.
Interviewee	Probably could because in fact, Zhiyong is now asked to look at a very different scanner, a baby scanner. Okay, and then you have models with different baby models for age of a few months and seven years and 11 years children, different names and probably also different anatomies. I like to see heads completed directly or so. **So that is a different Word file and therefore to be flexible enough to just adapt for that.**
Interviewer	That can be done and for question five, what thing is still missing in the pTX Coil optimizer?
Interviewee	Now, you've seen the complete calculation that I go through. To do it I have this document and then I make the extraction and in fact, for all of them, I have one value that

	is the result. So what is the worst case in SAR, then I pick that on. I use that in my coil file. Now I've seen a list for 40 different cases. So if you the complete answer that I need is suitable for this simple reason. Not difficult to see the minimum value in the list. Sorry, if you look in my PowerPoints, we see the transmit chain.
Interviewer	Yeah, I think it's the maximum SAR you derived from the result report.
Interviewee	Yeah. So but you didn't. What I saw is you didn't show me that value for you. You could add this. You now fill that this one but here I need for the complete report for this selection.
Interviewer	The sixth question would be what do you think about the pTX Coil optimizer documentation? This one.
Interviewee	I don't think I see documentation?
Interviewer	I was referring to this procedure of launching.
Interviewee	Yeah, well, this is not good. **If this is an instruction of what I need to do to launch, then this is too cryptical for me.**
Interviewer	I see, and the seventh question would be how much time do you think you saved by using the optimizer comparing to without using the system?
Interviewee	Maybe like 30% or so. Okay. You know, of course, it depends on how much you want to do.
Interviewer	So, do you mean like, **based on the current status, maybe 30%? But if the further features we talking about are added. Maybe it will be better?**
Interviewee	Yeah
Interviewer	Yeah, there are three more questions. In your experience, how did you save your time?
Interviewee	**Oh, it automatically extracted information that I otherwise had to do manually.**
Interviewer	Okay. The ninth question will be is the optimizer displaying the requested result in a clear way?
Interviewee	**Quite good. I asked for a few more additions to be displayed.**
Interviewer	Yeah. Last one. The last one would be why would you or wouldn't you recommend optimizing for your friends or colleagues
Interviewee	First of all, I just got the first demonstration and I need a bit more acquainted with that. So I can also explain and **I think some features still need to be added to make it even more in line with what I completely need.** That's the first step it is to me. It's in a good direction.
Interviewer	Okay, yeah. And that will be the part where the interview will finish.

<u>Transcript from Test B:</u>

Interviewer	So this will be the interview for the test of the pTX Coil Optimizer. The first question I would like to ask Peter, my supervisor, is. Overall how was your experience with the pTX Coil optimizer?
Interviewee	Well, what mainly has been shown and demonstrated and also applied was the use of the analysis of data. And that was comprehensive towards good. **Good analysis. Could get the information that I want. I could make the selections that I want. Easy to do. The UI itself is slightly primitive, but it doesn't matter. It was clear enough**.
Interviewer	I totally agree.
Interviewee	So the **flexibility and analysis are what I like.** Could indeed make the selections that I want regarding the anatomy and the models and also the optimizing criteria all that was there, and the calculation that I needed, or indeed made by tool, so that's pretty good.
Interviewer	And the third question.
Interviewee	The third question is what do you think you like least about. The **complete infrastructure is where you have a connection between the simulation as here and the**

	one that analyzes the core models and the data that you get there at a decent interaction between various computers, or that part was not completely in place, but that is due to the IT limitations. I know, it has to do with security. But if you want to have it completely in place in our specific Phillips case, then we need to find out how we do this. And from what I saw now, that is the most distal part to find out how we make that work in practice. And the analysis part was, as I said, very well.
Interviewer	Okay. Thank you. And maybe we can move on to the fourth question.
Interviewee	If you could change something about the pTX Coil optimizer, what would it be? As I said, **the user interface is somewhat primitive**. That could be good enough. If I really am using this in more detail, I might at some point think have a different calculation that I need to add. So I just don't know. **But I should be some instructions of how to how to modify the logic if I want.**
Interviewer	Do you mean like the flexibility for you to modify the maybe how the parameters are calculated?
Interviewee	Yeah, if they could be that I think of something else in the calculation of or want to have some other calculation edits or something like that. So okay, yeah. **How you now made is exactly what I asked, which is very good. But I might seek to come up with some other ideas.**
Interviewer	Yeah, indeed.
Interviewee	What is missing? Yeah, well, of course, **the complete flow, from coil design to coil simulation to coil data that complete flow is not what I have seen.**
Interviewer	And I like to ask. So yeah. During the previous test, I show it. It's doable. Connecting from here, back to my place. Yeah, I just wanted to clarify that. Yeah. So it works outside the Philips environment.
Interviewee	That potentially it can work you showed that it could work from a different network. Yeah, that's doable, but due to the security setting or infrastructure here. So we need to show that it can be done but it is not.
Interviewer	For the sixth question, I still refer to the slide or the instruction on how the system works.
Interviewee	Oh, what you showed was clear. **You have a very clear presentation about how it works and how it is organized.** In terms of documentation that still is, I like to have is, suppose you want to change the Java code or to actually do.
Interviewer	Okay. Yeah, the seventh question, how much time?
Interviewee	Well, yeah, **I think it's if I now start with a document, and I have to go through this myself and have to do the analysis, it really cost me a few hours to do if I have this analysis tool, which can be done in maybe 15 minutes.**
Interviewer	The eighth question is, how did the system save your time?
Interviewee	**By having all the data available and have a very easy way to select that and find any of the cases that I want**. And it **displays it in a clear way**.
Interviewer	So this question nine?
Interviewee	Yeah. Then the tenth question, well, **I would recommend it because if you want to have the analysis of these data.** And of course, the data have to has to be available by the simulator engineer. Yep. If that is true, then you have an easy way to access that information.
Interviewer	Yeah, exactly. So it enables the translation from data into information. I think it's clear for me and I really thank you for the time.

Appendix C.

This is the overview of the table that tracks the progress of the project. The whole table has been divided into three segments, each segment contains a period of three months.

<u>January 18 – April 4:</u>

Category	Sub-category	Task	3	4	5	6	7	8	9	10	11	12	13
			18-Jan	25-Jan	1-Feb	8-Feb	15-Feb	22-Feb	1-Mar	8-Mar	15-Mar	22-Mar	29-Mar
Administrative	TU/e	Study project arrangement											
Administrative	Philips	Take Philips campus rule test											
System Modelling	Study UC context	Study MRI											
System Modelling	Stakeholder Analysis	Analyze stakeholders	ver1.0										
System Modelling	Study UC context	Study ownCloud.											
Administrative	Philips	Move from TU/e PC to Philips PC											
System Modelling	Study UC context	Study AH project proposal											
System Modelling	Study the Arrowhead Framework	Discuss with Mahdi											
System Modelling	Study implementation knowledge	Study Java library & framework											
System Modelling	Study implementation knowledge	Study Java IDE											
System Modelling	Study implementation knowledge	Study data exchange											
System Modelling	Study the Arrowhead Framework	Run the demo-car											
System Modelling	Study the Arrowhead Framework	Set up environment for AH											
System Modelling	Study implementation knowledge	Study basic Maven											
System Modelling	Study implementation knowledge	Study Java coding standard											
System Modelling	Study the Arrowhead Framework	Draw the toolchain diagram											
Project Management Plan	Formulate the PMP	Formulate CMP		ver1.0			ver2.0						
Project Management Plan	Formulate the PMP	Formulate the PMP slides											
Project Management Plan	Review the PMP	Define way to track the progress of work			ver1.0								
System Modelling	Study the Arrowhead Framework	Study "IoT Automation"											
System Modelling	Study implementation knowledge	Study Swagger API											
System Modelling	Study implementation knowledge	Study JSON											
System Modelling	Study implementation knowledge	Study MySQL											
System Modelling	Study the Arrowhead Framework	Study AH Management Tool											
System Modelling	Study implementation knowledge	Study software architectures											
System Modelling	Study implementation knowledge	Study microservice and SOA											
System Modelling	Study implementation knowledge	Study REST API											
Project Management Plan	Formulate the PMP	Formulate the PMP document				ver1.0							
Project Management Plan	Formulate the PMP	Study ISO 16326											
Project Management Plan	Formulate the PMP	Study WBS											
System Modelling	Study the Arrowhead Framework	Study local cloud											
System Modelling	Study the Arrowhead Framework	Study the AH architecture											
System Modelling	Study the Arrowhead Framework	Discuss with ASML students											
System Modelling	Study UC context	Draw operational scenario diagram											
System Modelling	Design system architecture	Draw system architecture diagram					ver1.0 (SC)	ver1.5 (SC)			ver2.0 (SC)		ver3.0 (MC
System Modelling	Study the Arrowhead Framework	Draw AH core systems sequence diagram											
Project Management Plan	Review the PMP	Move work documentation to Jira											
Project Management Plan	Formulate the PMP	Study system development lifecycle											
System Modelling	Collect user needs	Discuss with Zhiyong						ver1.0					
System Modelling	Collect user needs	Discuss with Peter						ver1.0					
System Modelling	Study implementation knowledge	Study basic Java											
System Modelling	Design system architecture	Draw use case diagram							ver1.0			ver1.5	
System Modelling	Study UC context	Draw real world scenario diagram							ver1.0				ver1.5
System Modelling	Study the Arrowhead Framework	Study AH documentation rule											
System Modelling	Risk Analysis	Analyze risks							ver1.0 (process)				
Intermediate Presentation	Return Day	Formulate return day slide							day 2				
Project Management Plan	Review the PMP	Discuss with Han											
Project Management Plan	Review the PMP	Discuss with Audrey											
System Modelling	Study the Arrowhead Framework	Trace the demo-car											
Intermediate Presentation	D8.4 report	Formulate AH document								ver1.0			ver1.5
Demo	Design the hardware configuration	Draw hardware configuration diagram									ver1.0		ver2.0
System Modelling	Requirement List	Formulate the requirement list									ver1.0		
System Modelling	Requirement List	Study requirements listing											
System Modelling	Study implementation knowledge	Study Spring Boot											
System Modelling	Design system architecture	Formulate API list											
System Modelling	Study implementation knowledge	Study network basics											
Intermediate Presentation	Vaccine workshop	Formulate the workshop video											WP2

April 5 – July 4:

Category	Sub-category	Task	14	15	16	17	18	19	20	21	22	23	24	25	26
			5-Apr	12-Apr	19-Apr	26-Apr	3-May	10-May	17-May	24-May	31-May	7-Jun	14-Jun	21-Jun	28-Jun
System Modelling	Stakeholder Analysis	Analyze stakeholders			ver2.0										
Project Management Plan	Formulate the PMP	Formulate CMP				ver3.0									
Project Management Plan	Review the PMP	Define way to track the progress of work				ver2.0									
Project Management Plan	Formulate the PMP	Formulate the PMP document			ver1.5										
System Modelling	Collect user needs	Discuss with Zhiyong			ver2.0							ver3.0			
System Modelling	Collect user needs	Discuss with Peter			ver2.0										
System Modelling	Study implementation knowledge	Study basic Java													
System Modelling	Risk Analysis	Analyze risks		ver2.0 (product)											
System Modelling	Study the Arrowhead Framework	Trace the demo-car													
Demo	Design the hardware configuration	Draw hardware configuration diagram				ver3.0									
System Modelling	Requirement List	Formulate the requirement list			ver2.0										
Intermediate Presentation	Vaccine workshop	Formulate the workshop video	WP8												
System Modelling	Study the Arrowhead Framework	Modify the demo-car													
System Modelling	Study implementation knowledge	Standardize the way to trace code													
Project Management Plan	Review the PMP	Re-evaluate the complexity of the project													
Intermediate Presentation	D8.4 report	Fill in the tech evaluation form													
Intermediate Presentation	D8.4 report	Formulate the D8.4 report													
System Modelling	Study implementation knowledge	Study the sequence of system modelling													
System Modelling	Design system architecture	Formulate system modelling document		ver1.0	ver1.5										
Intermediate Presentation	Vaccine workshop	Attend Vaccine workshop													
Demo	Set up the development environment	Set up version control (GitLab)													
Intermediate Presentation	Periodic report	Formulate description for contribution to WPs													
Intermediate Presentation	Periodic report	Formulate use case overview													
System Modelling	Study implementation knowledge	Study database and Spring connection													
Demo	Set up the development environment	Set up multiple databases													
Demo	Design the scenario	Design the SRP v.s. SRC interaction													
Demo	Set up the development environment	Run the demo 4													
Intermediate Presentation	Ecsel review	Formulate the slide													
Demo	Implement the API	Implement file transfer across application systems													
Demo	Implement the API	Implement report inerpretation													
Demo	Set up the development environment	Migrate the application to skeleton													
Demo	Demo session	Presentation													
System Modelling	Study implementation knowledge	Study the WAN, LAN, and port forwarding													
Demo	Set up the development environment	Implement port forwarding for cross LAN													
Demo	Set up the development environment	Implement provide and consume service for SRP													
Final Report	Formulate the report	Formulate the structure													
Final Report	Formulate the report	Analyze the report from the ST senior													
Demo	Set up the development environment	Confirm the testcloud3 certificates													

July 5 – September 26:

Category	Sub-category	Task	27	28	29	30	31	32	33	34	35	36	37	38
			5-Jul	12-Jul	19-Jul	26-Jul	2-Aug	9-Aug	16-Aug	23-Aug	30-Aug	6-Sep	13-Sep	20-Sep
Demo	Implement the API	Implement report inerpretation												
Final Report	Formulate the report	Formulate the structure												
Final Report	Formulate the report	Analyze the report from the ST senior												
Demo	Verify the API	Test by Peter												
Final Report	Formulate the report	Formulate the report												
Final Repoet	Formulate the report	Review by supervisors												
Intermediate Presentation	D8.5 report	Formulate the D8.5 report												
Intermediate Presentation	Lubeck workshop	Formulate the workshop demo and pitch												

Appendix D.

Here we provide the project management plan.

Project overview

Purpose, scope and objectives

For a magnetic resonance imaging (MRI) system with ultra-high-field, parallel transmit coils (pTX coils) with optimized control setting is crucial for performing MRI scans in high speed and good quality. During the optimization process of the control setting for the pTX coils, complex algorithms and models are required and applied to the RF Coil Design Environment and pTX Coil Simulator.

The scope of the project is applying the Arrowhead Tools to implement a data exchanging platform (AHT Framework) that has a user interface and individual interfaces with the RF Coil Design Environment and pTX Coil Simulator. With this data exchanging platform, the output of different algorithms and models can be easily retrieved by different users and advanced algorithms can be implemented for smoothening the pTX Coil control setting optimization workflow.

Assumptions and constraints

The following assumptions and constraints are made for this project:

- The AHT Framework will be developed in Java, using Eclipse as the IDE, and applying the Arrowhead Tools.
- The RF Coil Design Environment and pTX Coil Simulator are already established.
- The Arrowhead Tools is ready to be used.
- The formats of the data transmitted are defined and provided by the related stakeholders.
- The project is one of the use cases in the Arrowhead Tools Project.
- The project schedule shall be aligned with both the PDEng program of TU/e and the milestones of the Arrowhead Tools Project.
- The AHT Framework shall have individual interfaces with the electromagnetic simulation software, pTX coil models, human body models, B_1^+ maps, and SAR maps.

Project deliverables

The content and delivery date of the deliverables are listed below:

- Project management plan (Feb 15th): The document covers the project overview, context, planning, assessment, and supporting plans.
- Demo session (TBD): The demo session that shows how the data will be transmitted through the interface will be provided to the related stakeholders when a data exchange interface is implemented. As there are multiple interfaces, the demo session will be provided multiple times.
- Final presentation (TBD): The final presentation concisely shows the process of development and demonstrates the final result.
- Final report (TBD): The document elaborates on the methods used, design decisions made, and evaluation of the final result.
- Source code (TBD): The source code of the AHT Framework, will be provided alongside supporting documents regarding how to deploy the AHT Framework.
- Intermediate presentation (April 1st): The presentation regarding the status of the use case will be given during the Arrowhead Tools Project training workshop.

Schedule

Figure 1 shows the brief schedule of the top-level activities in the work breakdown structure shown in Figure 5. The void cell in the first half of January represents a period of holidays.

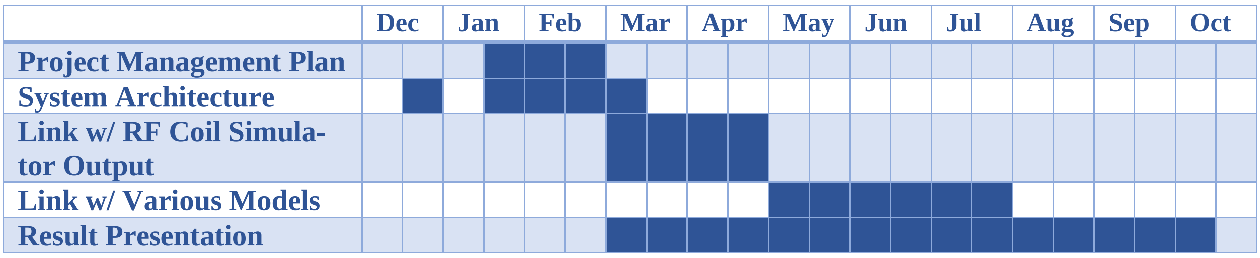


Figure 1 - Top-level project schedule diagram

Project context

Process model

Figure 2 shows the development process flow of this project. The development of the AHT Framework is breakdown into four major work activities shown in the blue boxes. In the blue boxes, the work activities are shown on the upper part, the deliverables are shown on the bottom part with bold fonts, and the factors to be tested or reviewed are shown in the white box in the middle. On top of the blue boxes, it shows that the V-model will be applied for each activity. Between the blue boxes, the arrows show the information flow between activities.

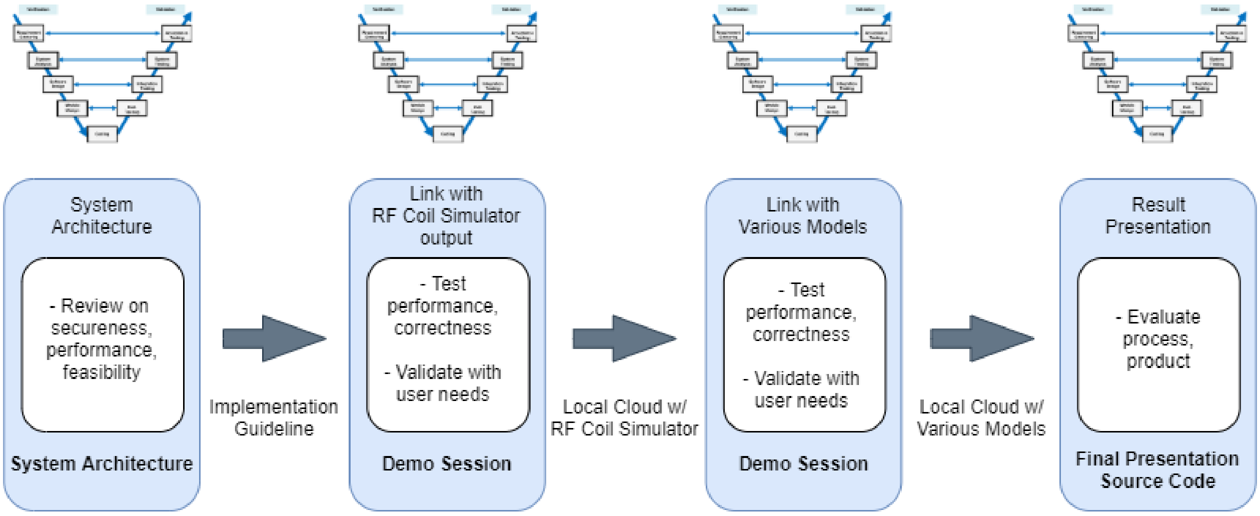


Figure 2 - Development process flow diagram

Process improvement plan

The first draft of the development process shall be reviewed by the TU/e program manager and the mentor. During the project period, a monthly meeting with the project steering group has been arranged. In each meeting, the project steering group members shall be reminded of the process status of the project at the moment. The improvement points shall be identified during the meetings.

Infrastructure plan

The development environment is listed and described below.

- Hardware: As the pandemic is ongoing, the trainee is working from home, using the laptop from Philips.
- Operating system: Microsoft Windows 10.
- Network: The trainee may use credentials to access the resource from Philips, TU Eindhoven, and the Arrowhead Tools Project.
- Software: The source code and supporting documents regarding Arrowhead Tools are stored in an open GitHub repository. For Java development, JDK 11 has been installed and Eclipse

is used as the IDE. For running the implemented software, JRE 11, Apache Maven 3.6.3 configured for GitHub Packages, and MySQL server 8.0 are installed.

Methods, tools and techniques

The Kanban method is used to manage the works in the project. On the Kanban board, the tasks are categorized into five categories, which are To do, In Progress, Today, In Review, and Done. On top of the Kanban board, the Roadmap is formulated to show the overall progress of the project. Both the Kanban board and the Roadmap is implemented on Jira Software.

To identify the tools used for optimizing the pTX Coil, the development of the pTX Coil is divided into two engineering processes (EP), one for the mechanical and electrical design, the other for the RF field simulation. The two EPs and the tools used are shown in Figure 3. The MR pTX Coil Engineering Process stands for the mechanical and electrical design, while the MR pTX Coil Fields Engineering Process is for the RF field simulation.

The tools that are mandatory for the pTX Coil optimization in the scope of this project are specified with bold arrows in Figure 3. The blue arrow suggests that it is an output of one stage of the EP, while the black arrow suggests that it is an input for a stage of the EP.

Below enlists the tools used in the project, including the ones that are not shown in Figure 3.

- Arrowhead Tools
- Eclipse
- JDK / JRE 11
- Maven 3.6.3
- MySQL Server/Workbench 8.0
- Microsoft Office
- Human body models,
- pTX Coil electrical model
- EM simulation software
- B_1^+ map
- SAR map

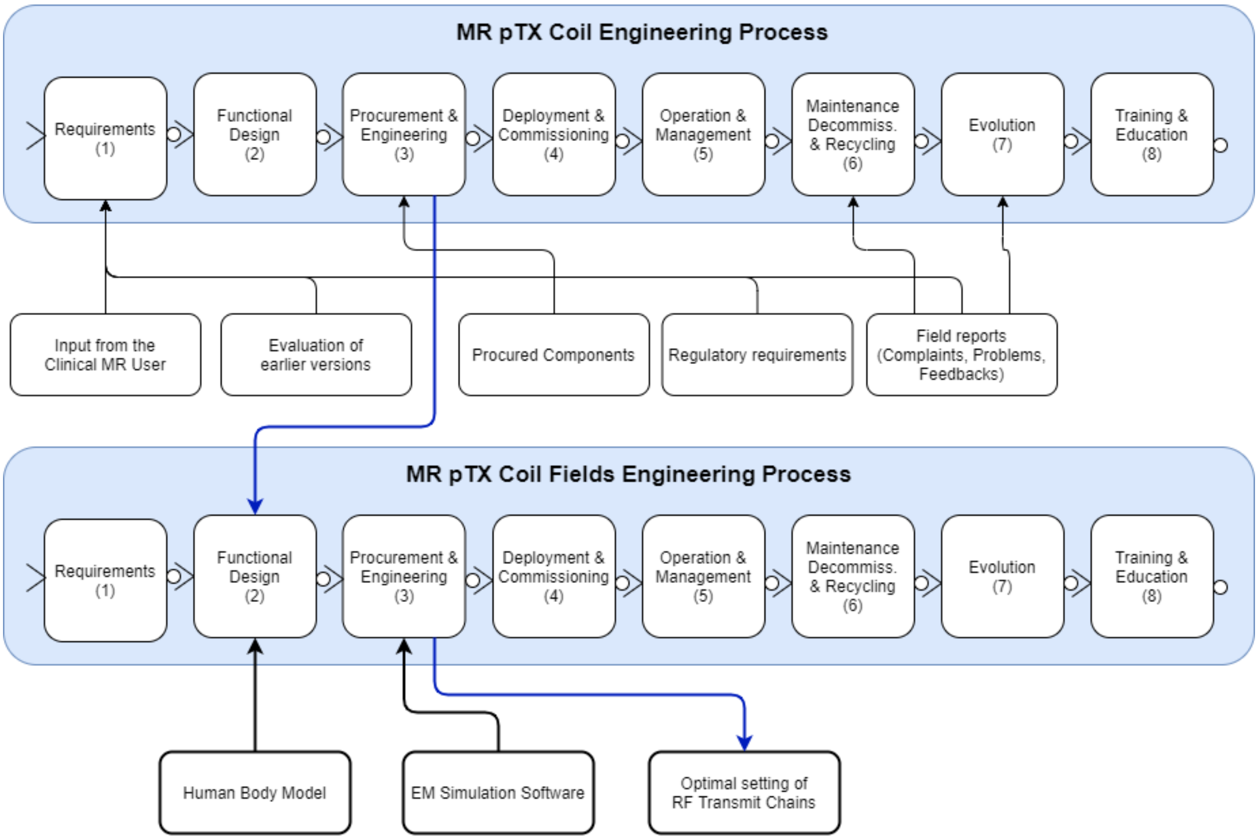


Figure 3 - Engineering process and toolchain diagram

Product acceptance plan

The project management plan shall be reviewed and approved by the PDEng program manager and Philips project mentor.

For the data transferring interfaces of the AHT Framework. A test plan shall be developed to test the performance and correctness of the data transferring actions. The test plan shall verify that the data transferring interfaces are implemented according to the specifications.

For the user interface of the AHT Framework. Demo sessions will be provided to the stakeholders who are the end-users. The interfaces have to meet the requirements that addressing the users' needs.

Project organization

The organizational structure of the project is shown in Figure 4. Riske Meijer is the program manager of the PDEng program of TU/e. Önder Babur from TU/e is the supervisor. Wan-Yi is the PDEng trainee from TU/e, working on the Arrowhead Tools Project in Philips. Frans Rosbak is the project leader from Philips and work package leader of Arrowhead Tools Project. Peter van der Meulen is the mentor from Philips and the use case leader of the Arrowhead Tools Project. Jurgen Molink is the project co-leader from Philips.

Besides the trainee, all the people mentioned above are members of the project steering group.

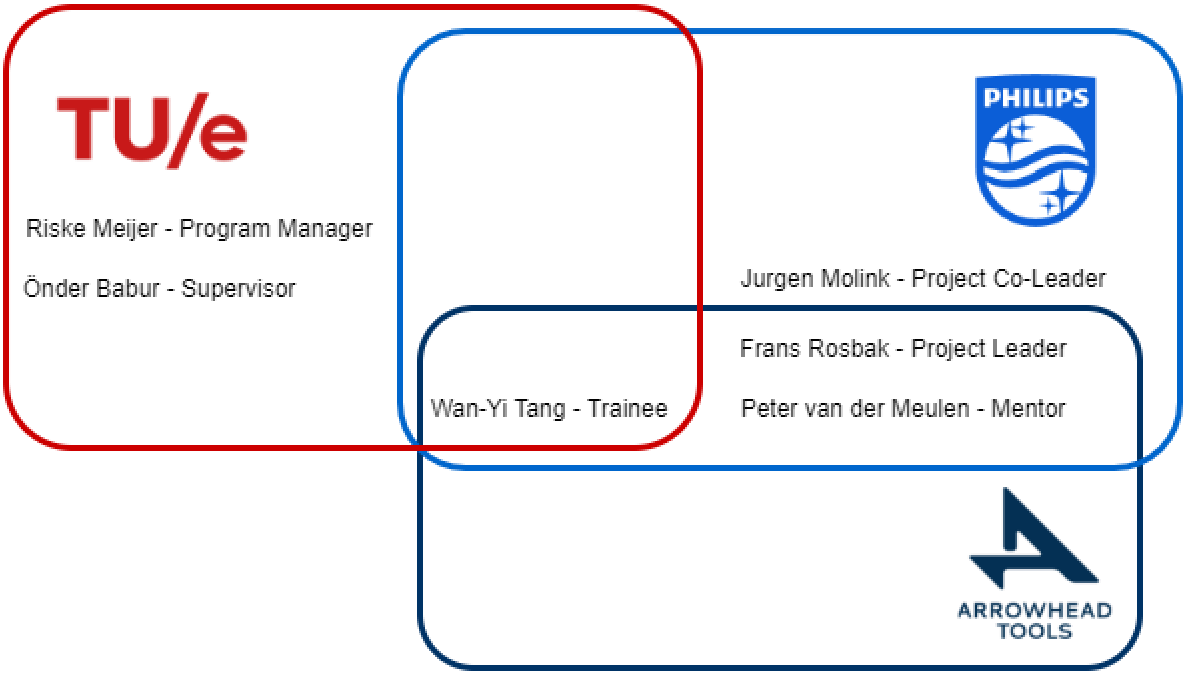


Figure 4 - Organizational structure diagram

Project planning

Work activities

The work activities are depicted in the white boxes shown in Figure 5.

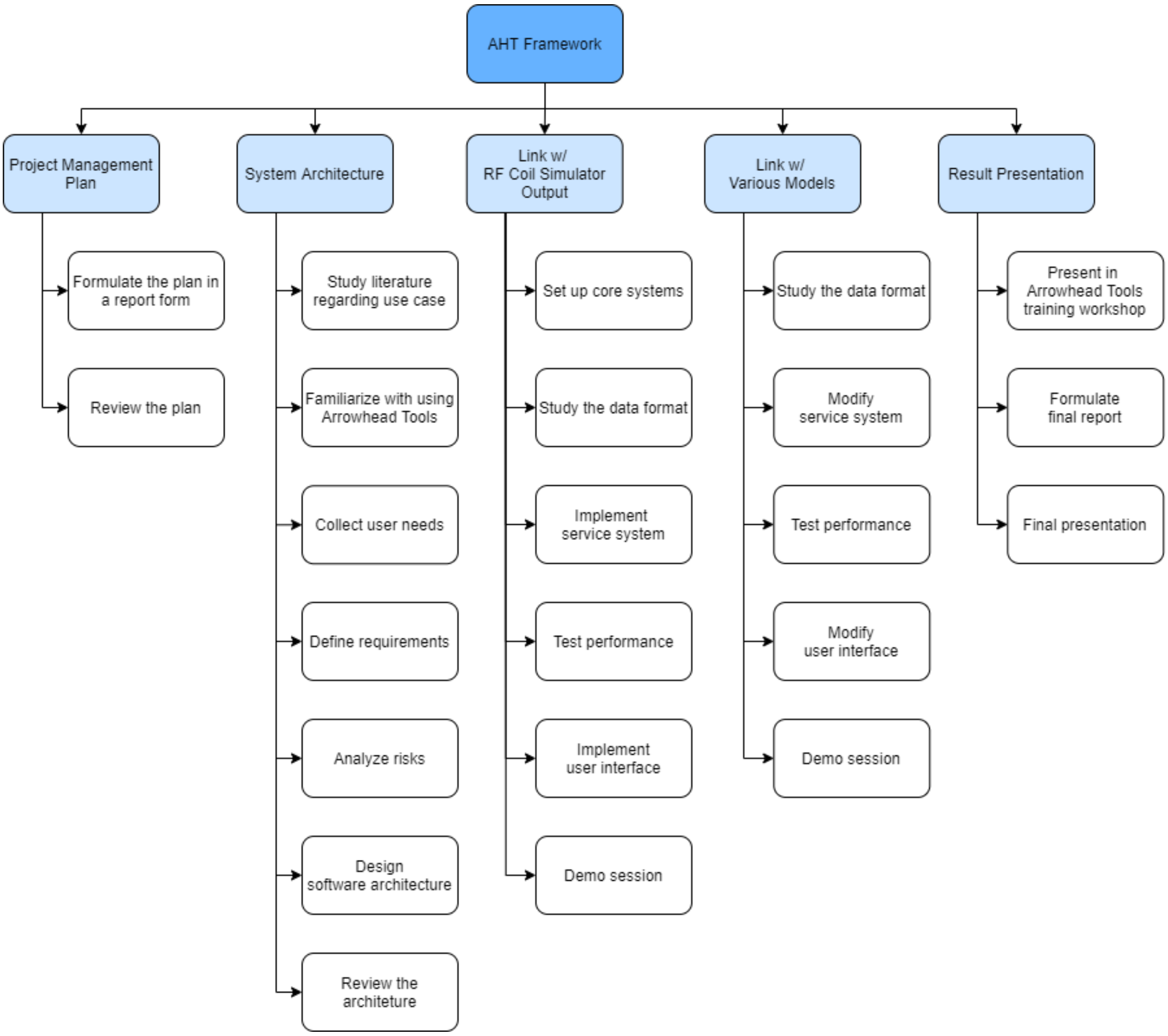


Figure 5 - Work breakdown structure diagram

Schedule allocation

The schedule for the project can be found in Figure 6. Though the arrangement of the schedule seems like waterfall style, the iterative behavior will show up as there are tests and demo sessions which may lead to modifications in the implemented results.

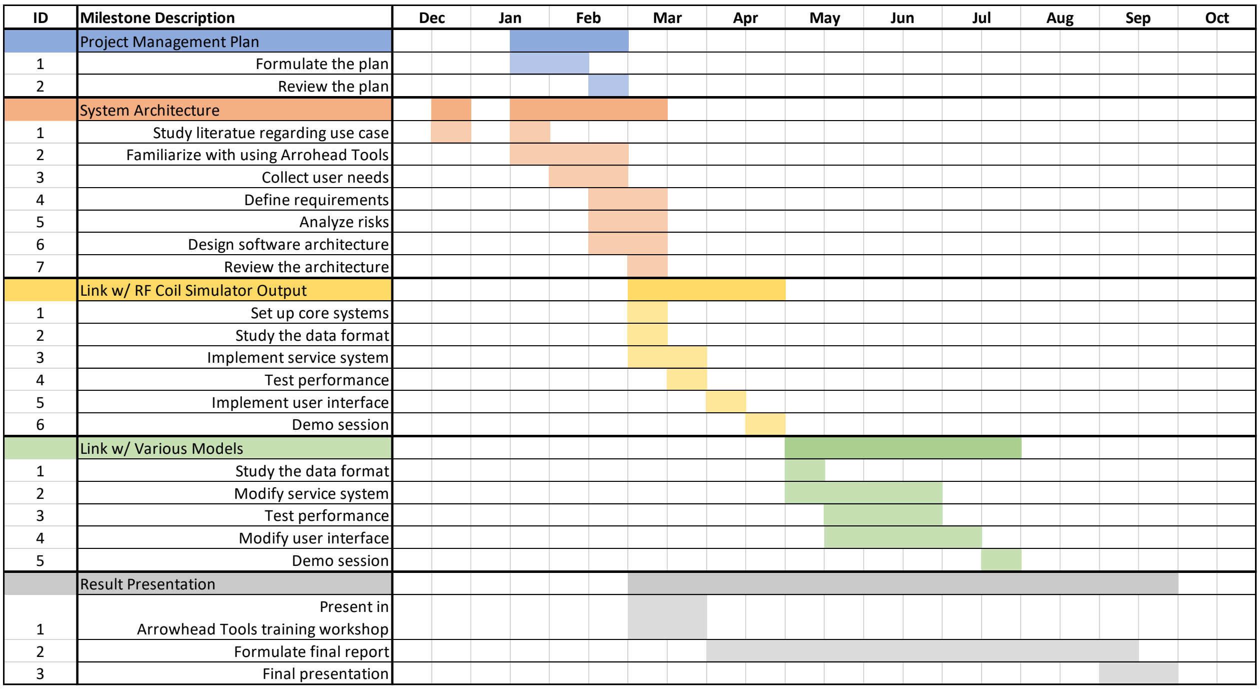


Figure 6 - Project schedule diagram

Project assessment and control

Scope change control plan

During the project period, multiple regular meetings have been arranged since the very beginning. On weekly basis, there is a meeting with the mentor, also, the supervisor will join the meeting bi-weekly. In the regular meetings, the trainee will present the progress at the moment and the action points for the following week. The mentor and supervisor can provide instant feedback if they notice any action is not in the scope of the project.

On the other hand, if the trainee is asked to do an activity that is not in the scope of the project, the trainee shall reject the request by stating that the activity is out of scope.

Schedule control plan

The schedule will be monitor by the combination of the Kanban board and the Roadmap. When progress delay happens, the milestones afterward shall be postponed. However, if the schedule significantly delays, the trainee shall assess the progress and identify if the delay is due to technical difficulties or lack of working hours.

Quality assurance plan

The source code of the AHT Framework shall follow coding standards addressing the variable naming convention, coding style, comment style, etc. Since the trainee is the only developer, peer-reviewing the code is not available. As a result, the code shall be analyzed by a static analysis tool.

The reports shall be written in the style aligned with the guideline provided by the acquirer, which is the PDEng program and the Arrowhead Tools Project.

Supporting process plans

Risk management

A complete risk management plan shall be formulated after the requirements are defined. The elements which will be addressed in the plan are the description of the risks, the damage from the risks, the likelihood of the risks to happen, the impact level of the damage, the severe level of the risk based on the likelihood and impact of the risks, and the mitigations for the risks. A brief example is shown in Figure 7.

Risk	Damage	Likelihood (L)	Impact (I)	Risk Value (R = L*I)	Rate	Mitigation
Limited stakeholder availability at the start of the project.	Delay of critical design decisions and technical progress.	4	4	16	Extreme	Questionnaire formed before the scheduled meeting with stakeholders. A parallel approach to address other important aspects of the project while waiting for a response. Reach out to the mentor and project leader when having difficulty in contacting certain stakeholders.

Figure 7 - Risk management plan example diagram

Configuration management

The project is software-based with one developer and stakeholders from three organizations. As a result, there are two issues for the configuration management to deal with, one is to make sure all the files are trackable for the developer, another is to make sure that certain files will be stored in the storing system where the stakeholders have assigned. The storage systems used in the project and the content in each system are listed below.

- OneDrive – Philips: The storing system contains all the project assets.
- OneDrive – TU Eindhoven: The storing system contains a copy of the meeting minutes, project management plan, and presentation slides.
- ownCloud: The storing system is managed by the Arrowhead Tools Project. The deliverables for the Arrowhead Tools Project will be placed in the assigned directory.

To ensure that all the files are trackable, a directory map is formulated for tracking the files in the storing system, also, the documents formulated by the developer shall be named according to the following naming convention:

YYYYMMDD_WTang_Name of the Document (the name should first address the content, then the type of the document)

Ex. 20210211_WTang_Weekly Progress Meeting 1 Agenda

Reviews and audits

The project status shall be reviewed on weekly basis during the weekly progress meetings with the mentor and the supervisor. In the progress meetings, the trainee shall provide a presentation, using slides made out of Microsoft PowerPoint.

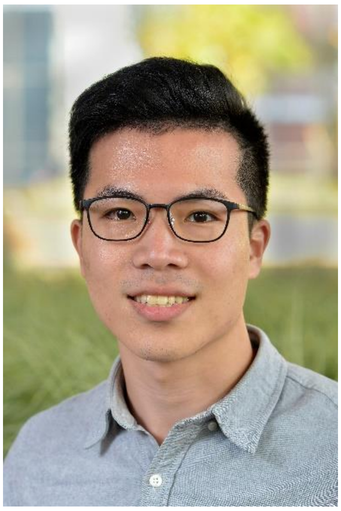
Figure 6 shows the time for reviewing the project management plan, the system architecture, and the time for reviewing the implementation results, which will be conducted as demo sessions.

Verification and validation

To verify if the data exchanging performances are aligned with the proposed specifications, after the data exchanging interface with one data provider is implemented the trainee shall perform a test before implementing the user interface. For the tests, the trainee shall formulate test plans and the stakeholders shall provide test data.

To validate if the user interface of the data exchanging platform is meeting the expectations of the end-users when the user interface is implemented, the trainee shall provide a demo session.

About the Author



Wan-Yi Tang received his bachelor's (2015) and master's (2018) degree in mechanical engineering from National Tsing Hua University, Hsinchu, Taiwan. His master's thesis, "Development of 3-Axis Machine Tool with Direct Pose Feedback" was to apply a newly designed measurement device for online compensation of a 3-axis milling machine to improve the positioning accuracy. Still eager to learn more, he started the Mechatronic Systems Design PDEng program in 2019. During the program, in the projects he participated in, he took the role of configuration manager, team lead, and developer. The projects were in the field of robotics (Tech United), advanced driver-assistance systems (Valeo), high accuracy measurement (Canon), and the Internet of things (Philips).

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PDEng AUTOMOTIVE SYSTEMS DESIGN
Track MECHATRONIC SYSTEMS DESIGN

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