AN INTELLIGENT CIRCULAR ECONOMY UPSTREAM MONITORING & OPTIMIZATION SYSTEM BASED ON INDUSTRIAL INTERNET OF THINGS

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Industrial Internet of Things (IIoT) has many beneficial applications upon the industry of Oil and Gas (O&G) and renewable energy production. Renewable energy production is already growing faster than traditional fossil fuel production. It has been estimated that the O&G sector can retain its current level of energy production for 40 years with the already discovered crude oil resources. In order to make sure that energy supply matches the demand, companies operating in the field of oil and gas are already heavily investing in energy efficiency, alternative energy processes and products. However, outdated technologies, legacy systems and prevailing conservative mindset hinder the development of the industry.

This master's thesis will be focused on the use of Industrial Internet of Things by the circular economy upstream which consists of data acquisition, analysis and visualization across the feedstock exploration and production phases in the field of oil and gas. New technologies such as cloud computing and analysis will be implemented to the current environment and further evaluated for the use of prevailing protocols such as OPC-UA which is the industry-leading communication protocol. The upstream sector will be evaluated for the purpose of designing, implementing and validating organization-wide system architecture model and experimental proof-of-concept level IIoT system for monitoring and optimization of the circular economy industry. The system will be evaluated and designed to support qualitative measurements such as a liquid fingerprint in the future. Considering the further use of the raw material, and based on the theoretical part of this thesis, an experimental prototype level IIoT system will be implemented and tested in practical terms.

This thesis proves that the analyzed, designed, implemented and verified IIoT monitoring and optimization system has significant financial and environmentally beneficial results in the industry of the circular economy. This thesis proves that prevailing outdated systems can be further developed with modern technologies and solutions which are extensively described in the organization's new system architecture model. The final conclusion indicates that Industry 4.0 and Industrial Internet of Things play a major role in the monitoring and optimization of the circular economy upstream industry.

Keywords: Industry 4.0, IoT, IIoT, AHP, Circular Economy, Upstream, System Requirement Analysis, RAMI 4.0, Ultrasonic, Arduino, Cloud, Microsoft Azure

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Abbreviations and Acronyms

ADC	Analog-to-Digital Converter
AHP	Analytic Hierarchy Process
AI	Artificial Intelligence
AWS	Amazon Web Services
BPCD	Barrels Per Calendar Day
BPD	Barrel Per Day
CICE	Circular Economy
CoT	Cloud of Things
DAS	Data Acquisition System
DCS	Distributed Control System
GCP	Google Cloud Platform
HMI	Human-Machine Interface
IIAF	Industrial Internet of Things Analytic Framework
IIC	Industrial Internet Consortium
IIoT	Industrial Internet of Things
IIRA	Industrial Internet Reference Architecture
IoE	Internet of Everything
IoP	Internet of People
IoT	Internet of Things
ISO	International Organization for Standardization
IP	Ingress Protection Marking
IT	Information Technology
ITS	Intelligent Transport System
IoT-A	Internet of Things – Architecture
M2M	Machine-to-Machine
O&G	Oil and Gas
OPC UA	Open Connectivity via Open Standards - Unified Architecture
OSI	Open Systems Interconnection
OT	Operational Technology
PLC	Programmable Logic Controller
PoC	Proof of Concept

RAMI 4.0	Reference Architecture Model Industry 4.0
SAS	SharedAccessSignature
SGAM	Smart Grid Architecture Model
SPI	Serial Peripheral Interface
SSL	Secure Socket Layer
TCP	Transmission Control Protocol
UCO	Used Cooking Oil
UDP	User Data Protocol
WtE	Waste-to-Energy
WSN	Wireless Sensor Network

Chapter 1

Introduction

Crude oil is naturally occurring nonrenewable liquid found in geological formations. It consists of hydrocarbons which have formed from sediments rich in organic matter during a long period of time [1]. Despite its long and vivid history, it has managed to maintain its popularity as the world's leading source of energy. In 2015, about 32.9% of global energy consumption was originated from the use of oil [1][2]. There are approximately 662 oil and gas refineries worldwide with a total capacity of 85.1 million barrels per calendar day (BPCD). Gasoline and diesel fuels are the primary products of the oil and gas sector. Roughly 63% of processes oil consumption is from the transport fuels [2]. While fuels being the primary product of oil, plastic production has its own great share of the petrochemical markets. By far, the oil and gas industry is the largest business sector in the world. It generates hundreds of billions of dollars globally every year [3]. Natural oil sufficiency and its negative environmental impact have been often discussed subjects in the energy sector. By the year 2020, the European Union (EU) Commission aims to replace 10% of the transport fuels in every EU country with renewable energy sources such as biofuels [4]. Traditional oil and gas industry is already experiencing significant transitions since the current trend towards renewable and alternative energy sources such as biodiesel is taking over the energy sector [5]. However, there are not yet such energy sources that are as easily transported and stored, easily and safely used, powerfully and widely applied than oil-based energy products [2]. This thesis will take a stance on the current lack of new technological solutions and smart infrastructures in the alternative circular economy-based energy production in the field of oil and gas.

The oil and gas industry supply chain is typically divided into three main sectors: upstream, midstream and downstream. This thesis will initially focus on the upstream industry since the organization is interested in implementing the IIoT system in the raw material supply, transportation and storing phases. Traditional oil refining upstream differentiates highly from the circular economy's waste material fuel refining. Its refining process begins after the nonrenewable crude oil is pumped from the ground. The pumping process demands large start-up investments since building and operating an oil drilling and pumping units are constructed on a single location that can provide large quantities of crude oil. Once the oil is extracted from the selected location, it is then stored into storage tankers and transported to oil and gas refineries. This process sector is called upstream. It involves oil exploration, drilling, and production [6]. Compared to traditional crude oil energy production, the circular economy based waste oil refining processes are highly dependent on the raw material qualities which can affect the cost of the final product up to 60-75% [7]. For example, biodiesel production demands category one (1) animal fats or waste oils. The acquisition of these raw materials can be challenging since the supply sources are in distributed locations. Furthermore, the raw material such as used cooking oils (UCO) and animal fats need to be separated and categorized through the entire value chain to ensure the highest possible quality. Since the raw material suppliers are geologically distributed all around the world, intelligent IIoT based monitoring and supply chain optimization systems are required in the optimization of the upstream processes. This thesis has been implemented as a commission. The organization has determined requirements that the solution should be a low-maintenance, efficient and affordable IIoT system that can monitor the liquid level and the quality of the raw material through the upstream supply chain and optimize the logistical activities.

The main critical challenges concerning the circular economy upstream industry IoT solutions are described as follows:

- Recognizing the strategic feasibility of the Industry 4.0 and Industrial Internet of Things (IIoT), and recognize the needs of the oil and gas organization.
- Monitoring the waste oil quantity at the supply, refinery and during transportation, optimizing waste collection, analyzing waste oil generation and tracking messed pick-ups as well as reducing raw material overflows.
- Detecting possible storage unit leaks and ensuring service schedules.
- Creating more sustainable business and increasing social value by lowering energy costs and reducing environmental impacts.

Increasing investment in alternative environmentally friendly energy sources has emerged for environmental reasons. The most important reason is to prevent increasing global warming. The alternative energy industry is highly technology-dependent sector and has high potential to change the industry [8]. This thesis will take a stand on developing the technological segment of the oil and gas industry. By using the IIoT solution architecture, design and implementation proposed in the thesis the circular economy industry's raw material supply, transportation and storing activities i.e. upstream industry can be monitored and optimized in the future. It will increase the organization's productivity, efficiency, and sustainability.

1.1 Research Questions

The research questions for this master's thesis are:

- **RQ1** What is the current state of Industry 4.0 and IIoT in the traditional oil and gas industry? Is it strategically feasible to implement Industry 4.0 and IIoT in the oil and gas industry?
- **RQ2** What are the system requirements in monitoring and optimizing renewable raw material flow to a point where it can be efficiently transformed into more useful products?
- **RQ3** What are the prevailing IoT reference architecture concepts? What architectural design is the organization practicing? How to implement or extend the present architecture to meet the requirements of the oil and gas industry?
- **RQ4** What are the most suitable IIoT technologies, standards and protocols for the circular economy upstream?
- **RQ5** How to implement and verify the IIoT system in an experimental proof-of-concept level to meet the circular economy as well as the oil and gas industry-specific requirements? What are the system related regulations and directives, and what kind of extensibility should the system have?

1.2 Objectives of the Thesis

The objectives of this thesis are to identify basic elements of a circular economy based raw material collection, storing and refining. It will form a comprehensive understanding of the current stage of industry 4.0 and evaluate the strategic feasibility of the IIoT in the field of oil and gas. Finally, it will orientate in utilizing IIoT technologies, standards and protocols in the raw material related processes in the circular economy upstream industry. Understanding the differences between traditional crude oil production and alternative waste material production plays a major role in the design and implementation of the IIoT upstream monitoring and optimization system. The experimental proof-of-concept level system will be implemented and verified from the view of the circular economy industry.

The research questions of this thesis (Section 1.1 Research Questions) will be approached by implementing and verifying IIoT proof-of-concepts level prototype based on the system requirements and design constructed in the (Chapter 3) System Requirement Analysis and Introduction to the IoT Reference Architectures and (Chapter 4) Technical Design of the IIoT Upstream Monitoring System. System requirement analysis will comply with the RFC 2119 requirement levels published by the European Commission. System design activities will focus on elements such as measuring the correct environmental factors, transferring the measurements efficiently and storing the information safely into the cloud. Finally, the findings are applied to the practical implementation of the experimental proof-of-concept level IIoT raw material monitoring and optimization system.

1.3 Thesis Structure

Chapter 1 is titled “Introduction”. In this chapter, the thesis will give a basic understanding of the problem which prevails among the current energy production. It will focus on the lack of technological solutions which are causing the industry to unnecessarily waste resources. It will review the traditional oil and gas industry problems and introduce the desirable solutions that can have a positive influence on the trillion-dollar business sector.

Chapter 2 is titled “Fundamental Concepts of Industrial Internet of Things (IIoT)”. In this chapter, the thesis will introduce the Industrial Internet of Things (IIoT) and the fourth industrial revolution called Industry 4.0. This thesis will present two different use cases which can be exploited in the monitoring and optimization of the circular economy industry upstream sector. Identifying the key opportunities and strategic benefits of IIoT in the circular economy industry plays a major role in this chapter.

Chapter 3 is titled “System Requirement Analysis and Introduction to the IoT Reference Architectures”. In this chapter, the thesis will focus on analyzing and evaluating the needs and requirements of the circular economy as well as the oil and gas industry. Prevailing IoT reference architectures are identified and evaluated. Organization’s present architecture will be evaluated and extended to meet the needs of the IIoT and future systems.

Chapter 4 is titled “Technical Design of the IIoT Upstream Monitoring system”. In this chapter, the thesis will identify, evaluate and select compatible system technologies, standards and protocols based on the requirements identified in the previous chapter. The comprehensive protocol stack is constructed and evaluated.

Chapter 5 is titled “Technical Implementation of the IIoT Upstream Monitoring System”. In this chapter, the architecture diagram will be constructed based on the selected protocol stack and evaluated against the organization’s current and future needs. Proper components will be selected based on prevailing regulations and directives. System extensibility will be evaluated separately in this chapter. Finally, the IIoT proof-of-concept level prototype will be implemented and validated based on short-time testing. Environmental data will be transferred to cloud and processes with an analytics tool.

Chapter 6 is titled “Future Work”. In this chapter, the thesis will present the open questions that were recognized during the thesis. They will be further introduced and the selection of these topics will be justified in more details. These topics will be proposed as future work.

Chapter 7 is titled “Conclusion”. In this chapter, the thesis will present a conclusion to the presented research questions. The research questions will be reviewed and the summary of results will be presented in this chapter.

Chapter 2

Fundamental Concepts of Industrial Internet of Things (IIoT)

Industrial Internet of Things (IIoT) refers to interconnected cyber-physical systems and network of the systems in industrial environments [9]. It provides better visibility and awareness into the organization's operations and properties through the unification of components, software and hardware standards, cloud computing as well as storage platforms. It offers unique insight for transforming industrial operations by inspecting large sets of environmental data with the aid of advanced analytics tools. This has a positive impact on reducing unplanned downtimes and increasing efficiency and operating profits through assets monitoring and optimization. Operational efficiency and increased productivity are the main results gained from the optimization process. The complexity of current industrial systems has outmatched the human operator's capabilities to recognize and act on industrial inefficiencies [9]. Most often this results in operational facilities operating well below their maximum capabilities. These problems alone create the need for new industrial solutions [9].

Even though the technologies, standards and protocols used in today's industrial environments such as Machine-to-Machine (M2M) communication and collaboration have introduced the core of Industrial Internet of Things decades ago, the overall scale of industrial operations is remarkably broader [9]. Increased number of IIoT technologies and standards provide more comprehensive techniques to exploit larger data sets in less time. Advanced technologies like real-time hosted cloud analytics can analyze enormous sets of data at the speed of wire. This enables the organization to store larger sets of data in geologically distributed cloud databases for safer and faster data processing and analysis. A more comprehensive and accurate analysis can be performed in ways that could not have been possible previously because of the relatively small sampling pools. These have been presently enabled by more powerful and efficient software algorithms. This enables industrial process operators to optimize the industrial activities in an efficient manner and provide the insight needed to boost the operational productivity, efficiency and reduce the operative costs

[9]. Besides the economic benefits of IIoT, it can also create new kinds of hybrid business models and technologies that can increase innovations among the industries, as well as relocate and make better use of organization's workforce [10].

The interesting point with the IIoT regarding the real-life business concerns is that with the power of 1% savings, large industries such as oil and gas can reduce capital spending, for example, on equipment by $90 billion per annual, Table 1. The power of 1% savings will cause the industry of the circular economy to save capital spending remarkably by adding monitoring and optimizing activities in the upstream value chain. The exploitation of the IIoT technologies in the optimization of the supply, transportation and storing activities will be highly beneficial in the long-term. Thus, IIoT is a powerful tool that can create business growth in unexpected areas. Furthermore, it can create completely new opportunities and innovations to increase the value of the organization [10].

Scenario	**Description**	**Potential Economic Impact in 2025**
Human	Monitoring and maintaining	$170B-1.6T
Home	Controlling and security	$200B-350B
Retail	Automation and inventory optimization	$410B-1.2T
Offices	Energy management and security	$70-150B
Factories	Efficiency management and optimization	$1.2T-3.7T
Worksites	Efficiency management, predictive maintenance, health and safety monitoring	$160B-930B
Vehicles	Predictive maintenance and analytics	$201-740B
Cities	Traffic control, resource monitoring, management	$930-1.7T
Outside	Real-time routing, navigation, tracking	$560-850

Table 1*- The economic impact of IoT [11].*

2.1 Introduction to Industry 4.0 Design Principles

Industrial revolution refers to the transition from an agricultural economy to an industrial society, Figure 1. The significant development of the cyber-physical IoT systems and the use of them in the industrial field has constructed the foundation for the ongoing fourth industrial revolution called Industry 4.0 [11]. It is a top priority for many universities, research centers and companies to understand and exploit the existential meaning behind the Industry 4.0 [11]. It is impossible to define an explicit timeframe for the first industrial revolution since the humankind has used renewable energy sources such as water and wind over millennia. Only when the first economically usable steam engine and mechanical production facilities were discovered in the 17/18th centuries began the era of the industrial revolution [11]. A growing number of steam-powered technologies set the foundation for the innovative industry by initializing modern industrial society [11][12].

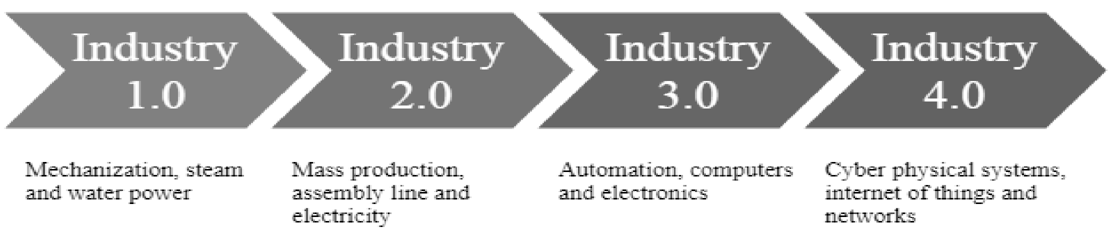


Figure 1*- The evolution of the industrial revolution.*

The second industrial revolution began with the discovery of crude oil, electricity and the processes to refine them for economic uses in the 1870s [12]. Development of combustion engine and belt-powered mass production facilities started the era of mass production. This exploded the productivity of consumer goods quantitatively and created the first known consumer society where people were able to afford a wider range of commodities [11][12].

The third industrial revolution introduced electronically-controlled systems such as automation systems, computers, and electronics [12]. They became common in the mid-twentieth century and started the third industrial revolution around the 1970s [12]. Intelligent machines and robots became more popular among the industries. This increased productivity and shifted human operators from the production lines to the function of monitoring automated processes performed by the robots. Electronics, information and communication technologies started the era of automation and automated assembly lines. The third industrial revolution was remarkably profitable for the low-wage countries since the industrial nations shifted their focus from production to creating services and outsourcing the production [11][12].

The fourth industrial revolution introduced cyber-physical systems and a network of the systems. The term industry 4.0 became publicly known in 2011 [12]. It presented an opportunity to virtually connect every system with the internet, and the development of wireless network generated new intelligent services never seen before. Combination of software and hardware components enabled the generation, collection, transformation, and analysis of larger data volumes [11]. Through the history of the industrial revolution, human has heavily shifted from the production of consumer goods to be the observer of automated production. Industry 4.0 will continue this phenomenon by decreasing the need for human operators on the production lines and increasing the need for educated operators and process monitoring personnel [12].

Since the origin of the industrial revolution, humankind has over-extended natural resources and the limits of nature. Overconsumption and the destruction of natural resources are considered to have led to air pollution and the state of dramatic climate change. This can be only countered with drastic changes in the way we work, live and consume natural resources [12]. First and foremost, this thesis focuses on solving environmental problems by improving unoptimized processes in the field of the circular economy. In order to fully understand all the areas that need to be improved, processes need to be evaluated through Industry 4.0 design principles. Industry 4.0 design principles consist of four concepts which are interconnection, information transparency, decentralized decisions, and technical assistance [11]. These principles support industries in identifying, designing and implementing the IIoT applications.

2.1.1 Interconnection – Internet of Everything (IoE)

Internet of Everything (IOE) is formed by connecting sensors, devices, machines and people over the Internet of Things (IoT) and the Internet of People (IoP) [11]. Collaboration, standards and security are the key concepts of interconnection. Wireless communication technologies and standards are acting at the forefront of increasing interactions. Through the IoE, wirelessly connected objects and people are capable of sharing information. This creates a solid base for the collaboration of reaching the agreed organizational goals. Interconnection requires that the entire environment has a fluid communication and flexible collaboration among all the components. Collaboration within the IoE can be divided into three types: machine-to-machine, human-to-machine, and human-to-human collaborations [11]. Initializing interconnections requires standardized communication protocols (Section 4.3.4). Such protocols enable flexibility among different component vendors. The flexibility of the component market and growth of IoE increases the threat of harmful attacks on Industry 4.0 facilities [11].

2.1.2 Information Transparency

Information transparency is formed from the synthesis of physical and virtual worlds where an increasing amount of wirelessly connected object and people are linked together [11]. It empowers the transparency between the participants to make appropriate decisions. It combines the information provided by both the physical and virtual world. Virtual world information includes elements such as simulation models, documentation and drawings [11]. It can be customized in complete isolation to enhance processes without jeopardizing the physical processes. Physical-world information is a combination of location and condition-based hardware produced environmental information. This needs to be usually transformed into a readable form to create higher-value content for the participants. Critical real-time process information provides valuable information for the organization's personnel to make the appropriate process- relevant decisions. Hence, it reduces the time spent on the process itself [11].

2.1.3 Decentralized Decisions

Decentralized decisions are versatile combinations of the relations between objects and people [11]. They enable autonomous decision making among different intelligent systems in accordance with the production policies and organizational goals. The policies include information transparency from inside and outside of processing facilities [11]. Increased overall productivity and better decision-making can be achieved by utilizing global information locally. Autonomous is a key in the IoE since the utilization of continuous production increases the overall productivity significantly. Only higher-level tasks such as exceptions, conflicts or interferences are tracked and evaluated more precise [11].

2.1.4 Technical Assistance

Technical assistance provides aid in fast onwarding decision making. As the industrial revolution moves forward, human operators are more and more losing their positions in the production lines and positioning themselves toward strategic decision making and problem-solving [11]. The increasing complexity of smart processes, complex networks and centralized decisions require a better understanding of the overall systems. Technical assistance is necessarily needed structure in providing support in quickly onwarding decision making. These systems need to be able to collect, analyze and visualize large quantities of environmental information to be able to provide aid and guidance in urgent problem solving on short notices [11]. For these types of systems to be efficient, safe and effective in supporting human operators in their tasks, it is necessary that the systems interact and function smoothly with the human-machine level. Furthermore, this requires proper training and understanding of such collaborations [11]. These design principles will be evaluated towards the organization's strategic goals later (Section 2.5) in this thesis.

As mentioned, the industrial revolution is a top priority for many industries and institutes. It provides numerous opportunities to actively shape the industry of the future. The economic impact of the fourth industrial revolution is expected to be massive since the operational productivity, effectiveness and efficiency are promised to be increased. This has the opportunity to develop entirely new products, services and business models [11]. The following (Section 2.2) Application upon Industry of Circular Economy examines the four design principles to identify and evaluate the need of Industry 4.0 in supporting upstream sector activities in the industry of circular economy and its suitability for business's strategic objectives. It evaluates the additional steps that are required for the industry to maintain its reputation as an innovation leader.

2.2 Application upon Industry of Circular Economy

Many oil and gas organizations have already implemented intelligent plant-wide information management and optimization systems to collect and analyze environmental information from inside the refineries [13]. However, the industry of circular economy introduces new critical challenges concerning the existing oil and gas legacy systems. These problems are related to geologically distributed feedstock supplies which are widely scattered and constantly evolving. Organization's operational cost structure which is already capital- and labour -intensive demands efficient solutions that are technologically lined-up with the existing systems. Industry 4.0 can provide several alternative solutions that meet the requirements of the circular economy upstream value chain [13]. As mentioned in the introduction, the value chain consists of upstream, midstream and downstream. For simplicity, this thesis will only focus on the upstream sector.

Transparency throughout the entire circular economy upstream value chain is required [13]. Especially, since the organization is extending its operational expertise more towards alternative waste material refining. Previously, the traditional oil and gas upstream sector were determined strictly based on the crude oil refining. Now it must evolve and improve to meet the requirements of the circular economy. This can considerably increase the ambiguity of the entire upstream value chain [13]. In terms of cost-efficiency, raw material supply and logistics are great improvement targets for the IIoT monitoring and optimization system since these activities have a major impact on the organization's end-products prices. Lowering the overall cost of the raw material from the supplier to the refinery forms a great basis for the implementation of the IIoT system. Increased productivity and operational efficiency will benefit the organization in the form of increasing operational profits. This thesis will mainly focus on the horizontal activities in the upstream value chain since that relates directly to the costs of end-products. The vertical value chain will be excluded from the thesis since it focuses more on supportive activities like sales and marketing. These activities are not in the target of the thesis.

Narrowing down the gap between industrial processes and aged ICT systems will enable the organization's resource data to be closer to the industrial operators and personnel. This enables better collaboration between the suppliers, transporters, refineries and other stakeholders along the upstream value chain. The comprehensive utilization of industrial level information can reduce the waste of resources throughout the entire value chain. Predictive quality and maintenance monitoring can save billions of dollars in industries like oil and gas since unscheduled shutdowns in refinery cost average of 20 billion dollars a year or 5% of refinery's production costs [9]. A single component failure such as pump breakdown costs from 100k to 300k dollars per day [9]. These kinds of scenarios are not typical only for the oil and gas industries but will also apply industry of the circular economy. Therefore, it is immensely important to identify, evaluate and strategically target the potential opportunities of the IIoT [9].

Properly designed and implemented IIoT system can provide an insight into upcoming failures or unscheduled maintenances which can considerably reduce the overall service costs. The ability to collect industrial data simultaneously from multiple data points throughout the value chain and exploit the data to determine the health of industrial equipment and predict potential failures has a significant impact on the efficiency of the industry [14]. Today's prevailing industrial processes are struggling on real-time decision making because the information is spread across the upstream value chain in varied formats. Decentralized information and its conversions to human-readable forms in real-time will provide the industrial operator and other personnel a powerful tool to monitor and optimize the conditions of the process facilities. With the aid of technical assistance, the average production time can be decreased for a single unit without compromising the end-product quality [9][15].

Besides the technical benefits of Industry 4.0 in the upstream sector, it can provide a platform for the future development of new technologies and innovations. It can increase the organization's strategic value as a sustainability responsible interactor. This can be achieved by decreasing the negative impact on the environment through better identification and monitoring of the organization’s assets [14]. Value creation steps designed to optimize the circular economy upstream industry are categorized into four following stages, Figure 2 and Figure 3.

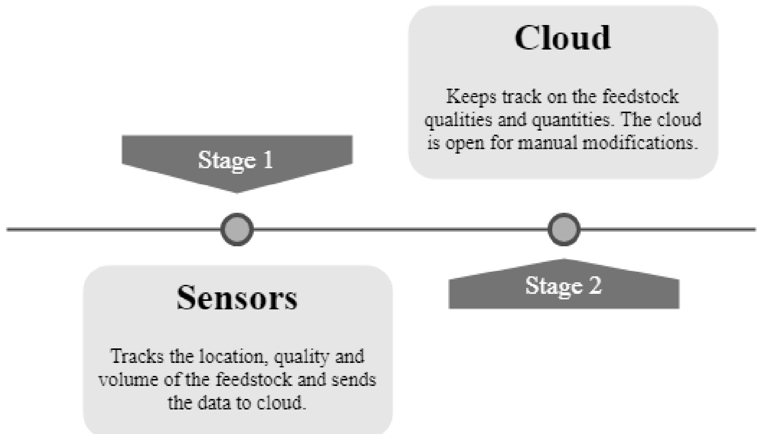


Figure 2- *The beginning of the upstream value chain.*

Value creation in the upstream industry of the circular economy begins with stage one and stage two, Figure 2. The beginning of the value chain consists of hardware components and cloud platform which are the foundation of any IIoT system. Components like sensors and actuators form the fundamental core of IIoT and M2M architecture. Environmental sensing and manipulation are the key activities of any IIoT system [11]. By the year 2020, about 40% of all information is coming from the connected intelligent sensors while the transportation sector is expected to be the largest producer. For example, tracking the location of a container vehicle has been always challenging for the oil and gas industry. Tanker tracking and real-time fleet management provide information about the location and health of the vehicle [14]. A major problem has been identifying the catastrophic situation and predictive maintenances before they occur. The problem has been that the industry is highly dependent on human input. Whether it has been the manual work or operator’s reaction to uncertain events, real-time tanker monitoring can save on massive transportation expenses by tracking the resources and combining comprehensive reports based on the information [16][17].

The cloud platform is a relatively new actor in industrial domain introduced by Industry 4.0. The only real distinguishing factor between the existing M2M communication and IIoT is that the IIoT can utilize broad internet connectivity which allows the sensors and actuators to transfer massive amounts of data into the cloud. In today's industrial domain, cloud infrastructure performs in a crucial role in storing industrial information [17]. Therefore, the cloud platform will play a major role in the implementation phase of the thesis.

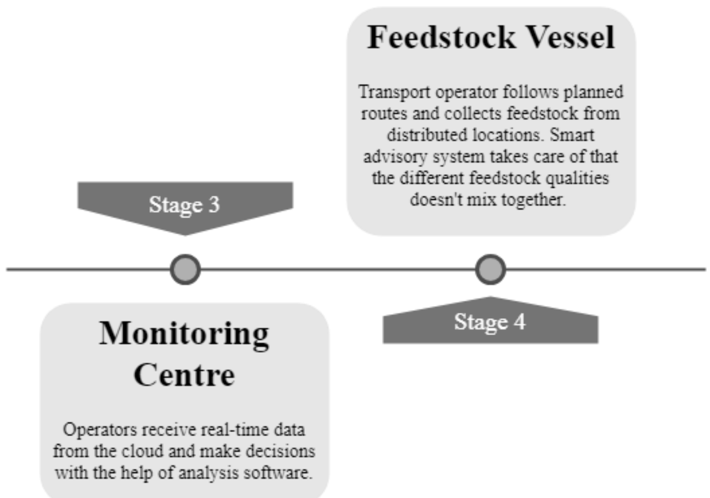


***Figure 3**- The ending of the upstream value chain.*

The ending of the upstream value chain consists of stages three and four, Figure 3. The monitoring center is the heart of the circular economy's core business activities. It can fetch real-time environmental data such as raw material location, quality and volume simultaneously from several geologically distributed locations. Real-time data analytics observes the incoming sensors data and the intelligent monitoring system sends alerts for the industrial operators to take immediate actions based on behaviour changes on certain events. Predictive analytics has an enormous role in processing large sets of complex data [17].

Raw material transportation has been always a challenging task to perform because of the lack of proper tracking equipment [17]. Overloading the truck causes unwanted risks which can cause catastrophic accidents. On the other hand, loading the truck under the weight limits will cause profit losses which reduce profitability. With the aid of IIoT accidents and unprofitable transportations can be reduced to the point where their negative effect is minimal. Raw material location, quality, temperature, pressure and volume tracking provides the organization insight about the overall efficiency and effectiveness [17].

2.3 Use Case: Intelligent Industrial Internet of Things

Industrial use cases are the most remarkable examples of intelligent environment monitoring. The ultimate target of the smart industries is to improve the operational potential and create a more sustainable business. This can be achieved with the technology provided by IIoT. The intelligent IIoT applications tend to be system-centric and highly dependent on the maturity of the technology [9]. Development of advanced technology and scientific intelligence secures the monitoring and optimization of new raw material suppliers. This requires modern actuators such as sensors, analytics and control systems that have improved connectivity, observation, management, and automation mechanisms [9]. Smart industrial IoT ecosystem is commonly composed of different devices and machines operating in energy, industrial or transportation environments. In such cases, data capacities and quantities tend to be relatively massive [9]. The data itself contains mission and safety-critical information that can have a severe impact on the organization's economy. Furthermore, it can have a significant effect on people working around it [18].

Discovery of alternative fuel solutions that satisfy the technical requirements and consumer demand is a real challenge. Alternative fuels tend to have higher cost rates since the production is not as advanced as traditional fuel production. It takes more time and effort to produce similar amounts of alternative fuels [18]. Optimizing and enhancing the fuel production processes is increasingly growing its popularity as it decreases the existing fuel prices, and thereby increases the use of alternative and more sustainable fuels. Non-technical requirements like regulations and government rules to reduce carbon footprint and greenhouse gases increase pressure towards industries [18]. Most of these problems can be solved with IIoT and it has been estimated that by 2020, there will be roughly 1.5 billion industrial IoT-enabled devices [18]. Most of these devices are different types of smart meters which have capabilities to track the features of the raw materials. This can be transformed into optimization patterns that help the industrial operators to predict upcoming maintenances and process failures, and advise the operator in the real-time decision making [18].

2.3.1 Intelligent Oil and Gas Industry in Practice

Improvements to lower the product prices are adding more pressure towards the oil and gas industries. IIoT monitoring and optimization have gained higher business priority since the current solutions are rather undeveloped. Enhancing operational efficiency is more complicated than ever due to the complexity of the industry and the data. Upstream industry loses an estimated 80 billion dollars each year in non-productive time [15]. Operators are forced to spend 70% of their time locating and modifying unoptimized data [15]. The upstream sector can gain new operational awareness by optimizing collected and analyzed diverse sets of data. Based on some rough estimates, large oil and gas organizations with an annual production of 270 million barrels could reduce production costs by more than 500 million dollars with proper IIoT in the upstream sector [19]. Sensile's oil and lubricant tank-level telemetry system is a great example, Figure 4. It transfers data via GSM network into the cloud. The data is automatically processed in the cloud and used for pick-ups planning with the aid of analytics [20].

Figure 4*- Sensile's oil and lubricant tank-level telemetry system (Direct quote from* [20]*).*

A major number of today's oil and gas organizations are operating with outdated analytic applications and only 13% feel that they are utilizing mature solutions [19][21]. Industry's data exists in unusable aged, i.e., legacy formats or spread across different digital systems. This distorts the accuracy in product qualities and delays production speeds affecting the end-product prices. Monitoring and optimization of the correct activities like blending and logistics have a tremendous role in 2 trillion dollars global industry. According to a case study made by Validere, exploiting IIoT and Artificial Intelligence (AI) increased oil barrel value by 5-9 dollars in 7500 barrel per day (BPD) oil and gas organization in Western Canada [21]. By harnessing the benefits of IIoT, Validere was able to reduce miscommunication, missed samples and re-tests. Industrial operators recognized issues earlier and made better and faster decisions based on more detailed information. Intelligent sensors, M2M –protocols and big data analytics enabled proper value chain monitoring and optimization and increased efficiency by reducing raw material costs [19][21]. Furthermore, it minimized delays in large projects [19][21].

2.4 Use Case: Intelligent IoT system in Transportation

An intelligent IoT system in transportation plays a crucial role in terms of efficiency and effectiveness. Traditional unintelligent transportation systems tend to prevent economic growth and drain existing resources. Unoptimized routes and raw material overflows increase the overall operational costs significantly. Different kinds of transportation equipment are being prepared for making driving more simple, effortless and economical while ensuring safer and more secure transportations [18]. Modern transportation vehicles are attached with versatile sensors for remote monitoring, diagnosis, and control. The intelligent sensors can form partly or completely automated processes by cooperating with one another through the ad-hoc network [18]. Smart sensor infrastructure, high-speed networks, and collaboration of advanced intelligent systems enable smarter transportation. Smart transportation systems are an inclusive part of smart industrial operations [18].

Intelligent transportation is gaining a lot of attention from the IIoT providers. Increasing use of IIoT can be already seen in the transportation sector. Connected and digitalized transportation vehicles are using hundreds and hundreds of microcontrollers to enhance the smartness, security, and safety of the vehicles. Intelligent systems send the latest information and time-critical data to the centralized monitoring system wherefrom it can be selected for more detailed analysis. The transportation industry has already decreased its carbon footprint by optimizing its logistical activities. A major part of produced energy is consumed by the transportation sector. It consumes more than 70% of the produced oil and releases massive amounts of carbon emissions into the surrounding environment [18].

There are two major ways to connect and collect transportation data. Vehicle-to-Vehicle implementation shares real-time data among vehicles. This can be a valuable function regarding transportation industries route planning activities since the vehicles can share position, location and speed between one on another. This can result in better decisions on routes and locations by avoiding overlapping activities. Furthermore, it will increase productivity and decrease unwanted hazardous situation on the roads. The second implementation is Vehicle-to-Cloud [18]. Hosting various edge devices efficiently and effectively is one of the main criteria for could platforms. Cloud environment can provide advanced services such as sensor and actuator management, monitoring and billing, and capability of planning and scaling [18].

At this point, it is reasonable to expect that companies are investing in vehicles to be self-, environment- and situation-aware. It has been strongly proven that well-developed intelligent logistical systems push the businesses towards a more sustainable and profitable direction. Rapidly growing world population and demand for alternative and affordable raw material solutions accelerate the demand for new transportation technologies. Technologies that can increase operational sustainability, efficiency and reduce environmental impact and optimize capacity, resources, and infrastructure based on demand. Optimization of transportation equipment availability, maintenance anticipation, and waste reduction decrease the overall operational costs [18].

2.4.1 Intelligent Circular Economy Industry in Practice

Intelligent Transport Systems (ITS) have been present in peoples' daily life for a while now [18]. Intelligent personal vehicles are loaded with smart technologies that can assist drivers in their daily tasks. Availability of advanced technologies such as cloud, M2M communication protocols, and real-time analytics are emerging in the field of transportation. The intelligent waste collection system is a great example of 'ITS' in the industry of the circular economy. For example, Enevo provides intelligent waste collection systems, Figure 5. They measure waste volume with ultrasonic sonar sensors and provide profits through savings. According to a case study made by Enevo in collaboration with McDonald's, they were able to decrease waste collection costs by 12% and increase recycling diversion by 50% at seven restaurants in Nottingham [22].

***Figure 5**- Enevo's waste collection IoT solution(Direct quote from* [22]*).*

The traditional way of managing waste collection was that business managers estimated the number of services for each restaurant. The waste collection was performed regardless of the free capacity the bins may have. Otherwise, if the waste collections were ever missed, extra time and effort were needed to resolve the problems. This had a negative impact on the business's financial and environmental values. Enovo's solution was to equip restaurants' waste bins with smart sensors that tracked waste volume, scheduled pick-ups and reported missed pick-ups. Based on the collected environmental data, Enevo established to create recycling baseline and reliable company-wide reporting system [22].

2.5 Upstream Supply Chain Management Framework

Upstream supply chain management framework demonstrates the key approaches (Figure 6) that shall be taken for utilizing the four design principles studied in the introduction to Industry 4.0 design principles (Section 2.1). The framework will be utilized for identifying and evaluating Industry 4.0 in the circular economy's raw material acquisition and storing. Industry 4.0 design principle framework must please multiple stakeholders across the value chain. It is important to scrutinize the potential benefits and opportunities of IIoT and evaluate additional requirements of the upstream industry [11].

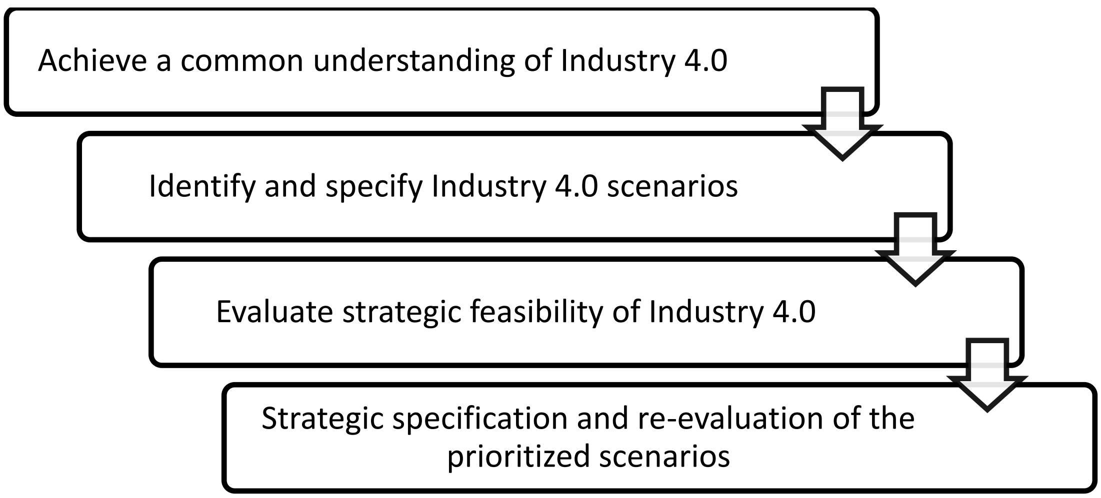


***Figure 6**- Industry 4.0 supply chain management framework* [11].

2.5.1 Achieve a Common Understanding of Industry 4.0

The common understanding of Industry 4.0 was created in the project's kick-off meeting and illustrated with the guidance of exemplary IIoT scenarios. Industry 4.0, as well as its main design principles, were introduced and discussed with the project members. This established a common understanding of Industry 4.0 and IIoT technology's benefits among involved project parties [11]. The organization made a decision to follow the design principles.

2.5.2 Identify and Specify Industry 4.0 Scenarios

Industry 4.0 scenario identifying and specifying were tentatively performed in the (Section 2.2) Application upon Industry of Circular Economy. Two major scenarios were identified for the circular economy upstream. These were the raw material supply optimization and raw material transportation optimization that was introduced in Figure 2 and Figure 3. Intelligent IIoT monitoring and optimization system can reduce service costs by up to 50% from the existing levels. It has an enormous impact on reducing carbon footprint and climate change. These scenarios are further detailed in Table 2 and Table 3.

Scenario: Raw material transportation monitoring and optimization
Scenario Description: • An automated material quantity and quality measurement system which ensures that only the same quality of the material will be mixed together. Can recognize 15 different raw material types such as used cooking oil, animal fats and natural oils. • An autonomous system that collects and transfers stored raw material measurements into an intelligent industrial data and stores it into a cloud where it can be manually modified and analyzed.
Current Situation: • Different qualities are mixed together which reduces the overall quality and value of the end-products. This decreases efficiency and productivity. • All the raw material qualities are manually entered into the database which is becoming a huge task since the raw material portfolio is continuously growing.

Table 2*- Raw material transportation monitoring and optimization scenario.*

The goal is to utilize different kinds of waste streams and non-edible oils for the reason of lowering prices, increasing the sustainability and flexibility of the blends. Currently, alternative fuels are refined from 15 different raw material types. The raw material portfolio is aimed to be broadened in the coming years. Each raw material shall meet strict quality requirements and shall be tested and analyzed carefully. Based on the quality analysis, the raw material will be evaluated against the limitations of each refining sites. Raw material quality must be monitored for political, economic and cultural reasons.

Raw material quality information will be automatically converted into common formats which list all the currently used raw material qualities, and their properties. Updating the summary files has been previously done manually which has become a massive task. Adding new samples into the files takes unnecessarily too much time. Different raw material qualities must be initially analyzed and evaluated since some of the end-users do not allow the use of certain raw material mixtures, for example, for cultural reasons. The scenario includes an easily updatable intelligent database which can be also manually updated. Warnings should occur if some of the values are clearly out of the norms. The system should be able to keep track of the analysis methods and sample sources. Furthermore, calculation rules must be easily modified.

Scenario: Raw material supply monitoring and optimization

Scenario Description:

- Reduce energy cost and environmental strain with an autonomous collection and scheduling system for raw material pick-ups.
- Generate sustainable business by reducing waste cost, optimizing waste collection, and ensuring services and fault states.
- Generate better efficiency by reducing raw material overflow with autonomous pick-up routes.
- Analyze waste generation by collecting data from distributed suppliers such as restaurants and factories.

Current Situation:

- Raw material waste collections are manually ordered, planned and assigned.
- Quality of the raw material is not tracked. The lowest quality of raw material will determine the overall quality of the stock. Good quality material will be wasted in the process of making low-quality products.
- Storage volume is not monitored which leads to overflows. The material will be wasted in the process of making low-quality products.

Table 3*- Raw material supply monitoring and optimization scenario.*

Smaller containers collect used cooking oils and animal fats from various distributed raw material suppliers such as factories and restaurants. Quality reports are taken once from each container and sent into the cloud in uniform formats. The first scenario is to design and implement automated IIoT based quality and quantity measurement system that is implemented across the upstream value chain. The system should be used for estimating the raw material in the suppliers' containers and the amount of raw material that is estimated to be received in the refineries. The system shall rank the raw material suppliers and optimize the logistical activities like collection dates, routes and container vehicles identification statuses. Based on the estimations, further processes can be planned, and components needed in refining ordered.

2.5.3 Evaluate the Strategic Feasibility of Industry 4.0

Analytic Hierarchy Process (AHP) was constructed to identify and evaluate Industry 4.0's strategic feasibility against the organization's strategy and demand [25]. It presents a comprehensive vision of the project's likelihood of success before committing any resources on the project. It prioritizes Industry 4.0's compliances, organization's strategy and operational feasibility by comparing them to each other. It applies qualitative and quantitative evaluation to measure strategic feasibility. It evaluates the feasibility of three main categories which are the Industry 4.0 compliance, the organization's strategic objectives and Industry 4.0's suitability against the organization's demand and ability to implement the project [11].

Industry 4.0 compliance was constructed based on the four design principles (interconnection, information transparency, decentralized decisions, and technical assistance) introduced in (Section 2.1)

Introduction to Industry 4.0. Organization's strategic objectives and goals were broken into five sub-criteria which are climate change, decarbonization of transport, alternative fuels, circular economy and digitalization [23]. Lastly, feasibility was translated into five sub-criteria which are technical, economic, legal, operational and schedule (TELOS) [11].

		Weight
Industry 4.0 compliance	Interconnection	7.3%
	Information transparency	56.4%
	Decentralized decisions	25.3%
	Technical assistance	11.0%
Contribution to strategic objective	Climate change	61.0%
	Decarbonization of transport	4.0%
	Alternative fuels	9.0%
	Circular economy	19.6%
	Digitalization	6.5%
Feasibility	Technical feasibility	9.0%
	Economic feasibility	16.9%
	Legal feasibility	31.8%
	Operational feasibility	28.6%
	Schedule feasibility	13.8%

Table 4*-Strategic scenario evaluation table [25].*

Identified sub-criteria were compared with each other and evaluated among the project members who included sales and marketing, product management, project management and developers. The evaluation was performed in scale from 1-9, where the higher value is more important. This evaluation method highlights the scenarios with the highest score [25].

Information transparency and decentralized decision making were the most supported elements in the Industry 4.0 compliances. It sets the requirements for communication, openness and accountability. Information should be transparent between the virtual and physical worlds in a way that it is easy to view the actions. Information should be decentralized in a way that the organization can manage multiple raw material sources easily and effortless in a single location. Interconnection and technical assistance gained the lowest support. Collaboration between different wireless components and people will be given less attention in this thesis. The final IIoT system will initially serve a single purpose and therefore it is not required to study connections between the different systems. Technical assistance will be essential in monitoring and optimizing the feedstock supply collecting routes, therefore it shall be added to future work. For the purpose of this thesis, it shall be excluded from the implementation and verification of the proof-of-concept level system.

Climate change was clearly the most supported element in the strategic objectives. The other strategic objectives mostly act as supportive elements in achieving the control and regulations set by climate change. However, during the query, the objectives were evaluated separately. The circular economy gained strong supporting in slowing down the climate change which indicates that there is a real strategical demand for the introduced IIoT system.

Feasibility (TELOS) evaluation pointed out that the organization considers the IIoT project legally and operationally possible. There are existing problems relating to feedstock supply management where to IIoT can provide extensive solutions. Technical feasibility i.e. the organization's technical expertise to complete the project gained the lowest support since IIoT hasn't been practiced before in the organization. The purpose of this thesis is to present a modern solution for the old-fashioned industry and legacy systems. At the same time, the organization can safely explore the possibilities enabled by the IIoT.

2.5.4 Strategic Specification and Re-evaluation of the Prioritized Scenarios

Strategic scenario evaluation was performed across the organization. The top prioritized scenarios were brought out, Table 4. The results were reviewed and further detailed with the organization's internal and external experts. Scenarios were re-evaluated and chosen for the system requirement analysis. Information transparency and decentralized decision making were selected from Industry 4.0 compliances. Climate change and the circular economy were selected from the strategic objectives. Feasibility objectives emphasized the safe exploration of the opportunities provided by the IIoT. These objects were stated to be supportive in monitoring and optimizing the circular economy upstream industry. The selected scenarios were further discussed with the organization's internal and external experts. The selected scenarios gained support across the organization. Therefore, the project was formally initialized.

2.6 Summary

This chapter has presented the key concepts of Industry 4.0 and the Industrial Internet of Things (IIoT). Industry 4.0 design principles were introduced and strategically evaluated against the organization's demands and requirements. Different use cases were introduced and evaluated to be used in the field of oil and gas, and transportation industries. Supply chain management framework was introduced and exploited in identifying, evaluating and selecting Industry 4.0 and Industrial Internet of Things scenarios to meet the requirements of the circular economy upstream industry. Industry 4.0 and IIoT were both recognized to be performing seamlessly in the monitoring and optimization of the circular economy upstream value chain. Because of the Analytic Hierarchy Process (AHP), system transparency and decentralized decision making were selected from the Industry 4.0 compliances. Climate change and the circular economy raised the highest support from the organization's strategic plan. Lacking expertise in IIoT was brought up during the AHP; therefore, this thesis will also function as a safe introduction to the new operations and technologies.

Chapter 3

System Requirement Analysis and Introduction to the IoT Reference Architectures

Chapter 2 presented an overview of the Industry 4.0 and Industrial Internet of Things (IIoT). It presented versatile use cases to utilize IIoT and justified the reasons to exploit IIoT in monitoring and optimization of the circular economy upstream industry. **Chapter 3** will further extend the topic with a comprehensive requirements analysis. Through the identification and specification of the key requirements, a comprehensive system design and development plan will be produced. These will evaluate the key functionalities, operativeness, compliance, usability, safety and security, documentation, maintenance and support. Furthermore, the system requirement analysis specifies the key areas that provide the largest value for the stakeholders. The outcomes are further detailed and prepared for proof-of-concept level IIoT system implementation. Three of the most used industrial level IoT reference architecture concepts are introduced and evaluated. The one that meets the organization's requirements will be selected for the use of the circular economy upstream system.

3.1 Introduction to System Requirements Analysis

The system requirements analysis has a major impact on the overall architecture design of the IIoT system. It defines the needs, conditions and requirements to meet the propriety of a new project or product. It is important that the design compliances with the organization's prevailing standards and practices. The final architectural design of the system is supposed to serve all the stakeholders without causing any conflicts [24]. The system requirement analysis will evaluate and further detail the objectives introduced in the (Section 2.5.2) Identify and Specify Industry 4.0 Scenarios and (Section 2.5.4) Strategic Specification and Re-evaluation of the Prioritized Scenarios.

The system requirements analysis and specification part of this thesis will comply with the European Commission's requirements towards IoT technology development which specify the current best practices for analyzing and evaluating system requirements [24]. It will follow requirement specification vocabulary standards defined by the RFC 2119 (Request for Comments – IETF documents) as best current practices [25]. The following system requirement definitions are directly referenced from the source [25] and are as follows:

- MUST - This word, or the terms "REQUIRED" or "SHALL", means that the definition is an absolute requirement of the specification.

- MUST NOT - This phrase, or the phrase "SHALL NOT", means that the definition is an absolute prohibition of the specification.

- SHOULD - This word, or the adjective "RECOMMENDED", means that there may exist valid reasons in particular circumstances to ignore a particular item, but the full implications must be understood and carefully weighed before choosing a different course.

- SHOULD NOT - This phrase, or the phrase "NOT RECOMMENDED", means that there may exist valid reasons in particular circumstances when the particular behaviour is acceptable or even useful, but the full implications should be understood, and the case carefully weighed before implementing any behaviour described with this label.

The European Commission's IoT project system requirement classification schema (FOCUS-D) consists of six central categories: Functionality, operativeness, compliance, usability, safety and security, documentation, maintenance, and support [24]. These functions are further detailed and evaluated in the following sub-chapters.

3.1.1 Functionality

Functionality category consists of the detailed functionality, data and accuracy, interoperability and responsibility practices. They will determine the specific functionalities that the IoT system must provide to accommodate the needs of the stakeholders. A preliminary description of the key functionalities was given in (Section 2.2) Application upon Industry of Circular Economy. The key functionalities were strongly related to real-time industrial data acquisition, analysis, and monitoring. The data consists of the raw material location, quality, volume, time and other factors affecting accuracy. These are retrieved from multiple locations simultaneously. Analytics software shall observe the incoming sensors data precisely and the intelligent monitoring system shall send alerts for the operators to take immediate actions based on behaviour changes on certain events [24]. Requirements such as connectivity and the system's overall performance are determined by the high throughput, scalability, low latency i.e. delay and jitter i.e. variation in delay [24]. Since the real-world industrial processes are highly time-sensitive the system requires short reaction times. System scalability is one of the key characteristics since an increasing number of endnodes need to be accommodated in the future [9]. The industrial environment will require system robustness since it needs to be able to survive in harsh conditions. A network of endnodes must be designed in the way that possible losses are localized, and the scope of communication modified in real-time. Whether the endnodes experience any failures they should be able to store the data locally and restore themselves for example through energy harvesting [9].

Data and accuracy requirements specify the data sources and destinations that the system shall use. It specifies a data model for data entities and relationships and the time that the system shall store the data. Furthermore, it specifies how long the data should be visible for the operators and which level of accuracy the system should display the times. Data from the edge devices shall be stored at least five times per day. Analytics shall be able to utilize real-time data acquisition if needed in the future. Data shall be archived in cloud storage for as long as it is needed. The process operator will decide when the data can be deleted from the system. For the optimization reasons, the measurement interval will be shorter at the beginning of the project and set to its final interval later in the project [24].

Interoperability determines the relationships and interfaces for the IIoT systems that are required to comply with the legacy systems that the company is sustaining. It defines the legacy systems and the characteristics of these systems that shall interact with the implementable IIoT system [24]. Each system shall comply with the organization's analytics platform and existing database to provide transparent data to the stakeholders. The organization is highly interested in RAMI 4.0 reference architecture model and Microsoft Azure Cloud since they are already utilizing them in the production. Opportunities and benefits related to them will be explored later in this thesis.

Responsibility requirements determine the organization's personnel who have the capability to perform certain system functionalities [24]. For example, data monitoring shall be done by the authorized personnel of the company. Activities like adding new entities or deleting as well as modifying the existing entities shall be done only by the administrative personnel.

3.1.2 Operativeness

Operativeness category represents availability, performance, capacity, scalability, reliability, installation and portability practices [24]. Availability requirements define the availability for the operational use. This consists of specific time periods such as date and time when the availability of the system is mandatory to meet the business requirements. Organization's operations require that the system shall be available every day 24h of the week. Support for the system will be provided at the working hours.

Performance requirements determine the overall performance of the system which may vary based on the different functionalities and system configurations [24]. For example, the operator shall be able to track the location of the raw material in real-time. This requires that the system is capable of sending data continuously. Performance shall not weaken if more components are added into the configuration.

Capacity requirements define the overall volumes and peaks that the IIoT system must be able to manage [24]. It determines the number of transactions the system shall manage in the average time and peak seasons. The system shall be able to handle a large amount of transaction in short periods of time if the person decides to track operations in real-time. The cloud platform shall be able to scale its' configurations based on the organization's needs.

Scalability determines the requirements for the expected growth. The system must be able to handle fast and unlimited growth in devices and data volumes [24]. Forecasts and commitments about the growth targets must be constructed. The raw material portfolio is continuously growing so new data entities shall be able to be added. New raw material providers (suppliers) and edge devices shall be able to be added in the system on anytime. In case the system reaches its' limitations more computation capacity shall be added automatically or warnings given about the decreasing capacity.

Reliability determines the requirements for system reliability needed for certain operations. It determines the probability in which the system starts to experience unwanted failures [24]. The system shall be able to notify about the changing states of the systems' functioning. Device management shall be handled according to the best practices to avoid any kind of data distortion. The organization wants to achieve uptime as high as possible.

Installation determines the requirements according to the system installation and data migration [24]. It determines the personnel who have capabilities to install and operate the system. It determines the instructions to perform data conversions if so decided. The organization requires that the system is easily installable. It shall be installed by the raw material provider him- or herself with the effort as minimal as possible. The system shall be easily registerable to the infrastructure. Future expansions and software updates will be carried out by the organization.

Portability determines the requirements for supporting the portability of the IIoT system or other hardware and/or software systems or environments connected to it [24]. It determines if the system shall be portable or connectable to other platforms. It determines the types of platforms the system shall be able to support. The organization has decided that the system shall support the existing cloud platform and license which are already used in production. Connectivity to industrial legacy systems shall be supported. The system will be initially demonstrated with a commercial analytics tool which will be later changed to organization's self-produced tools.

3.1.3 Compliance

Compliance category consists of laws and regulations, external and internal standards, audit, business rules, technologies, cultural and political practices [24]. Laws and regulations determine both international and national limitations relevant to this type of IIoT system [24]. Different countries follow certain types of laws which the system shall follow. The organization shall strictly follow and respect the European laws in the matter of privacy and data acquisition i.e. general data protection regulations (GDPR). If the system is implemented in other than European countries the law and regulations of these countries shall be taken into account [24].

External and internal standards determine the activities that the organization is capable of practicing [24]. It determines which versions of the standards or protocols the system shall support and use in production. The organization follows strictly system protection standards and directives. The system shall be dust, liquid and oil resistant. It shall be evaluated against the ATEX (explosive atmosphere) directive and shall not cause any safety hazards when implemented in use.

The audit practice determines the requirements for controlling and operating the system [24]. It determines the set of rules which of the system shall respect. Initially, only the functionalities such as data transfer, connectivity and device management will be tested at the experimental proof-of-concept level with versatile functionality audits. Later in the project more comprehensive and extensive audits such as unexpected costs, inappropriate access, performance, vulnerability and update audits will be performed [24]. This kind of a system-wide audit can be added into the future work because of its large scale.

Business rule activities determine the requirements such as internal and external policies and procedures for the organization's daily practices [24]. These are highly relevant in determining the legality of the IIoT system's functionalities and operations related to its use across the organization. It is important that the personnel respect the cybersecurity rules and standards determined by the organization's security management. Business rules shall be exercised during all stages of information processing and it shall be available to everyone who needs it at all times.

Technological activities determine the requirements for the systems to use, or not to use. It determined the architecture, standards and protocols for the implementable system that must comply with the existing organization's internal solutions [24]. The organization has determined that only the approved technologies and systems with the legal licenses shall be used in the production. Such systems shall be compatible with the organization's standard information processing environments.

Cultural and political requirements determine the rules for social factors that may influence the approval of the system or the end-products that the system is in relation [24]. These are usually related to the end user's cultural or political regulations and preferences based on local habits. System's user interface (UI) and user experience (UX) related design or implementation activities shall comply with the local regulations and preferences. The system shall not reflect any other service or product that is used in a different political or cultural environment. Cultural and political requirements are in a central role in circular economy-related operations [24]. Since used cooking oils may contain animal-based fats and oils which may be restricted in certain countries based on religious reasons they shall be precisely monitored and separately processed.

3.1.4 Usability

Usability category consists of the physical environment, appearance and style, ease of use, personalization, internationalization, learning time and accessibility practices [24]. The physical environment sets requirements for the system about the environment in which it will be implemented. It determines system requirements related to environmental factors such as weather, dust, oil, corrosive and explosive conditions and whether it shall be implemented in such environments [24]. It must be resistant against temperatures, vibrations and noises. The system will be implemented inside the waste material container in a way that the device itself settles on top of the container. The sensors will be pointing the bottom of the container. The battery shall not drain empty in a short period of time. This will require the system to be robust, low-power, easy to install and maintain, and affordable.

Appearance and style define the external design and form of the system [24]. This plays a major role in the organization's marketing plan. Discovering the correct design forms may require several iterations of prototyping [24]. Organization's internal rules determine the corporate style guidelines for marketing material and logos. For the purpose of this thesis, appearance and style will be excluded.

Ease of use determines requirements for the ergonomic properties of the system [24]. It defines the most complex functionalities and activities that the system involves. For example, the system should be easily approachable whether unwanted activities or errors occur during the operations. Edge devices shall be easy to install and misbehaviours informed by the monitoring system. Operations to restore the system shall be easy to implement through the cloud portal.

Personalization activities determine the requirements for personalizing the system for the needs of the user or organization [24]. It determines whether the system shall be configurable with different data visualization formats or not. Different stakeholders, as well as the organization, shall be able to configure analytics layout with versatile charts, tables and gauges according to their own interests. Missing fields and themes can be implemented afterwards based on demand.

Internationalization activities determine the requirements for the system's operating language, the language of the supports and personalization presets [24]. It determines the language characters such as Chinese, Arabic and other languages that shall be supported. It determines whether multiple languages should be displayed at once. The organization's existing systems operate in Finnish and English. Real-time analytics and reports will be implemented in both languages.

Learning time determines the requirements about the time and effort needed to learn the system [24]. It determines the learning time before the end-user can use the system and perform simple functions independently [24]. Since the organization is already familiar with the tools, more extensive instructions are not required. System operators shall pass the organization's internal online course and practices before operating the system.

Accessibility determines the requirements for the system usability and adoption for people with physical or cognitive disabilities [24]. This may be regulated by laws in certain countries. The system shall comply with the regulations and standards of accessibility set by the organization. The system has no danger to human life and it shall be operated with the permission of the organization.

3.1.5 Safety and Security

Safety and security category consists of safety, access protection, integrity, and privacy practices. Safety practices determine the requirements about the likeliness to loss, damage or harm of using the system [24]. It determines the safety-critical aspects for the system such as whether it creates a danger to humans, properties or environment. It determines the standards and laws which the system shall respect. Regulations of the different countries shall be considered when defining the safety factors of the system [24]. The organization has determined cybersecurity standards that prohibit the expose or leakage of any kind of operation critical data to public operatives. The system itself shall not be dangerous for human life and facilities. It must comply with the required standards and safety protocols.

Access protection determines the requirements for accessing the system [24]. These are determined by the organization's security department and shall be considered when designing the system. It defines the access policies to the system and access to certain functionalities. The administrators shall have more transparent access right compared to the common operator. System access is provided by the organization which is valid for the agreed time.

Integrity practices determine the requirements for the integrity level of the system. It defines the protection activities against threats such as Trojans, viruses, spyware and other types of malware that can damage the system or security of the organization [24]. It determines the actions that shall be taken against malicious attacks and whether the information needs to be more heavily protected [24]. To prevent any kind of information abuse or malicious attacks, personnel shall use reinforced multi-factor authentication when accessing the cloud data. All internet transactions will be heavily encrypted. The communication will be implemented as a ‘one-way’ communication which prevents access to the organization’s internal network. Infrastructure will be protected with several firewalls.

Privacy practices determine the requirement for both personal as well as the organization data that is collected and stored in the system [24]. It determines the quality and sensitivity of the collected data and the methods used for managing it. The system will comply with European Union General Data Protection Regulation (GDPR) regarding data collection, storing and disclosure of sensitive information. Regulations can highly differ depending on different countries. The system shall comply with the country-specific regulations.

3.1.6 Documentation, Maintenance, and Support

Documentation, maintenance, and support category consist of documentation, maintenance, support and training related practices [24]. Documentation determines the requirements for the different types of documentation and their scope and coverage [24]. It determines the minimum documentation and all the languages that must be provided. It specifies the person responsible for producing and updating the documentation. The organization has defined its own documentation rules. Each of the documentation shall be written in clear English language and shared on the Atlassian Confluence documentation platform. The documentation shall be updated whenever changes or updates occur in the project, and each member of the project is responsible for updating the documentation.

Maintenance practices determine the requirements for system maintenance [24]. It determines the proper personnel to maintain the system, and whether different parts of the systems shall be maintained by different personnel. It specifies the maintenance interval for each of the critical features and defines the correct form of documentation [24]. The system shall collect operation sensitive data and generate comprehensive logs to support upstream monitoring and equipment condition tracking. The organization has appointed specific personnel to be responsible for modifying and updating the system infrastructure.

Support practices determine requirements about the scope, content and the level of support required in each step of the project [24]. It determines the mandatory support activities needed for the system to be operating properly. It defines the level and urgency of the support. It specifies the content of documentation generated based on the support request. The organization will provide help desk services via email and phone. Email support shall be active during typical working hours. Phone support shall be active anytime during the day and week. Documentation shall be prepared based on each support request and it shall follow the organization’s uniform formula which is available in the Confluence.

Training determines requirements about the activities provided to train the user to operate the system safely, securely and effectively [24]. It determines the training program for different user levels and activities. The organization will create online training entities to educate users about the different features of the IoT system. Training is required before the user can safely and securely operate the system. Different user levels are trained separately.

3.2 Introduction to Reference Architecture Concepts

Reference architecture concepts provide comprehensive guidance on the system design and implementation based on the organizational requirements [18]. These we recognized in the previous sub-chapters under the (3.1) Introduction to System Requirements Analysis. Reference architecture concepts allow a deeper development of unique technologies, systems and system architectures [18]. Well-known concepts and the best common practices define the building blocks for the system design in varying environments. The key objective of the reference architecture concepts is to connect physical and digital worlds together and merge Information Technology (IT) and Operational Technology (OT) layers into a single system [18]. Internet of Things plays a major role in transforming and merging these worlds together. 'Information Technology' provides features such as flexibility, agility and speed, security and business insight which are eventually merged together with the 'Operational Technology' features such as utilization, efficiency, continuity, and consistency by emphasizing connectivity, optimization and analytics [18]. These activities, as well as their scope and content, can be recognized and evaluated with the selection of proper reference architecture concept [18]. They are aimed to be used in identifying, understanding and evaluating the most critical patterns and issues of IT and OT across the industrial environments and organizational value chains. It is critical to have a comprehensive system architecture that is highly flexible, scalable and can serve various components, technologies and stakeholders across the entire IIoT ecosystem [18].

The most common reference architecture concepts are highly dependent on the structure of machine-to-machine architecture and communication protocols [18]. These are typically the base of any active industrial application. There are several different IIoT reference architecture concepts operating across the world. IIoT reference architecture concepts such as the Internet of Things Architecture (IoT-A), the Industrial Internet Reference Architecture (IIRA) and the Reference Architecture Model Industry 4.0 (RAMI 4.0) were developed independently with divergent approaches, scopes, and objectives [26]. In the following sub-chapters, the reference architecture concepts which are composed in Table 5, are compared and evaluated for the purpose of optimizing the circular economy upstream industry. During the comparison, the existing architecture concepts are taken into account.

	IoT-A	IIRA	RAMI 4.0
Scenario	Industry independent. Smart cities, transportation, energy, environment.	Cross-domain, industry-independent, wide-ranging industries. Manufacturing, transportation, energy.	Manufacturing.
Framework/ model	Architecture Reference Model (ARM).	Industrial Internet Architecture Framework (IIAF) and Industrial Internet Connectivity Framework (IICF). ISO/IEC/IEEE 42010:2011	Service-Oriented Architecture (SOA) and Smart Grid Architecture Model (SGAM). IEC 62890, IEC 62264 // IEC 61512
Description	Data-driven infrastructure & new business models. Focus on vertical challenges.	Standard-based open architecture. Business-value-driven and concern-resolution-oriented.	Industry 4.0 driven, service-oriented, lifecycle management, human-operated value chain, vertical integrated and horizontal value networks
Structure	(5 layers) Physical, context, functional, information and deployment.	(4 layers) Business, usage, functional and implementation	(6 layers) Business, functional, information, communication, integration and asset

Table 5- *IIoT reference architecture concepts.*

3.2.1 Internet of Things – Architecture (IoT-A)

Internet of Things – Architecture (IoT-A) is a European research project achievement to address the limitations of existing IoT architectures initialized in 2009 [27]. Limitations were related to integration and scalability in larger systems, and the missing ability to adopt stronger security principles and policies. IoT-A is a completely new reference architecture concept enhanced with an additional set of key building blocks. It provides top-down design guidance and architectural principles in delivering use-case-specific IoT projects [27]. It ensures seamless communication and service across various platforms and addresses the scalability requirements of a future IIoT [28]. It covers a wide range of IoT applications, development cycles and technologies to provide clearer business benefits and supply-chain management. It describes the essential building blocks and design choices for industry independent applications. It is extremely suitable for smart cities, transportation, energy and environmental applications. It consists of reference architecture best practices in designing new IoT architectures and systems that more conveniently fit the custom demands [29].

IoT-A strictly follows the concepts of Architectural Reference Model (ARM) which establishes backwards-compatibility to several different IIoT scenarios [29]. It consists of the necessary design patterns and models for addressing the vertical challenges in developing the vision to a final product. This creates requirements for the activities to understand the complexity of stakeholders' vision. They have a clear understanding of the vision that they want to achieve but it must be communicated forward. It is a combination of the reference architecture and the reference model [29]. It provides the best practices, guidelines and models for constructing the most suitable custom IIoT architectures and systems. It expands the existing architectural models and solutions with the vision of the business point of view. The design process emphasizes the utilization of concrete sets and complete application architectures rather than focusing on the abstract sets of mechanism and models [29]. The IoT-A consists of five layers which are physical, context, functional, information and deployment. These layers cover the design and implementation of the IoT system effectively. It has the average amount of layer compared to other models.

IoT-A has some disadvantages such as inflexibility under inevitable changes. ARM-based architectures and systems do not allow further development and modifications for the organizational private use [30][31]. Further development must be open for the ARM and IoT-A must be used as a base structure. System modifications and extensions can become challenging and costly if done afterwards. Concerns about increasing processing volume, throughput, response time, responsiveness, predictability have not yet been adequately addressed and they require further research and development. IoT-A based system's ability to handle and function under failures as well as maintain the system's availability is still open questions [30]. Support requests have been submitted according to the discovery services, context awareness and dynamic adoption [31]. These are still missing features that limit the use of IoT-A [31].

3.2.2 Industrial Internet Reference Architecture (IIRA)

Industrial Internet Reference Architecture (IIRA) which is based on the Industrial Internet Consortium (IIC) organization defines the best-practices and design principles for implementing comprehensive system usability practices across a broad spectrum of technical and business levels across the organization [32]. It was founded by AT&T, Cisco, IBM, Intel, and General Electric in 2015. IIRA provides guidance and recommendations in implementing comprehensive IIoT architectural practices through requirement identification and experimental testing. It provides several tools and methods to be implemented across the industrial value chains [32]. It is a standards-based framework for developing interoperable solutions, systems, and applications [32]. It highlights system-specific architectural concerns, patterns, and design concepts [33]. It is a cross-domain architecture which has wide-ranging interoperability in the field of IIoT. It broadly addresses the issues and concerns prevailing in the current industrial fields. It is highly used architecture among industries such as energy, transportation and public domain infrastructure [26].

IIRA is based on the ISO/IEC/IEEE 42010:2011 architecture standard concerning the system and software design and implementation. It provides Industrial Internet Architecture Framework (IIAF) which serves as a guideline through the documentation and communication activities concerning the IIRA [32][33]. It analyses the common architectural concerns systematically, resolves and documents the outcomes and viewpoint. The outcomes provide basis and content for the IIoT architecture [32]. This will allow more extensive system architecture design and drive technological development towards the addressed technological gaps [9]. IIRA consists of four layers which recognize and classify the central concerns about the system's business, usage, functional and implementation [26][32]. It has the most compact layer architecture design of these three architectures.

Although the IIAF defines the framework for building systems and applications, it is mainly just a blueprint for decision-makers to address the requirements of the ecosystem. It is a business vision and value-driven framework, and therefore it mainly provides comprehension and appearance about a complete architectural IoT design. It does not take a more comprehensive contribution to the physical system design or implementation [32].

3.2.3 Reference Architectural Model Industrie 4.0 (RAMI 4.0)

Reference Architectural Model Industrie 4.0 (RAMI 4.0) is a German strategic initiative to revolutionize manufacturing and production [34]. It was originally discovered and implemented to improve communication across networks of renewable energy sources by BITCOM, VDMA, and ZWEI [34]. It has a strong overall focus on business processes in manufacturing such as smart factories and process industries. It provides comprehensive sets of manufacturing-related information about the suppliers, subcontractors, customers and versatile departments within the organization. RAMI 4.0 increases operational visibility and transparency across the organization. It provides considerable savings regarding resources and increases efficiency and flexibility across the industrial value chain through automation [34]. It provides deeper understanding, digitalization and interoperability across industrial manufacturing [26].

RAMI 4.0 follows Service-Oriented Architecture (SOA) which combines the environmental information acquisition and operations to promote the central aspects of Industry 4.0 [26]. Although it focuses mainly on the horizontal manufacturing activities, it still promotes lifecycle management, human operable activities, vertical integration within the industry as well as horizontal integration over the value networks [26]. It provides much deeper aspects of digitalization and interoperability in the manufacturing value chain than the other architectural concepts. It introduces a new kind of organizational practices to control the entire value chain and product life-cycle effectively from the initial idea to the end-product [26]. RAMI 4.0 has been already adopted by major foundations and organizations in the fields of oil and gas [35]. The organization is following RAMI 4.0 and they are interested in the expandability of the architecture.

RAMI 4.0 architectural model is primarily based on the Smart Grid Architecture Model (SGAM) which describes the key activities on operating a manufacturing plant [26]. It is typically used as an extensive modelling tool for RAMI 4.0 models. The model consists of six layers which are business, functional, information, communication, integration and asset. It provides the most comprehensive layering of the presented architectural concepts. The comparison between the architectural concepts proves that RAMI 4.0 would provide the most appropriate architecture for classifying and developing the circular economy based industrial IoT systems. It has the flexibility and widely implementable practices for several industrial scenarios such as those that were defined in (Section 2.5.2) Identify and Specify Industry 4.0 Scenarios.

3.3 Summary

This chapter has presented requirements for the industrial level IoT system according to the functionalities, operativeness, compliances, usability, safety and security, and documentation, maintenance and supportive practicalities. The requirement analysis and the specifications are based on the European Union's Horizon 2020 research and innovation Programme. The analysis was constructed by complying with the RFC 2119 terminology of the best practices. The key point of the analysis was to identify the requirements for the IoT scenarios selected in (Section 2.5.2) Identify and Specify Industry 4.0 Scenarios. These requirements were used as a basis for the following reference architecture selection. Three commonly used industrial reference architecture concepts were introduced, evaluated and one of them was selected for further evaluation. As a result of the analysis, RAMI 4.0 promoted the strongest emphasis on Industry 4.0 principles and manufacturing practices. In the following chapter 4, RAMI 4.0 will be further detailed for the use of the circular economy upstream industry IoT system.

Chapter 4

Technical Design of the IIoT Upstream Monitoring System

Chapter 3 presented the process of requirement analysis that performed as the basis for the reference architecture concept selection. The main concepts, principles and standards were introduced through industrial use cases and evaluated to enable the application of Industry 4.0. RAMI 4.0 was selected to be the most suitable architecture for guaranteeing the full functionality and interoperability across the organization. **Chapter 4** presents further detailed RAMI 4.0 architecture and the key elements to enable Industry 4.0 in the field of the circular economy. The key concepts, standards and protocols will be introduced and evaluated for the needs of circular economy upstream monitoring and optimization system. Final outcomes provide assistance and guidance in the documentation, development, communication and deployment of the system [9][18][32]. Finally, a comprehensive architectural protocol stack will be selected to support the experimental proof-of-concept level system architecture and further implementation.

4.1 Introduction to RAMI 4.0 Model

RAMI 4.0 model represents a three-dimensional architecture (Figure 7) to enable and promote the main elements of Industry 4.0 [36]. The vertical axis consists of six layers which are business, functional, information, communication, integration and asset layers [36]. These layers represent the complexity of the Information Technology (IT) systems. They increase the understandability of the system by dividing it into smaller and more manageable forms [36]. These are further detailed in (Section 4.3) RAMI 4.0 Layers.

The left horizontal axis consists of type and instance which represent the product's life-cycle management. The axis is called life cycle and value stream management and it is based on the IEC 62890 standard [36]. Life cycle and value stream management are essential for the system development, and therefore it is further detailed in (Section 4.2) Life Cycle & Value Stream IEC 62890.

The right horizontal axis represents the responsibilities and roles within the field of manufacturing [36]. The hierarchy levels are based on the IEC 62264 and IEC 61512 standard. These are international standards for enterprise information technology and control level systems [26]. They illustrate the functional hierarchy of manufacturing industries and facilities. These models are embedded in the smart manufacturing value-added processes where the base level of intelligent manufacturing is explored from a product level to the connected world level. Hierarchy level consists of product, field device, control device, station, work center, enterprise, and connected world levels [26]. Further detailing of the hierarchy levels IEC 62264 and IEC 61512 is unnecessary since it is outside the scope of this thesis. Hierarchy levels IEC 62264 and IEC 61512 can be added to future work.

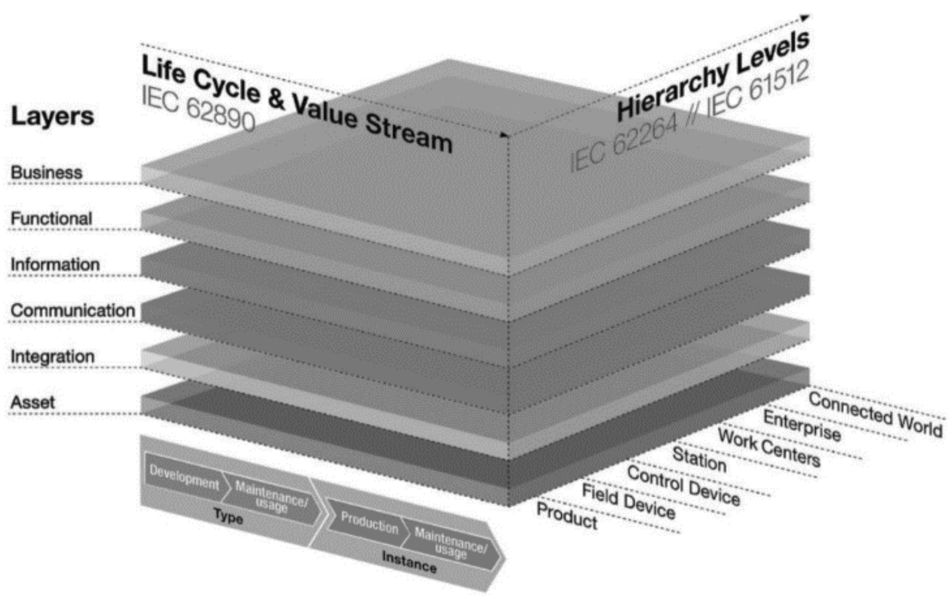


***Figure** 7- Reference Architecture Model Industry 4.0 (Direct quote from* [37]*).*

RAMI 4.0 model represents system-specific recommendations for different technologies, protocols, and standards [26]. It has a common data and information model which enable information identification, data modelling, service interfaces and scheme practices [26]. It provides reliable, easy and robust integration between the parts, machines, products and digital industrial processes. RAMI 4.0 defines easy and trustable data transferring through the organization and system infrastructure [26].

4.2 Life Cycle & Value Stream IEC 62890

Life cycle & value stream IEC 62890 (Figure 7) represents the asset and object relating practices that have value for the organization's value stream [26]. It identifies and evaluates the value types from the idea level to the development and maintenance of the system. It consists of production, usage and maintenance practices relating to the system's assets [26]. These practices are based on Industry 4.0 ideologies which make the model globally and uniquely identifiable. Life cycle and value stream based systems are highly communication capable because of the administrator shell and asset structure [26]. The administration shell consists of unique information for managing the assets and the assets' technical functionalities [26]. The life cycle and value stream IEC 62890 axis is divided into Type and Instance. The iteration between the Type and Instance can be repeated several times before the final system is accepted for production [38].

4.2.1 Type & Instance

The Type represents the development process from an initial idea to a final machine, product, software or a part of hardware [38]. It comprises the industrial processes from placing the design requisition, developing and testing the system to establish a properly functioning prototype or production facility. The prototype goes through several testing and validation processes, whereof it is selected for serial production [38]. Each machine, product or process has a unique Instance of a Type i.e. unique identification number. The Type turns into an Instance after it has been installed to a specific environment [38].

The circular economy monitoring and optimization project were initialized as a new idea of a portable IIoT environmental measurement system. The idea has been processed and analyzed basis on the requirement analysis. Proper architecture concept has been selected which was exploited as guidance in the development. After successful sampling, testing and comprehensive system validation, the system is delivered to the raw material suppliers [38].

The raw material suppliers are encouraged to give feedback based on the functionalities of the system. This will be used in further development. All the system related materials and documentation will be produced and stored in the way that follows and respects rules and regulations identified in (Section 3.1) Introduction to System Requirements Analysis.

Life cycle and value stream management provide essential information about the system development, maintenance and usage [38]. This can be collected and exploited to improve product's functionality, operativeness, compliance, usability, safety and security, documentation, maintenance and support. The life cycle and value stream management is completely digitalized and can be linked to other organizational activities such as predictive maintenance, material purchasing, order planning and tracking [38]. Therefore, the life cycle and value stream management can be seen as a value-adding activity [38]. The circular economy IIoT monitoring and optimization system will be implemented with the basic functionalities in the first iteration and further improved based on the feedback.

4.3 RAMI 4.0 Layers

RAMI 4.0 layers represent the properties and elements of Industry 4.0 systems and system entities [26]. They exploit standardized information technologies and protocols. The layers are located on the vertical axis of the RAMI 4.0 model and used for specific system design and implementation. Each of the layers uses services from the layer below and provide services forward for the upper layers. RAMI 4.0 layers consist of business, functional, information, communication, integration and asset layers.

4.3.1 Business Layer

The business layer represents the essential functions and elements in forming business-specific processes and connections among the processes [26]. It supports the business processes across the organization and creates links between the processes and process models. It follows organization-specific business models and compliances which were identified in (Section 3.1.3) Compliance. Business layer recognizes different stakeholders and their perception of the value, objectives and business vision of the system [26]. It primarily focuses on rationalizing the decisions and reasoning of the system [26]. Business layer activities such as strategic evaluation and verification were already performed (Section 2.5.4) Strategic Specification and Re-evaluation of the Prioritized Scenarios.

4.3.2 Functional Layer

The functional layer represents the logical functions of an asset or component [26]. It provides a description of technical functionalities that follow Industry 4.0 principles. It allows the system to support higher-level business processes across the organization [26]. It consists of web services, business intelligence, application and control software, and smart services [39]. Web services determine the services provided by the industrial machines and systems within the same network. It follows the Service-Oriented Architecture (SOA) in the provisioning of machine-to-machine communication [39]. Web services provide modularized, standardized and independent services that can be merged into existing RAMI 4.0 systems and applications [39]. Business intelligence represents versatile models and concepts that are implemented to support, operate and control the system-specific operational activities [39]. It provides collaboration activities to provide sensitive operational information between individuals and departments among the organization. Application and control software provides various virtual production, manufacturing and testing simulations to analyze the behavior of a specific component or system [39]. Various configurations can be tested in the virtual environment before applying them into physical production. Smart services represent the exploitation of industrial level systems in process and production monitoring and optimization [39]. It provides remote services via versatile intelligent sensors and systems. The organization can exploit these services in the development of new business models, products or services [39].

4.3.3 Information Layer

The information layer defines data and file formats and accuracy for the system [39]. It provides data integrity and other similar qualities of data for the systems that are under the influence of heavy functionalities. Information layer represents the information and services that the industrial edge systems offer, generate, use and modify according to functionalities of the assets and actuators [26]. It is connected to the upper functional layer via software interfaces and platforms such as cloud [39]. This is further detailed in (Section 5.10) Industrial Internet of Things & Cloud Computing. Information layer provides services such as information management which specifies the activities to acquire and modify high-level system data. It consists of operations such as data acquisition, transformation and analysis [26].

4.3.4 Communication Layer

The communication layer defines the standards and protocols for the communication services, events and transmission technologies [26]. It enables universal networking and communication via various interfaces and platforms. It provides control, transmission services and communication instructions for the lower integration layer [26]. Communication layer determines Industry 4.0 principles, standards and protocols for accessing information via unified communication technologies and formats across the entire IoT ecosystem. RAMI 4.0 communication layer is further detailed in ISO/OSI (International Organization for Standardization / Open Systems Interconnection) layers that consist of an application, presentation, session, transport, network, data link and physical layers, Figure 8.

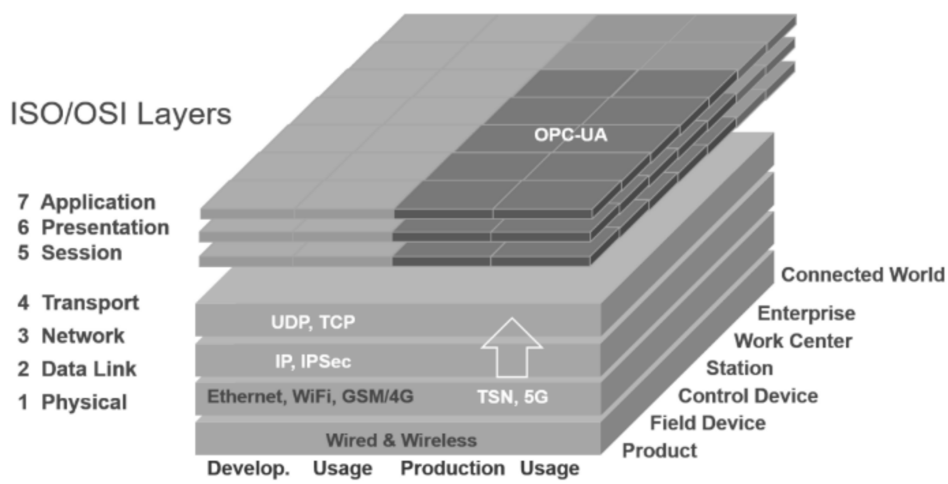


***Figure 8**- Communication Layer in ISO/ OSI Model (Direct quote from* [26]*).*

The model defines communication standards and protocol for the entire system across the axes of RAMI 4.0 life cycle and value stream, and hierarchy levels [26]. It enables organization-level information transparency, and therefore the RAMI 4.0 model is widely used in manufacturing environments such as oil and gas.

4.3.4.1 Application, Presentation & Session Layers

The Application Layer consists of several protocols which enable system functions to initiate, maintain and terminate processes according to the information provided by the application layer [40]. The application layer protocols directly serve the end-user by managing the entire system. It is the highest layer in the OSI model. Therefore, the rest of the OSI layers serve the application layer in the execution of the application operations. Application layer functions for achieving system-wide information and optimal operations by applying use-case-specific rules, models and logic [26]. These functions are enabled by the different application layer protocols, Table 7.

Protocol	Setting	Transport	Security	Relationship/ Topology	Features
DDS	Energy & Utilities	UDP	TLS/ SSL	Device-to-Device Publish/Subscribe	High-performance, real-time, scalable
CoAP	Smart energy, building automation	UDP	DTLS	Machine-to-Machine	Scalable, real-time, high-performance
AMQP	Financial, banking, IoT	TCP/IP	SASL/ TLS/ SSL	Point-to-Point Publish/Subscribe	Reliable, secure, efficient, portable
MQTT	Telemetry, remote monitoring	TCP/IP	TLS/ SSL	Device-to-Server Publish/Subscribe	Small size, low-power, easy to implement

XMPP	Real-time communication	TCP/IP	TLS/SSL	Request/Response Publish/Subscribe	Device addressing
HTTP REST	General Web	TCP/IP	HTTPS	Request/Response	Simplicity, universal
WebSocket	Mobile	TCP/IP	TLS/ SSK	Client/Server Publish/Subscribe	Full-duplex communication
OPC-UA	Industrial Process control	UA TCP	X.509 Certificate	Server, session, Publish/Subscribe	Interoperability, Firewall-friendly

Table 6- *Application Layer Protocols.*

There are several Application Layer protocols exploited in the field of IIoT, Table 7. However, publish and subscribe topology is essential for the IoT to be able to perform more efficiently and avoid unnecessary heavy workloads or bandwidth consumption [41]. The most commonly used IoT protocols that enable publish and subscribe topology are MQTT, XMPP, AMQP and DDS. These protocols will be introduced and evaluated more in detail.

DDS (Data Distribution Service) is a data-centric device-to-device middleware protocol even though it supports device-to-server operations [9]. Its main purpose is to establish a connection between different edge devices. It is a great protocol for industrial embedded solutions since it focuses directly on the devices that use data from other devices. It can meet high-performance requirements while respecting low-power systems. This differs from the other publish and subscribe protocols since they focus more on server-side operations such as collecting the data from edge devices. DDS enables fast communication and collaboration between different devices on the same network. It is a remotely accessible protocol and capable of publishing millions of messages to a large number of subscribers simultaneously. If the subscriber happens to be offline, DDS can store and forward messages. DDS is intended to be implemented in time-critical applications since it offers detailed QoS (Quality-of-Service) control, reliability, redundancy and multicasting [9]. It uses the connectionless UDP protocol which is quick since it just sends the data and immediately forgets the session. UDP makes it unreliable since it can lose valuable data being unable to resend it [9].

AMQP (Advanced Message Queuing Protocol) is categorized in publish and subscribe protocol, although it is not true publish and subscribe protocol but more like queuing protocol [9]. It was originally used in financial and banking industries since it is a highly reliable protocol for managing a large number of messages. It communicates over TCP/IP protocol and it is capable of recording every transaction and message it receives [9]. It can be deployed in the management and operations domain at the server-side.

MQTT (Message Queue Telemetry Transport) is a publish and subscribe protocol intended for data acquisition [9]. Its main purpose is remote monitoring and data collection from thousands of edge devices. It transports the data back to the management and operational domain which makes it a device-to-server protocol. It is based on Hub-to-Spoke topology in a point-to-point relationship since it only collects the data and sends it to the server. It does not support device-to-device connections. MQTT operates over TCP/IP protocol and it requires that the IoT system supports the same protocol [9]. Furthermore, it required a stable and reliable network connection. This may cause performance issues and packet obstruction while using infrastructures such as LAN or other non-WAN networks [9]. MQTT operates considerably efficiently in power usage when compared to HTTP REST protocol [41].

XMPP (Extensible Messaging and Presence Protocol) is a real-time communication protocol used in direct messaging and video conferencing [9]. It was originally developed to make human-style communication effortless and easier. It has user-friendly device addressing, therefore it is easy for the operators to identify and manage devices using technologies such as smartphone or URL (Uniform Resource Locator). However, it is not fast since it uses polling and only-on-demand technologies to check the presence of the devices. It is based on human interactions more than real-time operations. It is a great protocol for smartphones because it operates on TCP/IP, HTTP and XML protocol stack [9]. For low-power IoT devices it is unsuitable because of lack of processing capabilities. It can be also used in industrial environments where operators manage interfaces and favor scalability, addressing and security over real-time operations [9].

CoAP (Constrained Application Protocol) is an Application Layer protocols designed to operate in constrained networks [9]. It was found to be extremely useful in M2M and IoT environments which are unable to run HTTP protocol for transactions. It is highly similar to HTTP and therefore it can run commands such as GET, POST, PUT and DELETE [9]. It is a lightweight protocol that can run payloads of any type. Instead of using XML, CoAP prefers JSON (JavaScript Object Notation) lightweight operability. It can operate devices that have only 10KiB of RAM [9]. Although there are limitations of the devices, CoAP provides a strong DTLS encryption to protect the data. It uses session less UDP protocol to save resources and keep messages short.

HTTP REST is more like a web service API protocol designed to support service-oriented architectures [9]. It supports web and mobile application which it accesses through URL instead of heavy XML protocol. This makes it a lightweight protocol. It uses basic HTTP 1.1 commands such as GET, POST, PUT and DELETE. The output data is easier to parse which makes the REST protocol easier, faster and more flexible [9].

Websocket is an Application Layer protocol which enables two-way communication between a client and a remote host [42]. It is a full-duplex protocol which enables the use of TCP/IP protocol traffic in both directions in more real-time. WebSocket does not include headers in the communication packets and therefore it is more lightweight and faster. It provides a single connection for a single IoT device decreasing the number of connections and disconnections performed for each poll [42].

OPC UA (Open Platform Communications - Unified Architecture) is a global standard for industrial automation devices to enable connectivity, reliability, security and interoperability [43]. It is used for connecting equipment, products and processes in the manufacturing environment. It allows modern technologies to operate alongside legacy products [43]. It is an independent service-oriented architecture used by large industries such as oil and gas, automation and process control. It is based on a machine-to-machine communication protocol standardized for industrial automation [44]. It ensures seamless data flow among multiple industrial equipment and systems for data acquisition and control. OPC UA is a secure and reliable standard to exchange data in an industrial automation environment [45]. It follows the Service-Oriented Architecture (SOA) [44][37]. This enables the use of SOAP (Simple Open Architecture Protocol), HTTP and TCP/IP [46].

The Presentation Layer exploits versatile services provided by the protocols that were introduced in the application layer. It enables data exchange across the system according to the protocols. Presentation layer services manage the control of the data, display and exchange of the entries [40]. It enables open environment which can be operated with the acceptable cost in system modification, transformation and variability of the interface [40].

The Session Layer assists and supports versatile operation between the presentation entities. It provides administration level services which can bind and unbind versatile services together [40]. Furthermore, it controls data exchange, defines limitations and synchronizes data between the entities. The operation is called session dialogue service [40]. Session layer implements its functionalities from the Transport Layer.

4.3.4.2 Transport Layer

Transport Layer is responsible for transferring the data across the network. It ensures that the transferred and received data are identical and delivered error-free [47]. It provides versatile functions to enable end-to-end communication across the network. The transport layer consists of two transport protocols which are TCP (Transmission Control Protocol) and UDP (User Datagram Protocol). TCP is the most commonly used transport layer protocol. It is a reliable host-to-host communication protocol used between computers and networks [48]. It provides functions to open and close connections, as well as send and receive data across established networks. Each of the functions consists of the source port, destination port, sequence number, acknowledgement number, data offset, reserved, control bits, window, checksum, urgent pointer, options, padding and data. TCP provides operations for connection established, data transfer, flow control, multiplexing, reliability, security and precedence [48].

UDP is a communication protocol for packet-switch devices in interconnected networks. It requires the use of underlying protocol such as IP (Internet Protocol) [49]. This enables applications to send data packets across the network with a lighter protocol mechanism. It is a transaction-oriented protocol which does not guarantee data packet delivery or duplication protection. If these are required, TCP is a more suitable solution. UDP header consists of the source port, destination port, length, checksum and data octets [49]. The checksum procedure is similar to TCP's procedure. UDP determines the source and destination addresses, and protocols from the internet header. A single UDP/IP interface shall return the complete internet datagram in the response to a receive operation [49].

4.3.4.3 Network Layer

The network layer is responsible for packet forwarding. It includes operations such as packet routing between transport entities over multiple networks [40]. It provides sensor data aggregation, analogue-to-digital conversion and transportation. It is often located close to the sensors and actuators which collect the physical world data in analogue formats. The data needs to be aggregated and converted into digital formats. Data Acquisition System (DAS) connects as a part of the sensor network. It aggregates outputs and performs conversion functions such as analogue-to-digital conversions [50].

Internet gateway collects the aggregated and digitalized sensor data and routes it over the data link layer by using physical media such as Ethernet, Wi-Fi or Bluetooth. Packet routing is specified by the routing protocols. There are two different versions of Internet Protocols (IP) which are IPv4 and IPv6, Table 8.

Protocol	Address Size	Number of Addresses	Features
IPv4	32-bit	2^32	Compatibility, security and strong data encryption, flexibility and scalability, large routing capabilities.
IPv6	128-bit	2^128	Larger address space, readdressing, efficient routing and packet processing, multicast, security.

***Table** 7- Network Layer Internet Protocols (IP).*

IPv4 is the fourth version of the Internet Protocol (IP) and by far the most used network layer protocol [51]. It has address space of 32-bits which enables 2^32 unique addresses to be existing simultaneously. It was the first Internet Protocol applied to modern TCP/IP communication. Although the IPv4 address space has been depleted and the addresses are running out, it is not disappearing any time soon. Since most of the devices are running on IPv4, and IPv6 nodes are not compatible communicating with the IPv4 nodes it is impossible to replace the protocol. It is still a very secure internet protocol exploiting the latest data encryption protocols. It is flexible and scalable and performs flawlessly for organizations with large communication demand [51].

IPv6 is the sixth version of the Internet Protocol (IP). The rapid growth of the Internet and Internet-connected devices has created a demand for wider address space. Thus, IPv6 is intended to be the successor for the IPv4. IPv6 allows address space of 128-bits which enables 2^128 global addresses to be existing in the network. This enables a lot larger number of devices to be connected simultaneously to the network which is a requirement for IoT systems to perform properly. It provides more flexible settings for routing traffic and flexibility in assigning addresses [51]. IPv6 enables unique addressing for each IoT devices, whether it is behind a firewall or not. Therefore, it is much more firewall-friendly. There are some compressed versions of IPv6 such as 6LoWAPN which are better suited for IoT environments. It limits the IPv6 address space for specific devices which can be converted back to IPv6 regular IPv6 addresses in the routers [9].

There are some extensions for the Internet Protocols (IP) such as Routing Protocol (RPL) to address the challenges caused by the low-power demand. RPL is a powerful protocol when the system must have mobility. It supports several link layers and implements its' own routing pattern over lossy networks. The problems typically exist when implementing certain network topologies such as multi-hop mesh topologies or constantly changing between different topologies. RPL can support Point-to-Point (P2P), Point-to-Multipoint (P2MP) and Multipoint-to-Point (MP2P) topologies [9].

4.3.4.4 IIoT Communication Technologies, Standards and Protocols

IIoT communication technologies, standards and protocols are categorized into Wired Communication Technologies, Wide Area Network Technologies (WWAN), Local Area Networks (WLAN) and Personal Area Networks (WPAN) [40].

Protocol/ Standard	Physical Media	Data Rate	Network Topology	Features
IEEE 802.3	Industrial Ethernet Cable (CAT5, CAT6, CAT7)	10, 100, 1000 Mbps	The physical connection from the transponder to the reader.	High bit rates, long link distance, harsh environments, and resistance against temperatures, vibrations and noises.
IEEE 802.3	Standard Ethernet Cable	10, 100, 1000 Mbps	The physical connection from the transponder to the reader.	High bit rates, long link distance.
Modbus	RS-232, RS-485, RS-422, Ethernet	Dependent on physical media	Peer-to-Peer	Industrial application. Easy to install and maintain.
Profibus DP	RS-485, RS-485-IS, MBP, MBP-IS, fiber optic	9.6 kbps or 12 Mbps	Line, ring, star, tree. Dependent on physical media	Production automation. High-speed, low-cost connection, standardized protocol
Profinet	Ethernet, WLAN, Bluetooth	Dependent on Physical media	Line, ring, star	Industrial application. Robust, real-time, reliable

***Table 8**- Wired Communication Technologies and protocols.*

Wired Communication Technologies and Protocols represent the commonly used technical standards for industrial environments, Table 9. Industrial Ethernet and standard Ethernet are very similar in nature. Both use RJ-45 connectors with data rates of 10, 100, 1000 Mbit/s [9]. They provide high bit rates and long-distance linking. Industrial Ethernet has some advanced features for robust environments such as resistance against changing temperatures, vibrations and noises. However, the IEEE 802.3 protocol does not perform well in real-time critical applications. Thus, it is not suitable for industrial environment processes which require guarantee according to data transfer times and efficiency.

Modbus is one of the most commonly used automation communication protocols in connecting industrial assets. It is the oldest and most popular communication protocol in industrial automation and Supervisory Control And Data Acquisition (SCADA) systems [52]. It is typically used with Programmable Logic Controllers (PLCs) in an industrial environment. It can communicate over multiple types of physical media such as RS-232, RS-485, RS-422 and Ethernet [52]. Modbus supports the use of mixed protocols by embedding Modbus messages into Ethernet packets. The main communication structure is peer-to-peer. Modbus is similar to Profibus which is also a Fieldbus standard.

Technology	Bandwidth	Data Rate	Packet Size	Range	Network Topology
4G/ LTE	Cellular Bands < 6GHz	100 Mbps	--	Global	Point-to-Multipoint
5G	Cellular Bands 30 - 300 GHz	300-1000 Mbps	--	Global	Point-to-Multipoint
WiMax	2.3-2.5 GHz and 3.4-3.5 GHz	1000 Mbps	20 bytes	50km	Mesh
Dash 7	25 or 200 kHz	9.6, 55.55, 166.667 kbps	256 bytes	<5km	Node-to-Node, star, tree
SigFox	Ultra-narrow	100 bps	12 bytes	3-50km	Star
LoRaWAN	8x125kHz (EU) 64x125kHx (US)	<50 kbps (EU) <100 kbps (US)	User Defines	<15km	Star-on-Star

Table 9- *Wireless Wide Area Network (WWAN) technologies and protocols.*

Wireless Wide Area Network (WWAN) is a communication network that covers large geographical areas. It consists of commonly used technologies that are widely used for IoT applications, Table 10. Networks such as 3G/4G/5G/LTE are carrier broadband technologies provided by mobile operators [9]. They provide irreplaceable device connectivity in remote areas around the globe. Broadband technologies have large broadband capabilities and high data throughput. Therefore, they are essential communication technologies for rural as well as urban IIoT applications. However, broadband technologies require high power usage which influences on the system's battery life. These problems can be mitigated by connection several IoT devices into a local network router which handles the communication forward. This requires that the devices are fairly close to each other, which limits the use scenarios. Broadband technologies are rather inefficient in cases where the devices communicate only an insignificant amount [9].

WiMax (Worldwide Interoperability for Microwave Access) is a Radio Frequency (RF) technology with similar capabilities than Wi-Fi [9]. It was considered to be a competitor for the LTE network, but it was not able to supplant LTE because of its' popularity in the markets. It is highly functional for IIoT applications since it provides longer distances than Wi-Fi technology and very high throughput. It is not typically used in remote area application since its' bit-rate weakens when the ranges increase [9].

Dash 7 is an asynchronous communication protocol implemented between gateways, sub-controllers and endnodes [9]. It uses typical command and response operations to transfer messages between the endnodes. Endnodes must intermittently wake up and scan whether there are any messages sent by the surrounding sub-controllers. This decreases power usage and provides long-lasting battery life. However, operations range is fairly limited with the maximum distance of 5 kilometers [9].

SigFox is an end-to-end communication protocol used in applications which need to continuously send a small amount of data [9]. It provides the lowest energy consumption from device to cloud applications. It requires a third-party modem which is certified by the SigFox operator. It has a great channel blocking and message interception mechanism to provide additional security. It provides protection against replay attacks and formats the data in a way that only the right user can interpret the data [9].

LoRaWAN (Long Range Wide Area Network) is a long-range communication technology. It operates as a wireless hop over Semtech‘s radio scheme between the endnodes and network gateways [9]. It is defined as a MAC layer protocol. It is typically used in non-real time applications because of its’ low data ranges and limited duty cycles [53]. Some of the applications are bike-sharing smart tracking and bus schedule signs.

Protocol/ Standard	Bandwidth	Data Rate	Range	Network Topology	Features
IEEE 802.11g Wi-Fi	2.4 GHz	54 Mbps	<50m or Some kilometers	Point-to-Multipoint Point-to-Point	Large bandwidth
IEEE 802.11n Wi-Fi	2.4 GHz or 5 GHz	54-600 Mbps	<50m or Some kilometers	Point-to-Multipoint Point-to-Point	Better performance, support for MIMO standard.

Table 10*- Wireless Local Area Network (WLAN) technologies and protocols.*

Wireless Local Area Networks (WLAN) represents the wireless communication standards for limited areas such as office, school and home, Table 11. The commonly used WLAN technologies are based on IEEE 802.11g and IEEE 802.11n (i.e. Wi-Fi) standards which are improved extensions for the IEEE 802.11a and IEEE 802.11b standards [54]. IEEE 802.11g standard is a suitable solution for large exhibition halls and auditoriums. It is compatible with the older standards such as IEEE 802.11a and IEEE 802.11b. It has an extensive indoor range up to 50m when used as a point-to-multipoint network. In outdoor environments, it can be used as a point-to-point network enabling an operational range of several kilometers. IEEE 802.11n provides better performance compared to previous standards. The n-extension supports MIMO-technology with multiple inputs and outputs. This provides more reliable and smooth connection. IEEE 802.11n enables data ranges up to 600 Mbit/s [54]. Although the energy consumption is highly dependent on the hardware the IEEE 802.11n is significantly more energy-efficient than IEEE 802.11g standard [55].

Protocol/ Standard	Bandwidth	Data Rate	Range	Network Topology	Features
IEEE 802.15.4	subGhz, 2.4GHz	40, 250 kbps	>160m	Peer-to-Peer Star	Low-speed, low-range, low-power, real-time
Bluetooth	2.4 GHz	1,2,3 Mbps	10-150m	Peer-to-Peer Star	Active, real-time, high data rates, battery
BLE	2.4 GHz	125 kbps, 1, 2 Mbps	>100m	Star	Bluetooth Smart, short-range, low latency and bandwidth, lower power consumption and setup time.
ZigBee/ ZigBee IP	868/ 915/ 2400 MHz	250 kbps	10-100m	Star/tree/mesh/ hybrid	Active, low-power, versatile network topologies, great for local sensors and actuators, battery
Z-Wave	900MHz	9.6/ 40/ 100 kbps	30m	Mesh	Reliable, low-latency, up-to 232 devices
RFID	128-135 kHz 13.56 or 860-960MHz	<100 kbps	<15m	Star, single transponder to the reader	Passive, low-power, low data range, small data transfer, batteryless or battery-assisted
NFC	13.56 MHz	<424 kbps	<5cm	Peer-to-peer/ single transponder to the reader	Passive, low-power, contactless, secure file swaps, batteryless or battery assisted
Thread	2.4GHz (ISM)	--	--	Mesh	Secure, scalable, low-power and low-cost.

6LoW-PAN	--	--	--	Mesh/ star	Low-power, low data rates

***Table 11**- Wireless Personal Area Network (WPAN) technologies and protocols.*

Wireless Personal Area Network (WPAN) is a low-power communication standard intended to be used in short communication ranges. There are several technologies used for WPAN communication, table 12. For example, IEEE 802.15.4 is a low-power MAC Layer communication standard [9]. It provides energy-efficient technology for radio communication. It can provide data transfer rates up to 250 kbps and a range of 160 kilometers. IEEE 802.15.4 provides the basis for several communication standards such as ZigBee, WirelessHART and Thread. It can be exploited in establishing a wireless embedded internet together with 6LoWPAN and other internet protocol standards [9].

Bluetooth and BLE (Bluetooth Low Energy) are short distance communication standards. They use short-wavelength radio waves with a bandwidth of 2.4 GHz. BLE is a low-power version of the typical Bluetooth. It was designed for the use of IoT systems because of its resource and power usage friendly capabilities. Bluetooth enables devices to run on extremely small battery sources. It is extremely beneficial due to its capability to form ad-hoc network i.e. piconets when the devices enter the same radio proximity [9]. Bluetooth can connect simultaneously up to eight devices.

ZigBee and ZigBee IP are global wireless personal area communication technologies. They were designed to be used in industrial, commercial and consumer fields. ZigBee is a low-power and user-friendly technology. It is built upon IEEE 802.15.4 standard and it has been defined as a MAC layer protocol. It provides extensive application and security layer support compared to other standards. It is an essential standard in connecting different manufacturers' products to the same communication network. ZigBee IP was developed to support IP technology which is the global communication standard. It exploits technologies such as RPL and 6LoWPAN in enabling the use of IP [9].

Z-Wave is a low-power radio frequency communication protocol commonly used in home automation [9]. It uses low-energy radio waves for reliable and low-latency communication for small messages. It supports mesh topology which makes it highly scalable. The operating distance is very limited and it requires a larger number of devices to cover larger operational areas [9]. For the industrial IoT environment, Z-Wave is not suitable since it is designed to be used with light control systems. This makes it essential for light residential and commercial environments.

RFID (Radio-Frequency Identification) is a wireless technology used in versatile sectors such as industrial, commercial and retail IoT systems [9]. It uses electronic tags to retain a small amount of data. Tags can be used to communicate wirelessly over electromagnetic fields. It is very low-range technology powered by the reader electromagnetic induction. It can be used to identify and track inventory in an industrial environment. RFIDs would be essential for feedstock separation and tracking. It can be used to ensure that only identical feedstock is mixed together in the same containers.

NFC (Near Field Communication) is an evolved version from the RFID technology. It is commonly used personal area communication technology in contactless payment systems. It exploits small wireless links i.e. embedded chips to transfer a tiny amount of data. In a heavy industrial environment, there is not yet need for such technology.

Thread is an advanced IPv6 based protocol used in home automation. It is based on 6LoWPAN technology and supports the IEEE 802.15.4 protocol over a mesh topology [9]. It is highly secure since only authenticated devices can join the network. It provides scalability, low-cost and low-power consumption. However, it is a highly complex standard and has limited usage in the markets. This makes is it inessential in the industrial environment.

6LoWPAN (IPv6 over Low-power Personal Area Network) is an efficient IP compatible communication protocol [9]. It is essential for embedded sensors which transfer only a tiny amount of data over networks. It is defined as a network protocol that has its own compression mechanism and encapsulation. This gives it freedom from physical layer and frequency band. 6LoWPAN is a scalable, robust and self-healing standard. It is capable of transferring data packets over IEEE 802.15.4 and implementing IP protocols such as TCP, UDP, MQTT, CoAP and HTTP.

4.3.4.5 Data Link Layer

Data Link Layer is responsible for transferring data between the physical layer and the network layer [40]. It handles data flow scheduling in a way that the data does not suppress the sender or the receiver at any time. It is responsible for handling bit transmission errors and ensuring that the data arrives successfully. It enables data transfer in different communication networks such as WAN, LAN and PAN [40]. It describes MAC (Media Access Control) and LLC (Logical Link Control) which provide data packet transmission, frame synchronization, error checking and data flow control [40].

4.3.5 Integration Layer

Integration layer defines the physical assets and their digital specifications and capabilities [26]. It provides computer-supported monitoring, controlling and optimization activities for industrial processes by creating versatile events based on the assets [26]. It performs based on Human-Machine Interface (HMI) standardization which provides a dashboard or interface to connect the person to the system or machine [39]. It enables IO-conversion which enables industrial sensor signals, analog signals, to be converted into human-readable formats. It provides product identification functionalities which are the core of Industry 4.0. They are exploited in the identification of versatile objects and products across the organization's value chain. Different technologies such as barcodes, QR-codes and RFIDs are used in the system identification. These provide only temporary identification procedures, and therefore alternative solutions such as assigned system IDs and IP addresses will be exploited in the identification of the IoT edge devices [39].

4.3.6 Asset Layer

The asset layer defines the physical assets such as hardware interfaces, smart products, materials, systems and servers [26][39]. Assets and components are globally identifiable but unique objects which have capabilities of wired and wireless communication [26]. RAMI 4.0 assets are strongly tied with an administration shell, Figure 9. The administration shell turns assets and objects into Industry 4.0 components enabling storage of elements and property information. Administration layer implements and deploys the key elements from communication, information, function and business layers. It consists of relevant information for controlling and managing the assets and asset functionalities [36].

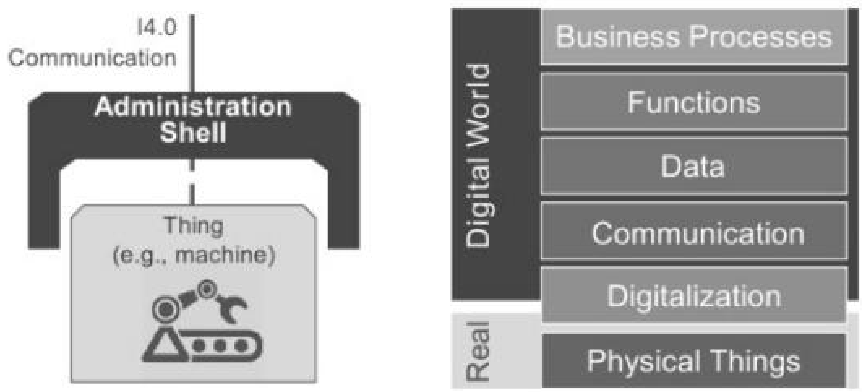


***Figure 9**- RAMI 4.0 Asset Layer (Direct quote from* [36]*).*

Endnodes such as components, sensors and actuators can collect data from the operational environment and industrial systems which will turn into human-readable formats. Low-power wireless technologies such as robotic cameras, liquid-level detectors and accelerators can operate over wired or wireless networks without the need for an A/C power source. Endnodes are evaluated based on their connectivity to the network. A local connection such as Ethernet, Wi-Fi or Field Bus is the simplest way to connect components to the organization's network. Remote areas where communications options such as power source are limited will increase the complexity of the system. This will affect the system's functionalities. It has a restrictive effect on the ways that the organization uses the data. The system can be designed based on data immediacy or depth of insight. If the system requires more immediate information, data processing is located closer to the edge devices [50]. For now, the organization is not interested in investing in edge computing. This will be suggested for future work.

It is important to find the correct communication protocols to provide a reliable connection between the endnodes. Communication protocols have an effect on the systems integration, interoperability and composability [9]. Communication protocols were introduced in (Section 4.3.4) Communication Layer and evaluated for the needs of the organization. Wired integration between the endnodes was recognized to be the most trustable solution but it limits the mobility and dimensions of the system [9][11].

4.4 Summary

This chapter has presented the RAMI 4.0 model in more details. RAMI 4.0 model's life cycle and value stream IEC 62890, hierarchy levels IEC 62264 and IEC 61512, and RAMI 4.0 layers have been introduced and further defined based on the requirements of the organization. System's type and instance were identified and recognized to be important in system development and life cycle management. Communication standards and protocols were introduced in application, transport, network and data link layers. The key concepts, standards and protocols have been identified and evaluated for the needs of circular economy IoT system. Circular economy protocol stack was constructed together with the organization's system architect and evaluated based on existing PLC systems, implementable IoT systems and extendibility of the future systems. The circular economy protocol stack was divided based on the organization's networks which were edge/ private, edge/ IoT and public networks where most of the cloud providers operate. The selected protocols are listed as follows:

- **MQTT, REST and OPC UA** (Application, Presentation and Session Layers)
- **TCP/IP** (Transport Layer)
- **IPv6 and 6LoWPAN** (Network Layer)
- **Wi-Fi, 3G or 4G (Broadband)** (IIoT Communication Technologies)

These standards and protocols will be used in the experimental proof-of-concept level implementation in (Chapter 5) Technical Implementation of the IIoT Upstream Monitoring System. For the simplicity, HTTP REST will be used with the request and response topology over an IPv6 network layer protocol which can be later optimized for the 6LoWPAN extension. Wireless Wide Area Networks (WWAN) such as 3G and 4G/LTE will be used in the production version of the system since it will be implemented in rural areas where the devices have long distances between each other. In the experimental proof-of-concept level system, Wi-Fi technology will be used to demonstrate the functioning of the entire system.

Chapter 5

Technical Implementation of the IIoT Upstream Monitoring System

Chapter 4 presented the technologies and protocols selected for the circular economy upstream industry monitoring and optimization IIoT system. These technologies and protocols largely determine the types of sensors and actuators. **Chapter 5** will represent a comprehensive system architecture model constructed together with the organization's system architect. Proper sensors technologies will be identified, evaluated and validated in order to respect the technical design and the selected protocol stack of the system. (Section 3.1) Introduction to System Requirements Analysis strongly defines the system-centric requirements and specifications that support the selection of the system's sensors and actuators. Based on the selected sensors and actuators, the thesis introduces system requirement, architecture and component compatible microcontroller capable of measuring, automating and optimizing the raw material acquisition process. Different intelligent data storages are identified, evaluated and validated for the use of the large organization. The data will be transferred from the selected cloud storage, analyzed and monitored with the organization's analytics software. At the end of this chapter, the experimental proof-of-concept level IIoT system is fully functioning. This chapter will follow the structure determined in the following figure 10.

5.1 Circular Economy Architecture Model

Circular Economy Architecture Model was designed and constructed together with the organization's system architect, Figure 10. In the design of the circular economy architectural model, several factors such as the legacy systems, implementable IoT system and the future extendibility were taken into consideration. The system was designed to be affordable, power-efficient, small in physical size, suitable regarding throughput and range based on the requirement analysis performed in (Section 3.1) Introduction to System Requirements Analysis. One key element was that the system must be compatible with the existing industrial standards and protocols. The circular economy architecture model consists of an organizational edge/ private network, public edge/ IoT network and interfaces for future technologies and networks.

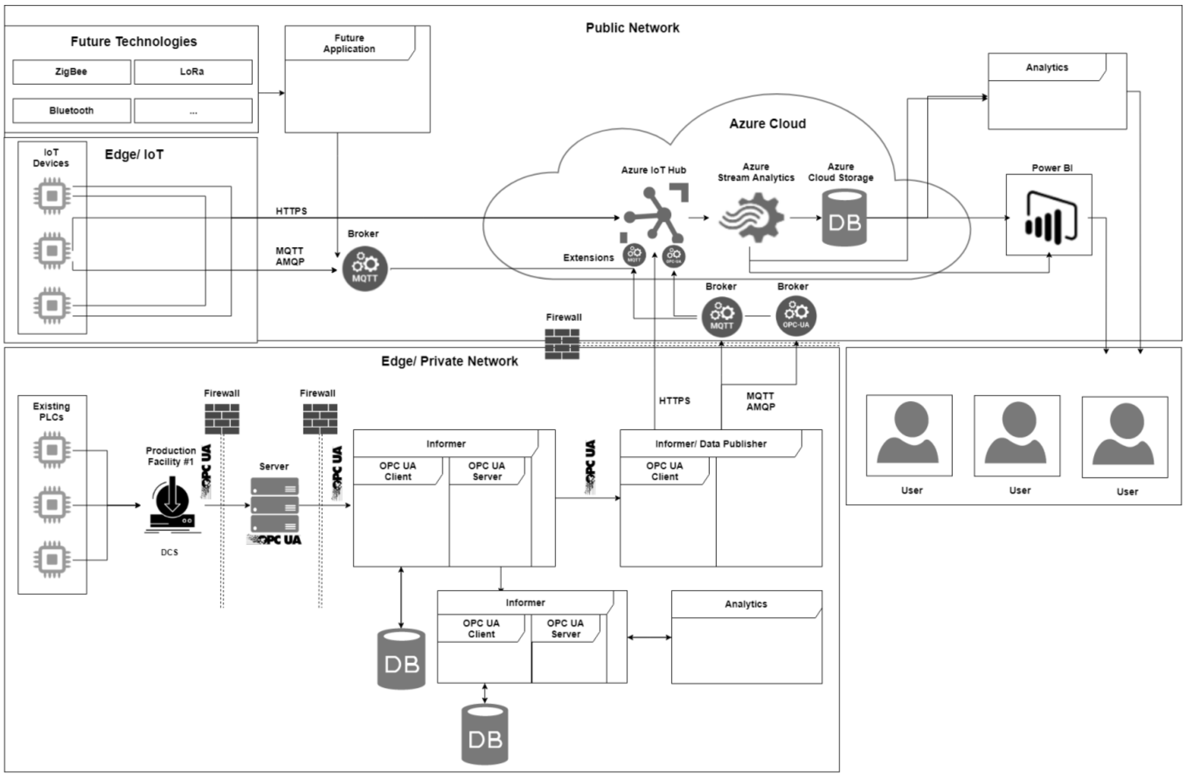


Figure 10- *Architecture model for the proposed IIoT system.*

5.1.1 Edge/ Private Network

Edge/ Private Network level consists of industry-level machinery and legacy systems. It has been implemented to support only one-way communication for security reasons. This enables a more secure network since the organization does not need to open firewalls into both directions. Industrial PLCs (Programmable Logic Controllers) transfer environmental data into the production facility's central DCS (Distributed Control System). These are production facility centric systems. DCS includes an interface for the facility's operators to control the units. This data type is transported via industrial level communication protocols such as Modbus, Profibus or Profinet. DCS transfers the data into the OPC UA server via OPC UA communication protocol wherefrom 'Informer' tool fetches the data. All communication transfers through the ‘Informer’ which can strain the system. Therefore, function-specific data can be separated into another ‘Informer’ instance which decreases the main system consumption. The data is stored into a separate database and transferred forward to the ‘Informer Data Publisher’. It uses application-level OPC UA protocol with publish and subscribe topology. The data is forwarded to the cloud which is connected to the other networks. Organization’s analytics collect the data from the cloud for more specific analysis and optimization. The private network will be kept intact for the time being but it can be modified to support two-way communication with MQTT or OPC-UA brokers. This thesis will mainly focus on the architecture and implementation of the external public network level system.

5.1.2 Public Network

Public Network level IIoT system supports MQTT, HTPP REST and OPC UA communication protocols. HTTP REST can be used directly to transfer the data into the cloud. Other communication protocols than HTTP REST transfer the data through a separate broker that enables the data transformation into the Azure IoT Hub which supports several communication protocols. It can support versatile extensions such as MQTT and OPC UA to enable direct communication with the cloud. The data is forwarded into the Azure Stream Analytics which listens to the IoT systems and receives the transferred data. Each of the systems is registered with unique identification details which makes it possible to analyze the data separately. Azure Stream Analytics forwards the data into Azure Cloud Storage wherefrom it can be fetched and visualized by the different analytics software. Microsoft Azure was selected as an infrastructure provider since it provides a wide library of technologies and services to meet the organization’s future technology demand.

Future technologies level requires architecture and system extendibility which have been considered widely during the architectural design process. The architecture shall support several communication protocols such as ZigBee, LoRa, Wi-Fi and Bluetooth in the future if the organization decides to extend the architecture. New communication protocols can forward the data into the future applications wherefrom it can be transferred through Microsoft Azure’s brokers into the cloud. Since the platform already supports future technologies, it is highly important to identify the suitable actuators and components to support the extendability of the system.

5.2 Sensor Types and Sensor Functionalities

Requirements for sensor types and sensor functionalities were set in (Section 3.1) Introduction to System Requirements Analysis. Desirable features and functionalities were defined for the system. One key feature concerned the affordability of the system and the sensors. Since the system will be implemented in several locations the price of the industrial level sensors may rise significantly, therefore the affordability of the entire system should be evaluated. This consists of effortless and easy system installation, low maintenance and operational cost [56].

Large industrial type system deployments that require extreme accuracy and precision for the components, long-term installation and deployment typically tend to be more expensive. These sensor types consist of chemical and gas sensors, pressure, load and weight sensors. They are typically electrical demanding sensors that have capacitive related characteristics. Each of these sensors usually cost \$150 - \$1000+ which limits the number of sensors that the organization is capable of using in the field [56].

Medium infrastructure-related residential and commercial sensors and advanced development kits that have consumer-based support and fast deployment functions tend to be in the medium price range. These sensors typically have low-medium accuracy and precision. Sensor types typically consist of weather and temperature, water treatment and flow, motion and velocity sensors. Each of the sensors usually cost \$50 - \$150 [56].

The lowest cost sensors support singular functionalities. These are typically targeted towards amateurs and Do-It-Yourself (DIY) projects and prototyping. These sensors consist of water treatment and flow, weather and temperature, motion and velocity sensors. Each of these sensors typically cost \$0 – 50\$ [56]. These types of sensors do not usually offer any kind of dust, liquid or explosion protection options.

5.3 Ingress Protection (IP) Ratings

Ingress Protection (IP) ratings define the levels of sealing effectiveness against foreign objects like tools, fingers, dirt and moisture. Ingress protection ratings are defined based on the European IEC 60509:1989 standards, Table 13. The first number indicates the effectiveness of the protection against moving parts, people and foreign physical objects. The second number defines the protection against different forms of moistures such as submersion, spray and droplets [57]. Additional protection characters can be added to enhance the protection of the system. For example, letters 'f' (oil resistance), 'H' (high voltage device) and 'W' (weather conditions) provide additional information on the protection of the system [58]. The circular economy monitoring and optimization IIoT system shall respect the Ingress Protection rating of IP68 relating to its casing and external components that are under the influence of external forces and substances. The system must be protected against weather conditions, corrosive chemical environments and the external cables must be shielded.

#	Intrusion Protection (1st digit)	Moisture Protection (2nd digit)
1	No protection	No protection
2	Protection against large parts. Solid objects that are larger than 50mm in diameter.	Protection against condensation.
3	Protection against object no larger than 80mm in length and 12mm in diameter.	Protection against water droplets (up to 15° from vertical)
4	Protection against entry by the tool, etc. 2.5mm or more.	Protection against spray (up to 60° from vertical).
5	Protection against solid parts greater than 1mm.	Protection against water spray from all directions.
6	Protected against dust.	Protection against low-pressure water jets from all directions.
7	Totally dust-protected.	Protection against strong waves and water jets.
8	--	Protection against temporary immersion.

9	--	Protection against long effects of immersion under pressure.

Table 12- *Ingress Protection (IP) Ratings [57].*

5.4 ATEX Directive

ATEX Directive defines requirements for equipment in potentially explosive atmospheres where different mixtures of dust, vapors, mists or gases can ignite under certain conditions [59]. Systems and machinery that are used in potentially explosive atmospheres such as petrochemical plants and offshore platforms shall follow and respect the regulations relating to ATEX Directive [59]. The circular economy monitoring and optimization system will be implemented in the upstream supply chain which contains no explosive substances. Thereby, the system does not need to follow ATEX regulations relating to explosive atmospheres. If the system is later implemented in different conditions which contain explosive substances, the system must be further evaluated and developed.

5.5 Tank Level Monitoring

Tank level monitoring was defined as a minimum requirement for the system because of its importance in optimizing the upstream processes. It provides crucial information to prevent unexpected interruptions during the processes that can have a negative influence on the organization's core business. There are different ways and several technologies to measure and monitor tank levels, Table 14. Technology specifications are provided by ABB Automation Company, and Endress and Hauser to measure, automate and optimize oil and gas industrial applications [60][61]. Similar types of technologies will be used for optimizing the circular economy upstream industry.

Component	Positioning	Solids	Liquids
Non-Contact Laser	Up to 200m	Up to 100m	Up to 30m

Ultrasonic	Up to 25m	Up to 15m	Up to 25m
Guided Wave Radar	Up to 20m	--	Up to 20m
Liquid Level Sensor	Up to 7.6m	--	Up to 7.6m

Table 13- *Tank level monitoring technologies [60][61].*

Non-contact laser such as VL53Lox is a time-of-flight distance sensor [62]. Its tiny laser source sends an invisible laser beam towards an object wherefrom it bounces back to the matching sensor. It uses a narrow light source to determine the distance of an object directly in front of the sensor. It can be used more precisely in narrow spaces, unlike ultrasonic sensors which bounce sonic waves widely across the container. Laser distance sensor can give an accurate measurement even at a long-range (50mm-1200mm) for $15 per component [62]. More expensive laser components can position up to 200m and they can have an operating distance to solids up to 100m and liquids up to 30m.

Ultrasonic tank level measurement sensors such as MB7137, MB7138 and MB7139 can measure the distance to a liquid surface from the time-of-travel [63]. It offers low power and accurate measurement at an affordable price. It does not require any unnecessary services or maintenance. It is a non-contact sensor which makes it easy to install. It has ultra-low power consumption (4 to 20mA) with constant functioning at 4mA. It uses a typical 12V power source and it can operate as low as 9V. It provides typical 1 to 5V analog outputs. It is typically powered with a battery or solar power sources [63].

Guided wave radar level measurement component uses a radar sensor alongside the waveguides [60]. Microwave energy pulses are directed to the liquid surface through flexible cable or solid rod. Combination of radar sensor and waveguides minimizes signal loss and eliminates false echoes. It is a two-wire loop component that is capable of reaching up to 20 meters with no moving parts. However, it is the contact component and requires maintenance and service over time [60].

The liquid level sensor measures several liquid levels with magnetostrictive sensing [60]. It provides an accurate view of the tank levels up to 7.6 meters. It can recognize the oil and water interfaces i.e. layers, and different emulsion levels in the liquid containers. It provides more accurate and reliable measurements than non-contact sensors. It is a contact component and requires more expensive installation, service and management [60].

5.5.1 Non-Contact Ultrasonic Sensor

The non-contact ultrasonic sensor was identified to be the most practical component for liquid level monitoring because of its ease of install and maintenance. Ultrasonic sensors such as HC-SR04 and HC-SR05 and more robust sensors such as MB7137 (Figure 11) were identified, evaluated and validated at the proof-of-concept level.

Figure 11 *- Different types of ultrasonic sensors [63][64].*

Component Name:	HC-SR04 or HC-SR05	MB7137 I2CXL-TrashSonar-WR
Operating Voltage:	5V	3.0-5.0V
Operating Current:	15mA	3.4A (average requirement)
Operating Frequency:	40kHz	42kHz
Maximum Range:	400cm	350cm
Resistant:	No support	IP67, optional F-standard

Ultrasonic sensors use electricity to generate ultrasonic sound waves which have constant velocity i.e. speed and direction of the motion [65]. Therefore, it can detect reflected sound waves and determine the distance of an object. The time that ultrasonic sound waves travel to the object and back to the sensor determines the distance of the object. When the 'Trig' pin of the ultrasonic sensor receives high voltage signal (5V) for 10µs (microsecond), the sensor transmits 8 cycle bursts of ultrasonic sound for the operating frequency of the component, HC-SR04 (40kHz) and MB7137 12CXL (42kHz) [65]. It starts to listen for the reflected ultrasonic waves which it eventually detects in the receiver. 'Echo' pin of the sensor is set to high voltage (5V) and width as a deferment for a period, Figure 12. The range is measured by the time between the trigger signal and the echo signal [65].

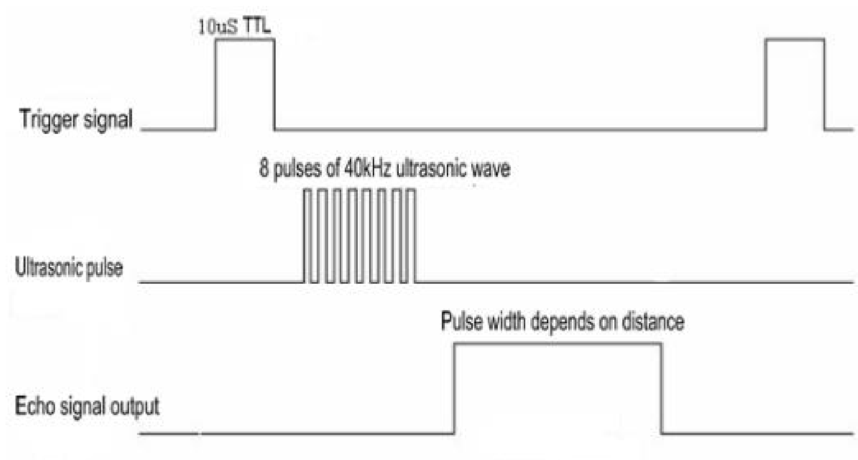


***Figure 12**- Ultrasonic sensor (HR-SR04) operational diagram (Direct quote from* [65]*).*

The velocity of the ultrasonic sound wave in typical conditions (air temperature 20°C) is approximately 344 m/s [65]. Because of the low velocity of the ultrasonic sound wave, the wavelength is short. Therefore, the accuracy of the measurement is high. However, different conditions such as temperature, humidity effect and air pressure influence the accuracy of the measurements [65]. The accuracy of the measurement is determined by the distance of the object (maximum range), the angle of the object and the size of the object. The angle of the object should be more than 45°. Preferred angle for the object is perpendicular (90°) [65].

5.5.2 Temperature, humidity and air pressure

The velocity of the ultrasonic sound wave is influenced by different external factors. These external factors consist of temperature, humidity, air pressure and turbulence [65]. The velocity of the sound wave can be calculated from the following formula:

$$V = 331.5 + (0.607 \times T) \text{ (m/s)}, \qquad T = \text{temperature (°C)}$$

Since the raw material (liquid) containers i.e. storage units are in various environments and conditions, it is highly important to consider changing circumstances and variables. Likewise, different types of objects, surfaces and materials effect on the accuracy of the measurement. Liquid has a rather smooth and hard surface which reflects ultrasonic sound waves efficiently. However, rough surface and soft material provide weak reflectivity and therefore are not suitable for this purpose [65].

Sealed liquid container or tank provides a great environment for accurate measuring. Turbulence and wind can be excluded from the measurement. However, temperature, humidity and air pressure shall be measured from the container to provide accurate measurement since the containers will be stored outside where the temperature varies. Different types of gas generations can be excluded from measurements since the raw material turnover is rather frequent and the substance has no time to change the form from liquids to gases. The sensor is unaffected by build-up dirt or other substances because of its self-cleaning effect. The temperature sensor will be implemented to correct the Time-of-Flight calculations to provide accurate measurements in changing temperatures.

5.6 Extensibility of the System

Extensibility of the embedded system such as vessel level monitoring system allows and accepts comprehensive and significant modifications and extension without breaking the system's capabilities and original functionalities [66]. Modifications and extensions shall be implemented without any major modification in the system's architecture, schematics or code. Extensibility of the system was set as a key requirement in (Section 3.1) Introduction to System Requirements Analysis and considered when designing the system's architecture in (Section 5.1) Circular Economy Architecture Model. The stable system architecture is flexible and supports versatile components such as sensors and actuators. A high probability of future modification must be accepted, and the system must be prepared for them.

Industrial demand and strict requirements towards liquid fingerprint, chemical sensing and wireless technologies in supporting the analytical processes have accelerated the development of new technologies and measurement methods. Liquid analysis and chemical sensing processes can be performed with different electrochemical, electrical, optical and mass sensitive sensors [66]. Sensors are typically categorized based on their transduction principles.

Wireless electrochemical sensors exploit modified electrodes to convert analyte's electrochemical interactions into current signals or voltages [66]. There are several transduction mechanisms such as potentiometric, amperometric, voltametric, fast cyclic used by the chemical sensors [66]. Most of the sensors in wireless electrochemical sensing are potentiometric sensors since simplicity and low power consumption. They measure the indicator electrodes' potential against the reference electrode. This can result in accurate measurements of pH, sodium ion (Na+), potassium ion (K+), magnesium ion (Mg2+), glucose and lactate [66]. Electrochemical sensors can use wireless technologies such as RFID, Bluetooth, ZigBee, GSM and NFC for data transfer and communication [66].

Wireless electrical sensors monitor analytical signals that arise from different chemical interactions with the analyte [66]. Analyte's electrochemical properties such as conductivity can cause changes in the controlled substances' properties. Energy change of the liquid surface or mass change can cause changes in the material's properties. These are the simplest sensors used in chemical monitoring. They use conductometric, impedimetric or capacitive transduction mechanism [66]. These mechanisms can measure properties such as carbon monoxide (CO), carbon dioxide (CO2), sulfur oxides (SOx), nitrogen oxides (NOx), oxygen (O2), ethanol and methanol [66]. These sensors typically use ZigBee, RFID, Bluetooth and ISM/SRM wireless communication technologies for data transfer and communication [66].

Wireless optical sensors measure the optical transformations caused by interactions of analyte-receptors [66]. Analyte's absorbance, reflectance, fluorescence, surface plasmon resonance (SPR), light dispersion and emitted luminescence intensity can be exploited as transduction mechanisms in construction of fingerprint for certain liquids [66]. Optical sensors can be used to measure pH, humidity, nitrogen dioxide (NO2), glucose, ammonia (NH3) and fluorescein [66]. These kinds of optical sensors tend to be more expensive and power consumptive due to the special high-power laser sources and optics. They typically use wireless technologies such as RFID, ZigBee, Bluetooth and NFC for data transfer and communication [66].

The circular economy system architecture defined in (Section 5.1) Circular Economy Architecture Model proves that the system is extendable with the identified chemical sensors and wireless communication technologies presented in this section. Furthermore, the wireless chemical sensors together with density sensors can provide an accurate view of the compounds of the materials.

5.7 Microcontroller Unit (MCU)

Microcontroller Unit (MCU) is a small computer on a single independent circuit board [64]. Microcontrollers are intended to be used in embedded electronics and IoT application because of their affordable price and small size. Microcontrollers provide a great option for data acquisition and monitoring in a circular economy upstream industry. Microcontrollers typically consist of one or more processor core (CPUs), memory, programmable input/output (I/O) elements and a small amount of RAM [64].

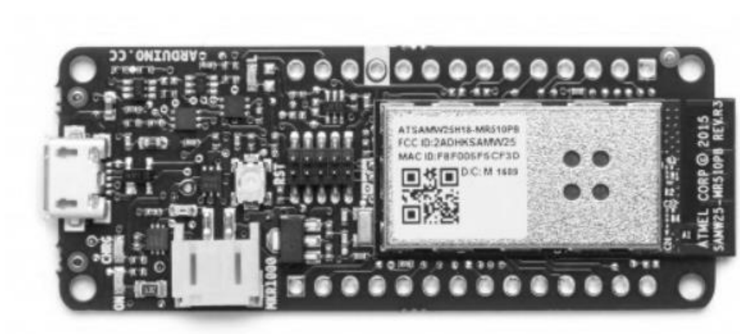


***Figure 13**- Arduino MKR1000(Direct quote from* [64]*).*

Arduino MKR1000 board was selected to be used in the experimental proof-of-concept prototype implementation phase, Figure 13. It uses SAMD21 Cortex-MO+ 32bit low power ARM Microcontroller unit [64]. It is a powerful and cost-effective board with low power features. It has integrated WINC1500 low power 2.4GHz IEEE 802.11 b/g/n Wi-Fi module that supports data rates up to 72 Mbit/s [64]. It exploits EXX508 crypto chip for secure authentication and communication, and therefore it enables high security [64].

The circuit's operational voltage is defined to be 3.3V. It can be powered with Li-Po battery with capacity over 700mAh. Smaller battery cells should not be used since they can be damaged by the circuit's recharging capabilities causing possible explosions or gasses [64]. The charging circuit allows charging of the Li-Po battery while connected to external power sources. The system can be connected to electrical outlets in more permanent positions or extended with several solar power solutions. MKR1000 will automatically switch the power source to utilize external power sources connected to its USB- power supply pin [64].

5.8 System Schematics

System schematics represent the connections between the components, sensors and the Arduino MKLR1000 microcontroller, Figure 14. More comprehensive connections are presented in Appendix A.

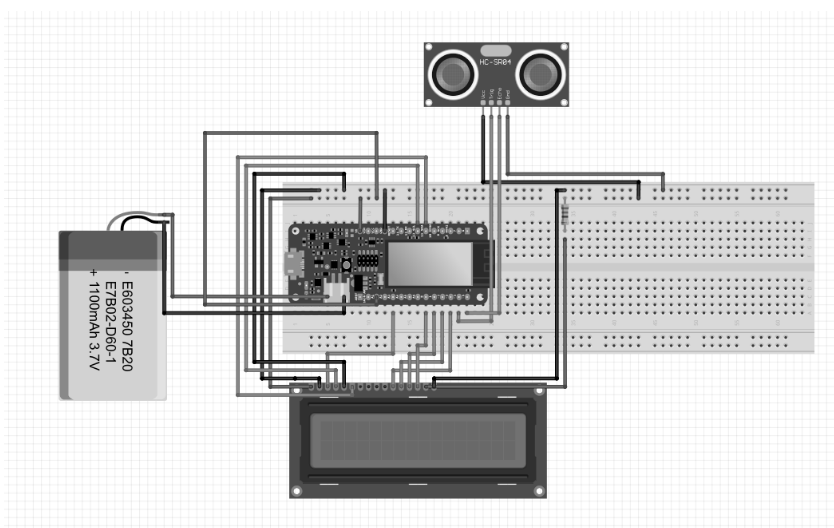


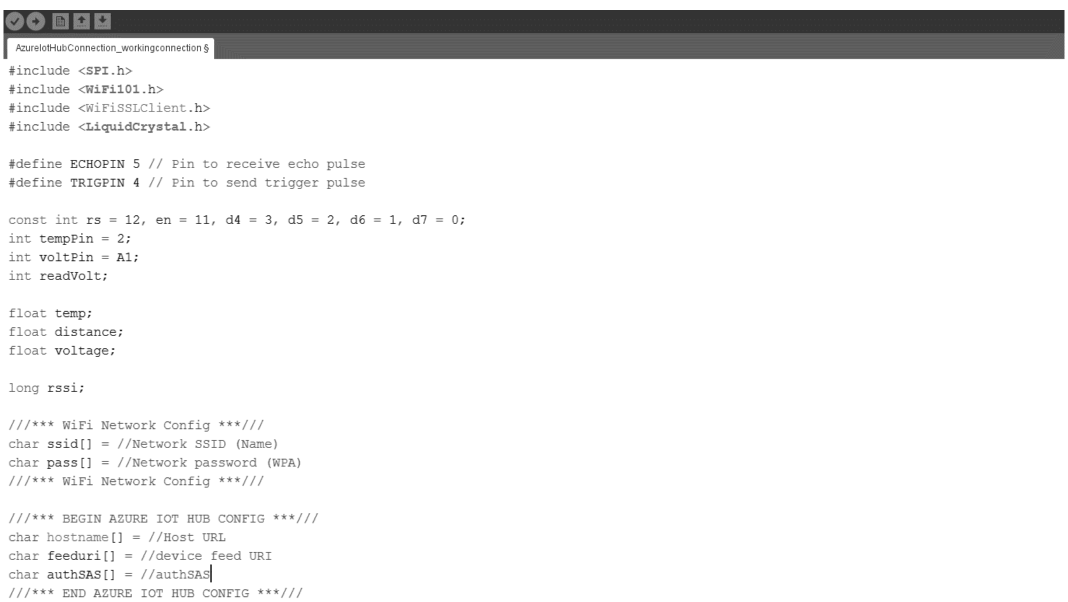
Figure 14*- Arduino MKR1000 breadboard connections.*

Arduino MKR1000 board can tolerate only 3.3V in its input and output pins [64]. Board is capable of outputting 5V to digital devices. However, bidirectional communication between the board and connected 5V devices require proper voltage and level shifting [64].

- ‘VCC’ pin outputs 3.3V regardless of the power source (battery, USB or Vin) [64].
- Digital pin 7 functions as a handshake between the Arduino Wi-Fi shield 101 and the underlying board. It should not be used for other functions [64].

5.9 Arduino IDE

Arduino Software (IDE) is an open-source environment used by Arduino boards [67]. It is written in Java and its functions are based on different processing and open-source software. It is used to control the inputs and outputs on the compatible Arduino boards. It supports languages such as C and C++ written together with special rules and code structures. It is a cross-platform application that can run on the popular operating systems such as Windows, Mac OS X and Linux whereas most of the boards are limited to Windows. The prototype constructed in this thesis was programmed with the Arduino IDE 1.8.9 version [67].


AzureIotHubConnection_workingconnection §

```
#include <SPI.h>
#include <WiFi101.h>
#include <WiFiSSLClient.h>
#include <LiquidCrystal.h>

#define ECHOPIN 5 // Pin to receive echo pulse
#define TRIGPIN 4 // Pin to send trigger pulse

const int rs = 12, en = 11, d4 = 3, d5 = 2, d6 = 1, d7 = 0;
int tempPin = 2;
int voltPin = A1;
int readVolt;

float temp;
float distance;
float voltage;

long rssi;

///*** WiFi Network Config ***///
char ssid[] = //Network SSID (Name)
char pass[] = //Network password (WPA)
///*** WiFi Network Config ***///

///*** BEGIN AZURE IOT HUB CONFIG ***///
char hostname[] = //Host URL
char feeduri[] = //device feed URI
char authSAS[] = //authSAS
///*** END AZURE IOT HUB CONFIG ***///
```

Figure 15*- Software variables for the system.*

The circular economy liquid level system variables are defined above, Figure 15. The software includes ‘WiFi101.h’ -library which allows the use of Arduino Wi-Fi shield 101 and the MKR1000 circuit. It enables crypto-authentication which supports WEP and WPA2 encryption. The board communicates over the Wi-Fi shield 101 by using SPI bus. Library ‘SPI.h’ (Serial Peripheral Interface) allows communication with the SPI devices while Arduino MKR1000 being the master device. It is a synchronous serial data protocol that allows quick short distance communication between the peripheral devices, or two different microcontrollers. The library ‘WiFiSSLClient.h’ allows the system to use SSL connection for the client. It forces the client to use SSL (Secure Socket Layer) technology which ensures the secure connection over the untrusted computer networks.

Network SSID name and the network WPA password, as well as the Azure IoT hub credentials, are configured in the Arduino software. Azure IoT hub configuration required the name of the IoT hub, device-specific URL and SAS (SharedAccessSignature) token authentication for device authentication.

The software begins by closing the existing connections before sending a new request or post commands. This will free the socket on the Wi-Fi shield 101. The program calls temperature, distance and voltage methods which collect the data from the sensors. The data is combined into a single string and forwarded as a request. The program checks whether there is a successful connection between the client and the host. If the connection is established the system forms an HTTP POST operation, Figure 16.

```
request = String("POST ") + feeduri + " HTTP/1.1\r\n" +
              "Authorization: " + authSAS + "\r\n" +
              "Content-Type: application/atom+xml;type=entry;charset=utf-8\r\n" +
              "Host: " + hostname + "\r\n" +
              "Content-Length: " + data.length() + "\r\n\r\n" +
              data;
```

Figure 16*- HTTP POST operation.*

After posting the data string, the system closes all the connections to save power. It will delay the program for 5 hours (18000000ms) until it posts new measurements to the Azure Stream Analytics and the Azure Cloud.

Arduino will provide the environmental measurement such as temperature and voltage in analog formats which need to be converted into digital formats. For example, to convert the analog temperature reading into a digital format the following operation must be performed;

***DigitalValue** = ((analogRead(AnalogPin) * (3300/1024))-500)/10;*

Arduino temperature pin gives a 10-bit reading from the analog-to-digital converter (ADC). The number 0-1023 is converter from ADC into 0-3300mV (3.3V) by multiplying with (3300/1024). Then, the millivolts are converted into the temperatures by [(analog voltage mV)-500]/10. The results are provided in Celsius formats.

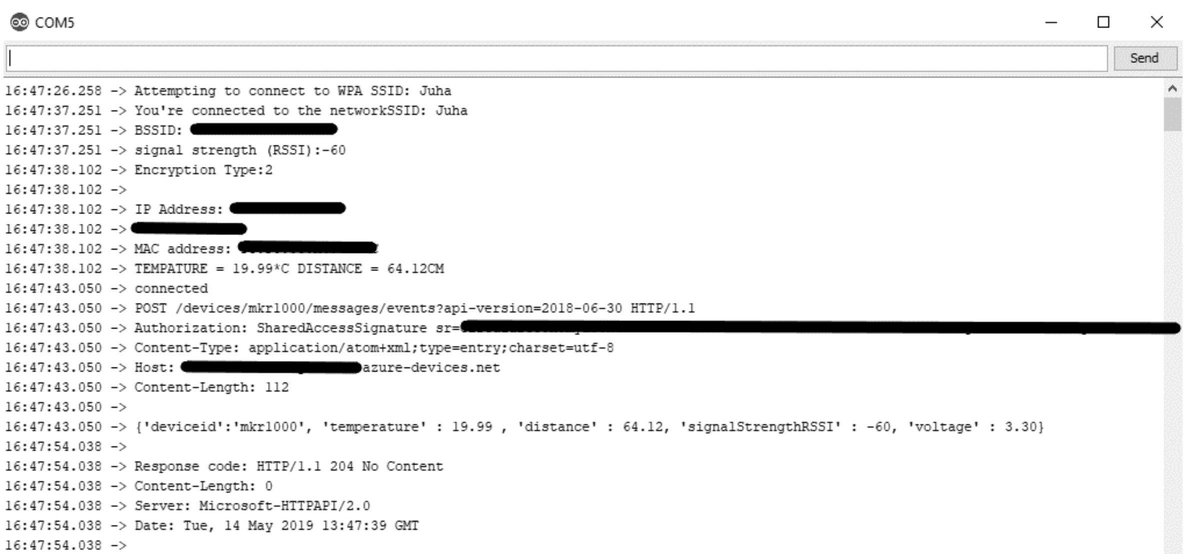


***Figure 17**- Arduino IDE's terminal displaying the system's functionalities.*

As a result of the circular economy liquid level measurement program, the Wi-Fi connection is established, several variables such as network information, temperature, signal strength, distance, voltage and device ID are measured, and transferred into the cloud, Figure 17.

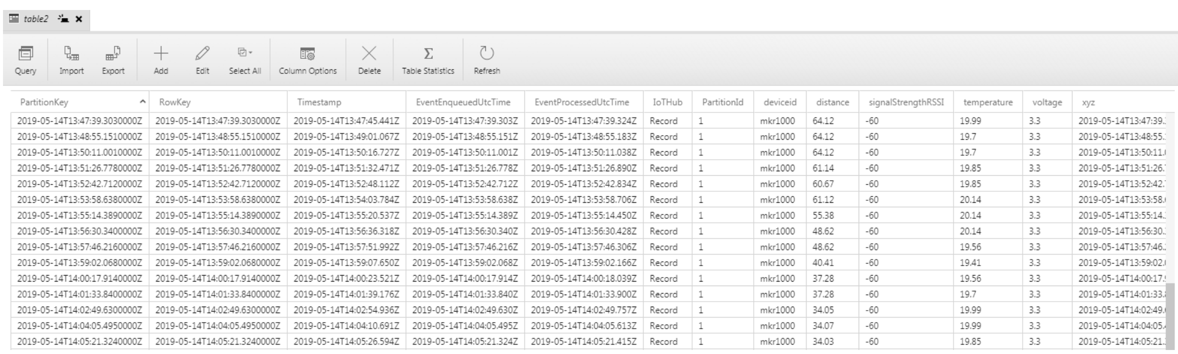
5.10 Industrial Internet of Things & Cloud Computing

The industrial internet of things is highly dependent on the development of cloud computing technologies for big data storage and analytics [68]. Networks of internet-connected devices require comprehensive cloud solutions and standards i.e. Cloud of Things (CoT) to promote the intelligent environment and heavy data acquisition [68]. The sector of IoT in the cloud computing area is expected to be dominant in the near future [69]. Despite today's trend towards cloud computing some of the industries such as oil & gas are facing various technical challenges. Especially concerns relating to privacy, security, technological readiness and cost slows down the development of the industry [69]. Data security, extremely large data sets and large investments in new infrastructure are complicating the migration to the public cloud solutions. Cautiously and slowly migrating industries such as oil and gas have begun to invest in private and hybrid cloud solutions [70]. However, private and hybrid cloud solutions are expected to be a temporary solution in the long run of technological development. Although, there are several problematic areas considering public cloud solutions, private and hybrid clouds cannot compete against more cost-efficient, flexible and faster solutions. Storing data outside the firewalls causes concern about the security of sensitive information and trade secrets. Data security is a top priority for the oil and gas organizations [70]. There are three cloud solutions that are highly different from each other when comparing to scalability, maintainability, security and affordability. These cloud solutions such as public, private and hybrid are presented in more details.

5.10.1 Public Cloud

Public cloud provides computing services available for all the users in public network. These services are typically offered by third-party service providers over the internet [71]. Public cloud services such as Amazon Web Services (AWS), Microsoft Azure and Google Cloud Platform (GCP) provide a broad selection of computing, storage, and networking products to serve the demand of big data on a low-cost basis. Cloud service providers are responsible for operating, managing and maintaining the systems. Organizations can save on large costs of having to purchase, operate, manage and maintain the on-premises infrastructure such as hardware and software. Industries can benefit from infinite scalability and high system reliability. However, public cloud models have possible security risks. Risk-averse companies such as government-owned and large industrial companies may prefer to maintain a private cloud on their own data centers or in a private cloud [70][9].

In this thesis, public Microsoft Azure cloud storage and computing services were implemented in an experimental proof-of-concept level. Microsoft Azure is the only cloud provider that allows OPC UA client-server connections to the cloud and back [43]. Circular economy IoT system was connected through Azure IoT Hub's stream analytics service into the storage account's database table. Environmental data were stored every one minute to test the functionality of the data storage, Figure 18.



PartitionKey	RowKey	Timestamp	EventEnqueuedUtcTime	EventProcessedUtcTime	IoTHub	PartitionId	deviceid	distance	signalStrengthRSSI	temperature	voltage	xyz
2019-05-14T13:47:39.3030000Z	2019-05-14T13:47:39.3030000Z	2019-05-14T13:47:45.441Z	2019-05-14T13:47:39.303Z	2019-05-14T13:47:39.324Z	Record	1	mkr1000	64.12	-60	19.99	3.3	2019-05-14T13:47:39.
2019-05-14T13:48:55.1510000Z	2019-05-14T13:48:55.1510000Z	2019-05-14T13:49:01.067Z	2019-05-14T13:48:55.151Z	2019-05-14T13:48:55.183Z	Record	1	mkr1000	64.12	-60	19.7	3.3	2019-05-14T13:48:55.
2019-05-14T13:50:11.0010000Z	2019-05-14T13:50:11.0010000Z	2019-05-14T13:50:16.727Z	2019-05-14T13:50:11.001Z	2019-05-14T13:50:11.038Z	Record	1	mkr1000	64.12	-60	19.7	3.3	2019-05-14T13:50:11.
2019-05-14T13:51:26.7780000Z	2019-05-14T13:51:26.7780000Z	2019-05-14T13:51:32.471Z	2019-05-14T13:51:26.778Z	2019-05-14T13:51:26.890Z	Record	1	mkr1000	61.14	-60	19.85	3.3	2019-05-14T13:51:26.
2019-05-14T13:52:42.7120000Z	2019-05-14T13:52:42.7120000Z	2019-05-14T13:52:48.112Z	2019-05-14T13:52:42.712Z	2019-05-14T13:52:42.834Z	Record	1	mkr1000	60.67	-60	19.85	3.3	2019-05-14T13:52:42.
2019-05-14T13:53:58.6380000Z	2019-05-14T13:53:58.6380000Z	2019-05-14T13:54:03.784Z	2019-05-14T13:53:58.638Z	2019-05-14T13:53:58.706Z	Record	1	mkr1000	61.12	-60	20.14	3.3	2019-05-14T13:53:58.
2019-05-14T13:55:14.3890000Z	2019-05-14T13:55:14.3890000Z	2019-05-14T13:55:20.537Z	2019-05-14T13:55:14.389Z	2019-05-14T13:55:14.450Z	Record	1	mkr1000	55.38	-60	20.14	3.3	2019-05-14T13:55:14.
2019-05-14T13:56:30.3400000Z	2019-05-14T13:56:30.3400000Z	2019-05-14T13:56:36.318Z	2019-05-14T13:56:30.340Z	2019-05-14T13:56:30.428Z	Record	1	mkr1000	48.62	-60	20.14	3.3	2019-05-14T13:56:30.
2019-05-14T13:57:46.2160000Z	2019-05-14T13:57:46.2160000Z	2019-05-14T13:57:51.992Z	2019-05-14T13:57:46.216Z	2019-05-14T13:57:46.306Z	Record	1	mkr1000	48.62	-60	19.56	3.3	2019-05-14T13:57:46.
2019-05-14T13:59:02.0680000Z	2019-05-14T13:59:02.0680000Z	2019-05-14T13:59:07.650Z	2019-05-14T13:59:02.068Z	2019-05-14T13:59:02.166Z	Record	1	mkr1000	40.41	-60	19.41	3.3	2019-05-14T13:59:02.
2019-05-14T14:00:17.9140000Z	2019-05-14T14:00:17.9140000Z	2019-05-14T14:00:23.521Z	2019-05-14T14:00:17.914Z	2019-05-14T14:00:18.039Z	Record	1	mkr1000	37.28	-60	19.56	3.3	2019-05-14T14:00:17.
2019-05-14T14:01:33.8400000Z	2019-05-14T14:01:33.8400000Z	2019-05-14T14:01:39.176Z	2019-05-14T14:01:33.840Z	2019-05-14T14:01:33.900Z	Record	1	mkr1000	37.28	-60	19.7	3.3	2019-05-14T14:01:33.
2019-05-14T14:02:49.6300000Z	2019-05-14T14:02:49.6300000Z	2019-05-14T14:02:54.936Z	2019-05-14T14:02:49.630Z	2019-05-14T14:02:49.757Z	Record	1	mkr1000	34.05	-60	19.99	3.3	2019-05-14T14:02:49.
2019-05-14T14:04:05.4950000Z	2019-05-14T14:04:05.4950000Z	2019-05-14T14:04:10.691Z	2019-05-14T14:04:05.495Z	2019-05-14T14:04:05.613Z	Record	1	mkr1000	34.07	-60	19.99	3.3	2019-05-14T14:04:05.
2019-05-14T14:05:21.3240000Z	2019-05-14T14:05:21.3240000Z	2019-05-14T14:05:26.594Z	2019-05-14T14:05:21.324Z	2019-05-14T14:05:21.415Z	Record	1	mkr1000	34.03	-60	19.85	3.3	2019-05-14T14:05:21.

Figure 18*- Azure table storage.*

5.10.2 Private Cloud

Private clouds are alternative solutions for managing and mitigating security threats. They are computing services provided over an organization's internal network instead of public networks. Private cloud i.e. corporate cloud demands high knowledge and capabilities of operating on-premises infrastructure [72]. Scalability, maintainability and elasticity have to be self-managed and controlled. Public clouds perform over the company's own administrative domain and private infrastructure [70]. Thus, it provides higher privacy and security since the service is running behind an organization's firewalls and hosting services. Thereby, third-party service providers are not accessible to sensitive data and the organization's operational secrets. However, the organization's IT department is responsible for managing the private cloud which can become a large cost [72].

5.10.3 Hybrid Cloud

Hybrid cloud solutions are basically combinations of private clouds and public clouds. Hybrid cloud is a private cloud infrastructure supplemented from an external public cloud [73]. It increases security-related performance while retaining scalability from the public cloud. It is a clever way to exploit the best functions of both worlds [70]. However, the hybrid cloud requires seamless compatibility between the organizational internal network and the public cloud. Non-suitable hardware and software need to be updated, and network architecture modified. This creates additional challenges that can be considered as future work.

5.11 Software Analytics – Microsoft Power BI

Microsoft Power BI was exploited in the experimental proof-of-concept phase as a software analytics tool [74]. It is a cloud-based business analytics tool enabling comprehensive data visualization and analyzation, Figure 19. It increases project insight with live dashboards that collect project-specific data in centralized locations [74].

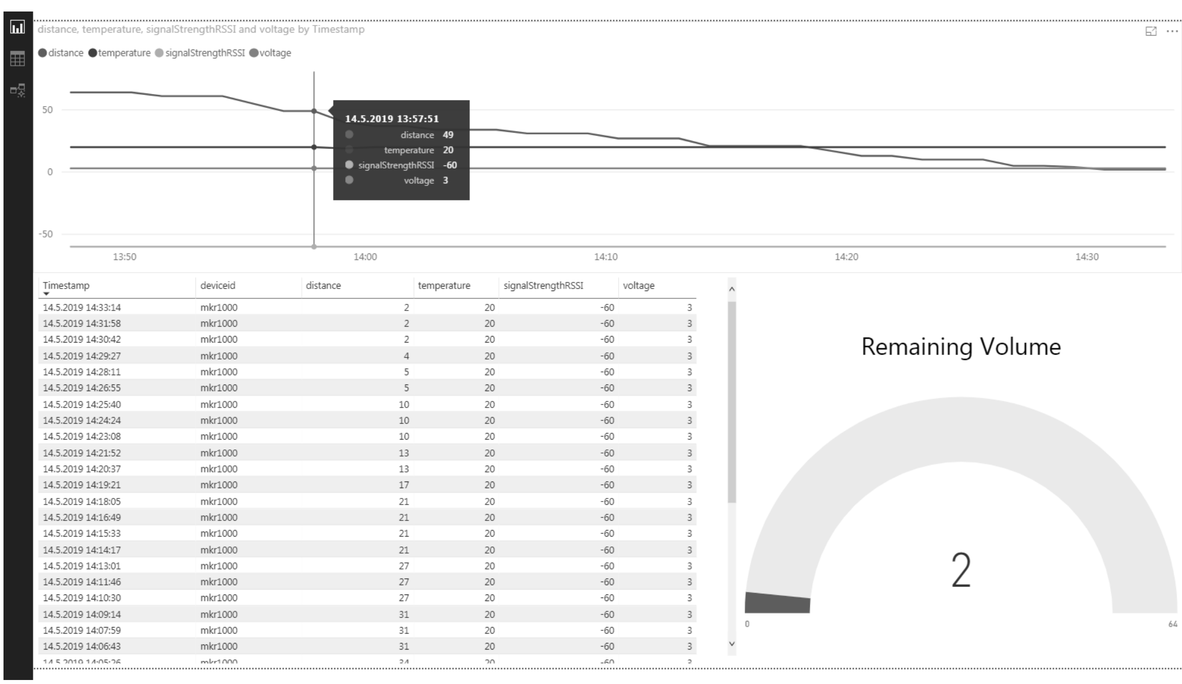


Figure 19- *Power BI analytics for the IIoT system.*

Microsoft Power BI was used to visualize and analyze the data stored in Azure storage account's data tables. The data was collected with a short test run of 40 minutes. Line chart was used to visualize the circular economy IoT system's values in the time axis. It provides environmental information about the distance, temperature, connection's strength and battery voltage. Distance indicates the remaining volume of the container. Any changes in the signal strength or battery levels indicate about upcoming problems or service request which can be planned before any downtime in the systems. Temperature can be used to calibrate the ultrasonic sensor's accuracy since the travel speed of ultrasound is affected by the air temperature. Table function provides more detailed information about the measurements. It categorizes the measurements by the device id and timestamp. Gauge element visualizes the container's remaining volume with a clear and simple way. Microsoft Azure IoT Hub enables seamless connection to Microsoft Power BI providing real-time data utilization across multiple operators, teams and locations. It can give alerts and notifications when the data changes or values reach certain limitations. Microsoft Power BI was used to visualize the comprehensive connectivity of Azure IoT Hub. In the future, the Azure IoT Hub will be connected with the organization's self-produced analytics software as pointed in the technical design of the IoT system in (Section 5.1) Circular Economy Architecture Model.

5.12 Verification of the IIoT Upstream Monitoring System

The verification of the circular economy IoT system has been performed by demonstrating the working experimental proof-of-concept prototype. The prototype was successfully used in data acquisition, analyzation and visualization. More comprehensive system verification regarding the long-term business analytical benefits and the operational advantages are impossible to perform with such of short operational time. However, reference implementations and solutions can provide accurate estimations about the successfulness of similar solutions and implementations. Longer-term testing can be considered as future work.

5.13 Summary

This chapter has presented the experimental proof-of-concept level prototype based on the system requirement analysis and the organization's system architecture. The system architecture was divided into three sections which were a private network, public network and future technologies level. The private network described the existing production level network technologies which were strongly focused on OPC-UA technology and closed network structure. Public network-level gained more focus since the experimental proof-of-concept level system's utilization was dependent on open networks and cloud environments which were the initial environment of the use. The public network and its extendibility were enabled by the extensive Mircosoft cloud solutions which shifted the focus more on the evaluation of the technology compatibility.

System protection standards and directives were represented and evaluated. The system was defined to follow IP68 protection standard with additional P-option. ATEX directive was defined as unneeded for now but re-evaluated in the future if the system's operational environment changes. Several liquid level measurement methods and technologies were identified and evaluated for the needs of the organization. The non-contact ultrasonic sensor identified as the most efficient and maintenance-free solution. Ultrasonic principles were represented and its functions were evaluated for liquid level monitoring. Future extendibility of the system was stated to be possible. Liquid fingerprint analysis was introduced and several methods and technologies were identified and evaluated for the future needs of the organization. Prototype level microcontroller was introduced and system schematics were constructed to describe the entire IoT system. Arduino IDE was introduced and used for controlling the microcontroller and sensors.

Different cloud solutions and providers were introduced. Public cloud was selected for streaming and storing the system's environmental data. Power BI was exploited as an analytics tool to visualize and analyze the system data. This will be replaced with the organization's own analytics tools and solutions. Short-term verification of the system was represented and long-term verification was set as future work.

Chapter 6

Future Work

This chapter represents the issues that were set as future work during this thesis. The Industry 4.0 design principles were introduced and evaluated for the need of oil and gas organization in (Chapter 2) Fundamental Concepts of Industrial Internet of Things (IIoT). During this chapter, technical assistance was introduced. As a result of the Analytical Hierarchy Process (AHP), the organization gave the technical assistance rather small weighting factor and it was left out from the scope of the thesis. It still has a major role in industry 4.0 and IIoT, and therefore it was suggested for future work. Further research on machine learning and artificial intelligence can be performed due to future expandability of the circular economy monitoring and optimization.

System requirement analysis represented subchapter called (Section 3.1.3) Compliance. In this subchapter, the system-wide audit was introduced and evaluated for the reason for testing and validating the system. A simple system function testing was selected to be implemented at the end of this thesis. The system-wide audit was suggested as future work, and therefore functionality, operativeness, compliance, safety and security, documentation, maintenance and support shall be tested in the future.

Hierarchy levels IEC 62264 and IEC 61512 were introduced in (Section 4.1) Introduction to RAMI 4.0 Model. The levels are constructed as a hardware-based structure where the entire value chain is tied to hardware. It inspects IoT's role in the entire organizational value chain which enables hierarchy-based communication including product, field device, control device, station, work centers and enterprise. The scope of hierarchy levels IEC 62264 and IEC 61512 was too large for this thesis and it was suggested as future works.

IoT edge systems were introduced in (Section 4.3.6) Asset Layer. Power consumption was discovered as a limiting factor for the IoT system. The system consumes more power whether it needs to transfer more data into the cloud. The amount of transferred data can be decreased by bringing the additional calculations from the cloud to the edge systems i.e. edge and fog computing. Whether the IoT system transforms into a more complex system in the future, edge and fog computing can be evaluated as future work.

Several cloud solutions and providers were introduced in (Section 5.10) Industrial Internet of Things & Cloud Computing. Hybrid cloud was defined as a too complex solution since it needed additional knowledge, hardware and software modifications. Benefits of hybrid cloud shall be evaluated in the future against the need of the large oil and gas organization.

Short-term IoT system validation and verification were constructed in (Section 5.12) Verification of the IIoT Upstream Monitoring System. Since long-term testing requires environmental measurement over a longer period to comprehensively verify the system organizational benefits and business potentials, it shall be constructed as future work.

Chapter 7

Conclusion

The motivation behind this thesis was to improve the circular economy upstream industry processes with the help of IoT monitoring and optimization system. The focus of this thesis was to identify the current state of Industry 4.0 and the Industrial Internet of Things and strategically prove its feasibility in the oil and gas industry (**RQ1**). Several IoT use cases formed the foundation for the feasibility research. Industry 4.0 design principles were introduced and evaluated among the organizational strategic values and TELOS feasibility study. Analytic Hierarchy Process (AHP) was performed by encouraging the organization's personnel such as sales and marketing, product management, project management and developers to participate in the evaluation process. As a result of the AHP, information transparency, decentralized decisions, climate change, circular economy and technical feasibility was selected as a foundation for this thesis.

System requirements were identified for the monitoring and optimization system to a point where the raw material flow can be efficiently and effectively transformed into more useful products (**RQ2**). The European Commission's Horizon 2020 IoT project towards identifying the centric system requirements was implemented towards a circular economy IoT system. Classification schema (FOCUS-D) introduced several analysis categories such as functionality, operativeness, compliance, usability, safety and security, documentation, maintenance, and support to be performed in the system requirement analysis process. The system requirement analysis vocabulary respected RFC 2119 standard for the best current practices. As a result of the system requirement analysis, requirements for the functionality, data accuracy and responsibility were identified. System availability, performance, capacity, scalability, reliability, installation and portability requirements were identified. Laws and regulations, audits, cultural and political practices introduced and presented forward for the organization's law department. Safety, accessibility, integrity and protection practices were evaluated and set as requirements for the system. Documentation, maintenance, support and training practices were selected and initialized across the organization.

The most common IoT reference architecture concepts were presented for the foundation of the system (**RQ3**). Internet of Things – Architecture (IoT-A), Industrial Internet Reference Architecture (IIRA) and Reference Architecture Model Industry 4.0 (RAMI 4.0) were introduced and evaluated based on the organization's requirements. RAMI 4.0 was recognized to be used in industrial manufacturing because of its comprehensive layer structure and existence in current use. RAMI 4.0 was further detailed and several technologies, standards and protocols were introduced for the use of circular economy IoT system (**RQ4**). Based on the selected practices, system architecture model was constructed together with the organization's system architect. The architecture model combined the existing private network that is used with the legacy systems, implementable IoT system and future systems. Azure IoT Hub, Stream Analytics and Azure Cloud storage were identified as a central structure for the entire architecture.

Experimental proof-of-concept level circular economy IoT prototype was constructed based on the selected requirements, standards, protocols and architecture (**RQ5**). Components were introduced and evaluated based on their functionality and protection ratings and directives. Extendibility of the system was evaluated and noted to be extendable to enable liquid fingerprint measurements in the future. The system was implemented and validated together with cloud stream analytics and storage services. Environmental data analysis and visualization were performed and the system was found to be working in its environment.

This thesis proves that the analyzed, designed, implemented and verified circular economy upstream monitoring and optimization IIoT system has a significant financial and environmentally beneficial results in the oil and gas industry. The final conclusion indicates that Industry 4.0 and IIoT practices play a major role in the monitoring and optimization of the upstream supply chain management.

References

[1] "Energy Resources - Oil," *World Energy Council*, 2019. [Online]. Available: https://www.worldenergy.org/data/resources/resource/oil/. [Accessed: 29-Jan-2019].

[2] *World Energy Resources | 2016*. World Energy Council 2016, 2016.

[3] J. H. Gary, G. E. Handwerk, and M. J. Kaiser, *Petroleum refining : technology and economics.* CRC Press, 2007.

[4] "European Commission," *European Commission*, 2019. [Online]. Available: https://ec.europa.eu/clima/policies/strategies/2020_en. [Accessed: 29-Jan-2019].

[5] D. Sumit, "Introduction to Oil and Gas Industry | Oil & Gas IQ." [Online]. Available: https://www.oilandgasiq.com/strategy-management-and-information/articles/oil-gas-industry-an-introduction. [Accessed: 17-Jan-2019].

[6] W. Z. Khan, M. Y. Aalsalem, M. K. Khan, M. S. Hossain, and M. Atiquzzaman, "A reliable Internet of Things based architecture for oil and gas industry," in *2017 19th International Conference on Advanced Communication Technology (ICACT)*, 2017, pp. 705–710.

[7] S. Mathur, A., Desai, J., Kashelkar, R., Sharma, "How rising commodity prices will impact companies - The Economic Times," *The Economic Times*, 2011. [Online]. Available: https://economictimes.indiatimes.com/how-rising-commodity-prices-will-impact-companies/articleshow/7296800.cms?from=mdr. [Accessed: 26-May-2019].

[8] M. I. Khan, T. Yasmeen, A. Shakoor, N. B. Khan, and R. Muhammad, "2014 oil plunge: Causes and impacts on renewable energy," *Renew. Sustain. Energy Rev.*, vol. 68, pp. 609–622, Feb. 2017.

[9] A. Gilchrist, *Industry 4.0 : the industrial internet of things*. Apress, 2016.

[10] P. Raj, A. C. Raman, and A. C. Raman, *The Internet of Things*. Boca Raton : Taylor & Francis, CRC Press, 2017.: Auerbach Publications, 2017.

[11] M. Hermann, T. Pentek, and B. Otto, "Design Principles for Industrie 4.0 Scenarios," in *2016 49th Hawaii International Conference on System Sciences (HICSS)*, 2016, pp. 3928–3937.

[12] U. Sendler, *The Internet of Things : Industrie 4.0 unleashed*. Springer-Verlag GmbH Germany, 2017.

[13] "Industry 4.0 in the oil and gas business." [Online]. Available: https://www.hydrocarbonprocessing.com/magazine/2018/december-2018/industrial-internet-of-things-iiot/industry-40-in-the-oil-and-gas-business. [Accessed: 01-Mar-2019].

[14] "IoT Solution to Transform Oil & Gas Industry." [Online]. Available: https://www.biz4intellia.com/iot-in-oil-gas/. [Accessed: 21-Feb-2019].

[15] "Revealing the power of IoT in Oil and Gas," *IoT Business News*. [Online]. Available: https://iotbusinessnews.com/2018/10/15/69300-revealing-the-power-of-iot-in-oil-and-gas/. [Accessed: 21-Feb-2019].

[16] "How can you Leverage Industrial IoT in Oil and gas Fleet Monitoring ?" [Online]. Available: https://www.biz4intellia.com/blog/how-can-you-leverage-industrial-iot-in-oil-and-gas-fleet-monitoring/. [Accessed: 21-Feb-2019].

[17] S. Verma, "IoT in Oil and Gas: 8 Easy Steps to Monitor Operations - DZone IoT." [Online]. Available: https://dzone.com/articles/iot-in-oil-and-gas-8-easy-steps-to-monitor-the-ope. [Accessed: 20-Feb-2019].

[18] P. Raj, A. C. Raman, and A. C. Raman, *The Internet of Things*. Boca Raton : Taylor & Francis, CRC Press, 2017.: Auerbach Publications, 2017.

[19] "Connected barrels Transforming oil and gas strategies with the Internet of Things A report by Deloitte Center for Energy Solutions," 2015.

[20] Sensile Technologies, "Remote monitoring of fuel and lubricant tanks." [Online]. Available: https://www.sensile.com/solutions/oil-and-lubricant-tank/. [Accessed: 23-Apr-2019].

[21] "Innovating oil & gas through AI & IoT," *Validere*, 2019. [Online]. Available: https://validere.com/wp-content/uploads/Validere-PR-Brochure.pdf. [Accessed: 15-Feb-2019].

[22] Enevo, "Trackable progress and stress free management."

[23] "Leaving a healthier planet for our children by creating responsible choices every day Annual Report," *Neste*, 2019. [Online]. Available: http://ir-service.funkton.com/download/ahBzfmlyLXNlcnZpY2UtaHJkchsLEg5GaWxlQXR

0YWNobWVudBiAgNDklbiKCAw/Neste_Annual_Report_2017.pdf?action=open. [Accessed: 25-Feb-2019].

[24] "BIG IoT-Bridging the Interoperability Gap of the Internet of Things Deliverable 2.3.a: Requirements Analysis and Specifications," 2016. [Online]. Available: http://big-iot.eu/wp-content/uploads/2016/04/Deliverable-2.3.a-Requirements-Analysis-and-Specifications.pdf. [Accessed: 27-Mar-2019].

[25] J. Bradner, "Key words for use in RFCs to Indicate Requirement Levels," *Harvard University*, 1197. [Online]. Available: https://www.ietf.org/rfc/rfc2119.txt. [Accessed: 28-Mar-2019].

[26] S.-W. Lin, S. Mellor, H. Munz, and E. Barnstedt, "Architecture Alignment and Interoperability An Industrial Internet Consortium and Plattform Industrie 4.0 Joint Whitepaper Contributors 1," 2017.

[27] E. Ho, "Internet of Things Architecture (IoT-A) - Alexandria," *University of St.Gallen*, 2013. [Online]. Available: https://www.alexandria.unisg.ch/id/project/215305. [Accessed: 03-Apr-2019].

[28] "(PDF) Internet of Things – Architecture IoT-A Deliverable D1.5 – Final architectural reference model for the IoT v3.0." [Online]. Available: https://www.researchgate.net/publication/272814818_Internet_of_Things_-_Architecture_IoT-A_Deliverable_D15_-_Final_architectural_reference_model_for_the_IoT_v30. [Accessed: 25-Mar-2019].

[29] F. Bauer, M., Bui, N., Carrez, "Introduction to the Arhitectural Reference Model for the Internet of Things," 2019.

[30] "PPT - IoT -A IERC AC1 Expert Workshop PowerPoint Presentation - ID:2154095." [Online]. Available: https://www.slideserve.com/thetis/iot-a-ierc-ac1-expert-workshop. [Accessed: 25-Mar-2019].

[31] A. Torkaman and M. A. Seyyedi, "Analyzing IoT Reference Architecture Models," *Int. J. Comput. Sci. Softw. Eng.*, vol. 5, no. 8, 2016.

[32] "The Industrial Internet of Things Volume G1: Reference Architecture," 2017.

[33] "Frequently Asked Questions about IIRA | Industrial Internet Consortium." [Online]. Available: https://www.iiconsortium.org/IIRA-faq.htm. [Accessed: 05-Apr-2019].

[34] "Plattform Industrie 4.0 RAMI4.0-a reference framework for digitalisation An

Overview," *Plattform Industrie 4.0*, 2019. [Online]. Available: https://www.plattform-i40.de/I40/Redaktion/EN/Downloads/Publikation/rami40-an-introduction.pdf?__blob=publicationFile&v=14. [Accessed: 22-Mar-2019].

[35] M. Weyrich and C. Ebert, "Reference Architectures for the Internet of Things."

[36] J. D. Contreras, J. I. Garcia, and J. D. Diaz, "Developing of Industry 4.0 Applications," *Int. J. Online Biomed. Eng.*, vol. 13, no. 10, pp. 30–47, Nov. 2017.

[37] G. Koschnick, M. Hankel, and B. Rexroth, "RAMI 4.0-Structure The Reference Architectural Model Industrie 4.0 (RAMI 4.0) Contact: Reference Architectural Model Industrie 4.0," 2015.

[38] F. Zezulka, P. Marcon, I. Vesely, and O. Sajdl, "Industry 4.0 – An Introduction in the phenomenon," *IFAC-PapersOnLine*, vol. 49, no. 25, pp. 8–12, 2016.

[39] S.-I. Ao and International Association of Engineers, "Topological Approach for Mapping Technologies in Reference Architectural Model Industrie 4.0 (RAMI 4.0)," 2017. [Online]. Available: http://www.iaeng.org/publication/WCECS2017/WCECS2017_pp982-990.pdf. [Accessed: 01-Jun-2019].

[40] H. Zimmermann, "OS1 Reference Model-The I S 0 Model of Architecture for Open Systems Interconnection," 1980.

[41] A. Acquaviva, "IoT concepts." [Online]. Available: http://sites.ieee.org/italy/files/2016/03/Acquaviva.pdf. [Accessed: 23-May-2019].

[42] A. Fette, I., Melnikov, "The WebSocket Protocol," *Internet Eng. Task Force*, 2011.

[43] Microsoft, "Why the OPC UA Standard – and What's Next? - Internet of Things," 2019. [Online]. Available: https://blogs.microsoft.com/iot/2018/04/11/why-the-opc-ua-standard-and-whats-next/. [Accessed: 23-May-2019].

[44] F. Zezulka, P. Marcon, Z. Bradac, J. Arm, T. Benesl, and I. Vesely, "Communication Systems for Industry 4.0 and the IIoT," *IFAC-PapersOnLine*, vol. 51, no. 6, pp. 150–155, 2018.

[45] "Unified Architecture - OPC Foundation." [Online]. Available: https://opcfoundation.org/about/opc-technologies/opc-ua/. [Accessed: 08-Mar-2019].

[46] S.-H. Leitner and W. Mahnke, "OPC UA-Service-oriented Architecture for Industrial Applications." [Online]. Available: http://pi.informatik.uni-

siegen.de/stt/26_4/01_Fachgruppenberichte/ORA2006/07_leitner-final.pdf. [Accessed: 23-May-2019].

[47] Oracle, “Introducing the Internet Protocol Suite (System Administration Guide, Volume 3),” 2010. [Online]. Available: https://docs.oracle.com/cd/E19455-01/806-0916/6ja85398m/index.html. [Accessed: 21-May-2019].

[48] “RFC: 793 TRANSMISSION CONTROL PROTOCOL DARPA INTERNET PROGRAM PROTOCOL SPECIFICATION,” 1981.

[49] J. Poster, “RFC 768 - User Datagram Protocol,” 1980.

[50] “How to design an IoT-ready infrastructure: The 4-stage architecture.” [Online]. Available: https://techbeacon.com/enterprise-it/4-stages-iot-architecture. [Accessed: 06-Mar-2019].

[51] A. Nizar and A. Ali, “Comparison study between IPV4 & IPV6,” *IJCSI Int. J. Comput. Sci. Issues*, vol. 9, no. 3, 2012.

[52] RealPars, “What is Modbus? | RealPars,” 2019. [Online]. Available: https://realpars.com/modbus/. [Accessed: 20-May-2019].

[53] T. M. Workgroup, “What is it ? A technical overview of,” no. November, 2015.

[54] S. Banerji and R. S. Chowdhury, “On IEEE 802.11: Wireless Lan Technology,” *Int. J. Mob. Netw. Commun. Telemat.*, vol. 3, no. 4, pp. 45–64, Aug. 2013.

[55] N. Gomez, K., Sengul, C., Bayer, “2013 IEEE Online Conference on Green Communications (OnlineGreenComm).,” 2013.

[56] M. Zennaro, “Intro to Internet of Things ITU ASP COE TRAINING ON "Developing the ICT ecosystem to harness IoTs",” 2016.

[57] “Ingress Protection Ratings,” *Integral Electrical Services Ltd.* [Online]. Available: http://integralelectrical.co.uk/image/data/pdf%60s/IP Ratings.pdf. [Accessed: 29-Apr-2019].

[58] “Ingress protection, IP code, IP rating, weatherproof, IEC 60509:1989.” [Online]. Available: http://eminex.ae/ingress-protection-ip-rating/. [Accessed: 29-Apr-2019].

[59] E. Commission, “Equipment for potentially explosive atmospheres (ATEX).” [Online]. Available: https://ec.europa.eu/growth/sectors/mechanical-engineering/atex_en. [Accessed: 29-Apr-2019].

[60] “Upstream Oil and Gas | ABB,” *ABB*, 2019. [Online]. Available:

https://new.abb.com/products/measurement-products/upstream-oil-and-gas. [Accessed: 04-Jun-2019].

[61] "Field instruments: Flow, level, pressure, temperature, analytics | Endress+Hauser," *Endress+Hauser*, 2019. [Online]. Available: https://www.endress.com/en/field-instruments-overview. [Accessed: 04-Jun-2019].

[62] "Adafruit VL53L0X Time of Flight Distance Sensor - ~30 to 1000mm ID: 3317 - $14.95 : Adafruit Industries, Unique & fun DIY electronics and kits." [Online]. Available: https://www.adafruit.com/product/3317. [Accessed: 02-May-2019].

[63] "XL TrashSonar WR - Trash Sensor | Trash Level Measurement," *MaxBotix*, 2019. [Online]. Available: https://www.maxbotix.com/product-category/all-environments/xl-trashsonar-wr-products. [Accessed: 04-Jun-2019].

[64] "Arduino MKR1000 WIFI with Headers Mounted." [Online]. Available: https://store.arduino.cc/arduino-mkr1000-with-headers-mounted. [Accessed: 02-May-2019].

[65] G. D. Lingden, "REMOTE MANAGEMENT OF LIQUID LEVEL USING RASPBERRY PI WITH ULTRASONIC SENSOR," 2015.

[66] P. Kassal, M. D. Steinberg, and I. M. Steinberg, "Wireless chemical sensors and biosensors: A review," *Sensors Actuators B Chem.*, vol. 266, pp. 228–245, Aug. 2018.

[67] Arduino, "What is Arduino?," 2019. [Online]. Available: https://www.arduino.cc/en/Guide/Introduction. [Accessed: 15-May-2019].

[68] W. Li *et al.*, "System modelling and performance evaluation of a three-tier Cloud of Things," *Futur. Gener. Comput. Syst.*, vol. 70, pp. 104–125, 2017.

[69] H. Elazhary, "Internet of Things (IoT), mobile cloud, cloudlet, mobile IoT, IoT cloud, fog, mobile edge, and edge emerging computing paradigms: Disambiguation and research directions," *J. Netw. Comput. Appl.*, vol. 128, pp. 105–140, Feb. 2019.

[70] R. K. Perrons and A. Hems, "Cloud computing in the upstream oil & gas industry: A proposed way forward," *Energy Policy*, vol. 56, pp. 732–737, May 2013.

[71] Microsoft, "Public Cloud," 2019. [Online]. Available: https://azure.microsoft.com/en-us/overview/what-is-a-public-cloud/. [Accessed: 16-May-2019].

[72] Microsoft, “Private Cloud,” 2019. [Online]. Available: https://azure.microsoft.com/en-us/overview/what-is-a-private-cloud/. [Accessed: 16-May-2019].

[73] Microsoft, “Hybrid Cloud,” 2019. [Online]. Available: https://azure.microsoft.com/en-us/overview/hybrid-cloud/. [Accessed: 16-May-2019].

[74] Microsoft, “Microsoft Power BI,” 2019. [Online]. Available: https://powerbi.microsoft.com/en-us/. [Accessed: 16-May-2019].

Appendix A - Technical Sheet

Appendix A represents the relevant connections between the components and the circuit as described in Section 5.8 System Schematics.

Arduino MKR1000	LCD	HC-SR04	TMP36
5V/ VCC	VCC/ A (Anode)	VCC	VCC
GND	GND/ K (Cathode)	GND	GND
12 SCL	RS (Register Select)	--	--
11 SDA	E (Enable)	--	--
A2	--	--	Analog Volt Out
A3	Vo (Contrast)	--	--
0	D7	--	--
1	D6	--	--
~2	D5	--	--
~3	D4	--	--
~4	--	Trig	--
~5	--	Echo	--

Table 14. *Technical specification sheet.*