Interreg North-West Europe REAMIT

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Improving Resources Efficiency of Agribusiness supply chains by Minimizing waste using Internet of Things sensors (REAMIT)

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Market Readiness Report

REAMIT: Improving Resource Efficiency of Agribusiness supply chains by Minimising waste using Big Data and Internet of Things sensors

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Executive Summary

The integration of real-time monitoring devices into the food industry can provide real-time solutions for the agribusiness sector and food companies, revolutionising the way they operate and enhancing efficiency, sustainability, and safety throughout the entire food supply chain. Internet of Things (IoT) technologies have the potential to transform the food sector by enabling innovative solutions for monitoring, tracking and managing various processes. This market readiness report is part of the €4.88 million North West Europe (NWE) funded project REAMIT (Resource Efficiency of Agribusiness supply chains by Minimising waste using Big Data and Internet of Things sensors). This report aims to explore the potential of IoT technologies in the food sector and identify forthcoming opportunities for their development into marketable products.

1. Food waste is a significant global problem, amounting to 88 million tons or €143B annually, with almost one-third occurring along agri-food supply chains. The EU has prioritised reducing food waste and aims to halve it by 2030 across all supply chain stages.

2. Sensor and IoT technology offer promising solutions to reduce food waste by continuously monitoring food quality throughout the supply chain. Real-time data sharing enables quick decisions to prevent potential quality issues from becoming food waste.

3. The REAMIT project addressed food wastage in interconnected supply chains across several European countries, focusing on fruits, vegetables, meat, and fish, which are commonly wasted in larger quantities. The project explored wastage at various stages, including farms, packaging sites, food processors, distribution, logistics, wholesalers, and retailers.

4. There are problems surrounding waste during each stage of the food supply chain. For example, production stage issues include food left in the field or abattoir, processing and packaging challenges involve inefficient techniques, transportation and storage problems include improper storage conditions and inadequate temperature and atmospheric monitoring, while retailing issues encompass inadequate aesthetics, improper use of food expiration dates, and inefficient supply chain coordination and demand forecasting, resulting in unsold food.

Potential Solutions to assist with waste problems and monitor food quality

5. The use of drones, robots, and IoT devices can enhance farming efficiency and supply chain collaboration, providing real-time data for better decision-making.

6. IoT devices connected to the cloud offer timely warnings and monitoring of food products, enabling swift corrective actions to reduce food spoilage and waste. They can also combine with data analytics and external data, like weather, to identify patterns and trends causing food waste.

7. Sensing technologies benefit agriculture and food processing by monitoring parameters such as crop patterns, environmental conditions, and product quality. IoT-powered sensors in vehicles improve traceability during transportation, but they may increase energy use for food preservation.

8. Temperature, humidity, and GPS sensors in IoT devices can track real-time data during storage and transport, reducing food waste. However, challenges like maintenance, equipment malfunctions, and data entry errors may arise.

Market overview of IoT

9. The IoT market is projected to reach $925.2 billion in 2023, with an expected compound annual growth rate (CAGR) of 13% during 2023-2026.

10. Advancements in connectivity, high-speed internet, and wireless communication technologies, along with decreasing hardware costs, have fuelled the rapid growth of the IoT sector, enabling integration into various devices.

11. Europe accounts for 23% of global IoT spending, with estimated spending of €184 billion in 2021, projected to grow at a CAGR of 10% through 2025, with healthcare as a significant market share.

12. The agriculture IoT market is expected to grow rapidly at a CAGR of 10.8% from 2021 to 2028, reaching €20.4 billion by 2028.

Assessment for market demand in food sector for the use of sensing technology

13. The REAMIT project conducted a quantitative survey with 315 agri-food businesses in the UK to assess their views on using IoT technologies for monitoring environmental parameters to reduce food waste.

14. The survey revealed that 47.6% of respondents currently use some form of IoT technology in their business operations, showcasing its potential to optimise processes, improve efficiency, and drive innovation.

15. 72.4% of agri-food respondents consider reducing food waste a significant part of their business objective, with 69.2% recognising IoT technologies' potential to assist in achieving this objective. Moreover, 67.9% believe that implementing IoT technologies could lead to long-term cost reduction, making it a valuable investment.

16. While IoT devices offer cost and waste reduction benefits, 65.7% of respondents believe integrating such technologies will also improve operations and potentially attract more customers, thereby enhancing their competitive edge. A majority (61%) believe their competitors already use IoT technology.

17. Currently, 28.5% of companies have implemented automatic monitoring of control systems for temperature, and 17.6% have implemented both automatic monitoring and control systems for humidity.

18. However, 52.4% of companies do not use any IoT technology, with approximately 43% of participants citing a lack of necessary skills as a barrier to adoption. There is a need for educational initiatives and training programs to enhance their skillset.

19. Additionally, 52.1% of respondents reported a lack of adequate resources, and 56.3% cited insufficient IT infrastructure as hindrances to adopting IoT technology. Addressing these challenges could promote wider IoT adoption in the agri-food sector.

Pilot Trials: The impact IoT technologies bring to the food sector

20. WD Meats needed to monitor temperature and humidity in a dry-ageing refrigerated chamber accurately to optimise the ageing process and reduce weight loss in hindquarters. REAMIT selected LoRaWAN sensors with a long transmission range and external humidity probe, ideal for closed, humid environments. The sensors successfully monitored the relationship between temperature and weight loss in different chamber sections. Lower temperatures in the dry-age chamber resulted in reduced weight loss on hindquarters, emphasising the importance of selecting sensors with external humidity probes for precise monitoring.

21. Musgrave faced breakdowns in refrigeration units during the last mile of cold chain transportation, leading to food waste with no detection method. REAMIT proposed an Eagle datalogger with temperature/humidity sensor, cellular capabilities, and an accelerometer. The sensor was placed strategically to detect temperature changes during transit, and external power sources were added for battery performance. The solution allowed Musgrave to detect

breakdowns and optimise temperature control during transportation, reducing food waste and ensuring product quality.

22. Picnic needed to determine the optimal number of icepacks for perishable goods during transportation to reduce waste and costs. REAMIT utilised LoRaWan connectivity with LoRaWan sensors used to monitor environmental factors in cooling boxes. The sensors effectively responded to temperature changes and maintained a stable signal, enabling Picnic to optimise icepack usage, reduce waste, and save costs.

23. Yumchop experienced refrigeration unit breakdowns, leading to food waste with no detection mechanism in place. REAMIT proposed traditional temperature and humidity LoRaWAN sensors across the factory and a remote vending machine to monitor frozen food storage in real-time. The central dashboard allowed real-time monitoring, and staff could take proactive measures to prevent breakdowns, minimising food waste.

24. Human Milk Foundation required real-time monitoring of temperature inside human milk bags during transportation to minimise milk waste and ensure safety. REAMIT proposed 10 cellular Digital Matter Eagle loggers with temperature and humidity sensors for real-time transportation monitoring. Connectivity issues were resolved remotely, enabling real-time monitoring and detection of transportation anomalies, reducing milk waste and ensuring quality.

25. Burns Farm Meats faced inadequate temperature and humidity control during the dry-ageing process, leading to high trim loss. REAMIT proposed LoRaWAN sensors to monitor temperature and humidity in refrigeration chambers. The solution allowed real-time monitoring and staff alerts, reducing trim loss, and optimising the dry-ageing process.

26. Biogros needed to monitor refrigeration units during transportation to detect potential breakdowns and reduce food waste. REAMIT implemented a real-time monitoring and alerting system with cellular Eagle loggers, monitoring ambient and chilled zones. The anomaly prediction model and dashboards enabled Biogros to take proactive measures, optimise their supply chain, and reduce food waste.

27. University of Nantes needed swift and precise evaluation of food quality during transportation. The University of Nantes and REAMIT developed a portable Raman sensor, eliminating vibrations with stationary moments for accurate analysis. The Raman sensor provided valuable insights into food quality, enabling the University of Nantes and REAMIT to maintain product integrity during transportation.

28. Ulster University explored an instant quantitative assessment of milk quality. UU and REAMIT developed a new machine learning model for the FreshDetect handheld spectrometer, an ultra-portable and lightweight spectra device. The produced model enabled UU to estimate with 95% accuracy whether milk was fresh or spoiled.

Future market scalability of IoT technologies

29. After recognising the potential of IoT sensors to reduce food waste through real-time quality monitoring, each company embraced the technology for demonstrations and motivation.

30. Modern technologies, like IoT sensors, enable businesses to comply with food safety regulations, ensuring food quality and preventing waste, becoming a key driver for their adoption.

31. Companies require additional confidence in data security and privacy measures, as mishandling these aspects could negatively impact their brand image.

32. The pilot companies highlighted the relevance of REAMIT's IoT technology in addressing real needs, such as reducing food waste, improving product quality, cutting costs, complying with regulations, and enhancing operational efficiency.

33. REAMIT's IoT technology not only reduces costs and food waste but also aligns with other company objectives, including maintaining a closed temperature supply chain system mandated by legislation, improving crop yield and product quality, and optimising logistics and transportation.

34. The current market conditions favour the introduction of REAMIT IoT solutions as they assist companies from various domains in achieving sustainability goals, environmental initiatives, waste reduction targets, data-driven approaches, net neutrality, and meeting evolving market demands.

35. While companies express interest in IoT technology, they require free trials and proofs of concept to ensure solutions align with specific business requirements and provide long-term value before committing financially.

36. Through assessment of each of the four solutions deployed to the pilot test companies, it is shown that the two most popular solutions have achieved a TRL of 9 and an MRL of 7. The other two solutions, which are still lab based, achieve a TRL of 6 and a MRL of between 5 and 7 respectively.

Contents

1. Project Overview

Food waste is a global problem [1], amounting to 88 million tons or €143B per year. It has been estimated that almost one-third of this food waste occurs along agri-food supply chains. It is therefore of highest priority for the EU to reduce food waste. In fact, the EU has committed to halving food waste by 2030 by focusing on all stages in the supply chain.

Improving Resource Efficiency of Agribusiness supply chains by Minimising waste using Big Data and Internet of Things sensors (REAMIT) is a €4.88 million North West Europe (NWE) funded project launched in 2019 and is focused on reducing food waste in various agri-food industries through the use of Internet of Things (IoT) sensors and big data analytics. The goal of REAMIT is to adapt existing Internet of Things and Big Data technologies to best fit the needs of the food supply chain management system in NWE.

Sensor and IoT technology present an opportunity to reduce food waste by continuously monitoring the quality of food as it moves along the food chain. Real time information on food quality has the potential to be shared in real time among food chain partners, warning of potential quality issues, and providing timely and rapid decision support to owners of food before it becomes waste. This report will examine the Market Readiness Level of such technologies by reviewing the successes and required areas of improvement from pilot test companies who participated in the REAMIT project.

Since 2019, the REAMIT project has been focusing on the use of innovative modern digital technologies to improve supply chain resource efficiency and reduce food waste. The project has been carried out in Ireland, Germany, France, UK, Luxembourg, and the Netherlands due to the amount of interconnected food supply chains and huge food waste produced in these countries. Subsequently, the project has primarily been focused on the wastage of fruits, vegetables, meat and fish, as these are known to be wasted in larger quantities within the agri-food supply chain. This encompasses different areas of interest such as farms, packaging sites, food processors, distribution, logistics, wholesalers, and retailers. This has been achievable by adopting active research.

The project involved researchers and practitioners collaborating with 20 enterprises within a business setting (agribusiness), by implementing and testing 8 technology solutions across NWE to achieve trustworthy results that have lasting impacts across the sector. If proven successful, the REAMIT project will have produced self-sustaining technologies and achieved their objective of saving 1.8Mt of food waste or €3B per year in NWE, and avoided 5.5Mt/year of CO_2 emissions. In return, businesses will reduce their food waste, sell more food and generate more revenue, which will also positively impact the amount of resources (water, nutrients, fertilisers etc.) conserved to benefit society at face value.

1.1 Problems surrounding waste in the food supply chain from 'farm to fork'

Food waste occurs in all areas of the agri-food supply chain from farming production, processing and packaging at sites, transportation and storage, retailing and final consumption Ramanathan et al. [2] identified several issues that can lead to food waste along the food supply chain as shown below.

In the production stage, multiple issues can arise, such as food being left in the field or abattoir, eaten by birds and rodents, harvested at the wrong time or via poor harvesting techniques, lack of skilled workforce and resources or attacked by diseases and pests. During processing and packaging there can be issues relating to inefficient techniques, losses during milling, cleaning and grinding, inefficient quality management and supply chain coordination and forecasting of demand can result in food waste. In transportation and storage stages, issues can consist of improper and inefficient storage conditions, inadequate control and monitoring of temperature and other atmospheric / handling conditions, inadequate infrastructure, pests, diseases, spillage, contamination and inadequate maintenance of temperature during shifting from one truck / warehouse to another, natural drying out of food and pilferage. Within the retailing of food there can be multiple issues relating to food waste, such as inadequate aesthetics (e.g., food items not uniform), inappropriate use of food expiration date and inefficient supply chain coordination and forecasting of demand resulting in unsold food. The final stage of the agri-food supply chain is consumption. During this stage, food waste can occur due to forgotten food left in the fridge and not consumed while the food is fresh, improper and inefficient storage conditions, errors in cooking resulting in waste, lack of portion size control and lack of awareness of food waste and methods of valorising waste.

The REAMIT project is focused on reducing waste in fruits, vegetables, and meats. For these categories, Mena et al. [3] found that inadequate temperature control was the most significant cause of food waste in fruits and vegetables, while contamination, weather variations, and damage during transportation were the primary contributors to meat waste. Food waste can have a major impact on the economy, society, and environment if not suppressed quickly and efficiently. The problem of minimising food waste can be addressed through a combination of technological and non-technological approaches [2]. None-technological approaches involve focusing on developing a skilled workforce in the agricultural, abattoir, processing and transport sectors. By having well-trained and efficient workers, the overall productivity and efficiency of these processes can be improved, leading to reduced waste. In addition, by implementing advanced monitoring, such as regular inspections and the use of specialised equipment, farmers can identify potential issues at an early stage and take appropriate measures to mitigate them. The early detection of pests and diseases for example, is crucial in preventing the spread of infections and minimising crop losses.

On the technological front, modern digital technologies offer numerous opportunities to address food waste. One such technology is the use of IoT sensor technology. IoT sensors can be deployed throughout the supply chain, from farm to consumer, to monitor various parameters such as temperature, humidity, and spoilage indicators [4]. These sensors provide real-time data, enabling stakeholders to identify potential issues promptly. For example, if the temperature in a refrigerated truck rises above the acceptable range, an alert can be sent to the relevant parties, allowing them to take immediate action to prevent spoilage and waste [5].

Advanced technologies, such as machine vision systems and spectroscopy, can be employed to assess the quality of produce without causing damage [6]–[8]. By accurately assessing the quality of food items, producers can make informed decisions regarding their distribution and utilisation, ensuring that only high-quality products reach the market. This not only reduces food waste but also enhances consumer confidence in the food they consume, leading to a more sustainable and efficient food system overall.

1.2 Potential solutions linked to sensor technology options in the market

Over the last few years, there have been various digital technologies that have been developed to assist and increase the efficiencies within various stages of food supply chains, from agricultural, produce, distribution and retail. These can include the use of drones and robots to improve farming efficiency and modern scheduling, forecasting and supply chain collaboration tools to improve operations. However, one area that has gained substantial commercial traction within the food supply chain is the Internet of Things. IoT devices, including sensors and connected systems, are being increasingly deployed to enhance visibility, traceability, and decision-making capabilities.

IoT devices can connect to the cloud and be monitored via web-based dashboards or smartphone-based applications. They have the potential to produce timely warning signals to notify food owners of any changes within the surroundings of their product to help with decision making. For example, if there is a malfunction in a temperature-controlled system, a warning could alert the food owner or relevant personnel. This prompt notification enables them to swiftly take corrective actions, such as adjusting the system, initiating repairs, or transferring perishable goods to alternative storage facilities. By addressing the issue promptly, the risk of food spoilage and waste is mitigated.

IoT devices are capable of working in partnership with a variety of communication networks, storage facilities, algorithms and visualisations to assist food owners in understanding their food waste, along with temperature and humidity within their supply chain. By combining automated detection algorithms with sensor data and meaningful visualisations, food owners can be notified by the system when it has identified reductions in food quality. This is vital during the early stages as the devices can assist food owners with the redirecting of food to nearby demand points for sale before it becomes waste. IoT devices also have the potential of being combined with externally available data, such as local weather. This can result in Big Data that can be analysed using modern data analytics techniques. This would result in a detailed understanding of the patterns and trends that cause food waste and help to reduce it.

The implementation of sensing technologies in the agricultural and food processing sectors offers significant benefits by enabling comprehensive monitoring of various parameters. For instance, in the agricultural domain, sensors can be used to track crop patterns using GPS or location data or analyse environmental conditions such as light levels, temperature, humidity and others alike [9]. By gathering real-time data on these factors, stakeholders can gain valuable insights into the growing conditions, enabling them to make informed decisions regarding irrigation, pest control, and overall crop management. Furthermore, sensors prove invaluable during the food processing stage, as they can help optimise the processes that transform raw material resources into final food products [10]. For example, temperature sensors can be employed to monitor and control cooking, cooling, or refrigeration processes, ensuring that food products are subjected to the precise conditions required for optimal quality and safety. Additionally, sensors can be used to monitor variables such as pressure, pH levels, and viscosity, providing real-time feedback on the progress of the processing operations. When combined, it can add additional efficiencies in operations planning.

The data collected from different sensors can be integrated and analysed, allowing for a comprehensive understanding of the entire supply chain. This holistic view enables stakeholders to identify areas of improvement, streamline processes, and optimise resource allocation. For instance, by analysing data on crop patterns, environmental conditions, and processing parameters, stakeholders can optimise production schedules, aligning them with crop availability, processing capacity, and market demand. This integrated approach helps reduce waste, minimise delays, and improve overall operational efficiency.

During transportation, sensing devices can capture the trajectory history of a product as it travels through the supply chain, thus offering improved traceability, validation and quality control [11]. There has been strong evidence to suggest that there are opportunities to use IoT-powered sensors in vehicles for food distribution and storage [12]. These sensors, when combined with location data, enable real-time monitoring of environmental conditions and the quality evolution of food products during transit [12]. Monitoring environmental conditions in real-time is instrumental to increase food shelf life and maintain its quality and safety. IoT-powered sensors can measure parameters such as temperature, humidity, and air quality inside transport vehicles. By taking immediate corrective actions, such as adjusting temperature settings or addressing ventilation issues, the risk of spoilage, contamination, or degradation of food products can be significantly minimised. Additionally, the real-time data can be utilised to track the origin, transit points, and delivery status of food products, ensuring transparency and accountability throughout the supply chain. In case of any quality issues or recalls, the ability to trace the product's journey becomes essential in identifying the source of the problem and taking appropriate actions.

Food loss in retail pertains to inadequate storage facilities and conditions. For example, fridge/freezer errors, or other areas such as controls and quality checks of shelving, whereby food passing beyond ‘best before’ dates or inaccurate stock predictions from overstocking [13]. To prevent this, the use of powered sensing IoT devices can provide a valuable opportunity for retail and other realms alike to decrease waste. These devices can assist by providing precise data to inform stock management and planning with subsequent impact on pricing (either competitive or lower) to assist consumers along with operational efficiency [14]. Nonetheless, whilst these solutions can assist with the reduction of food waste, they often lead to increased use of energy, especially for the preservation of food products. From the environmental point of view, the negative impacts of measures to reduce food loss and waste should not outweigh the benefits. Studies on the environmental performance of IoT technologies to minimise food waste have shown this, therefore, the environmental benefits overcome the burdens [15].

There are several types of sensors that can be used to monitor food quality. The selection of sensors depends on the specific parameters and properties of the food being monitored. However, the main types of sensors used for monitoring food quality are temperature sensors, humidity sensors, pH sensors, gas sensors, and optical sensors [12].

Temperature sensors measure the temperature of the food to ensure it is stored and transported within the required temperature range to prevent spoilage or bacterial growth. It is important when dealing with temperature-sensitive foods such as raw meat and dairy products [16]. By using IoT temperature devices, there is the potential to use a three-layer network that consists of temperature, humidity and GPS sensors along with a mobile network to track real-time data. This would provide data in relation to the time spent in storage or transport, and the temperature and humidity ranges they were exposed to. However, a few challenges can occur during the temperature monitoring, such as device maintenance, malfunction of cooling equipment, data entry errors if manual entry of data is required, fluctuation in outside temperature, especially if the transportation unit is open / closed during transportation when various delivery drop offs, etc. are occurring.

Humidity sensors measure the moisture content of the food. They are commonly used in applications where excessive moisture can lead to microbial growth or degradation, such as in grain storage or meat processing [17]. In grain storage, humidity sensors are essential for preventing the growth of molds, fungi, and insect infestation [18]. Grains have a natural moisture content, and if the humidity levels in storage facilities are too high, it can cause the grains to absorb moisture from the surrounding air, leading to decreased quality. In meat processing, humidity sensors are used to maintain the ideal moisture levels during various stages of production, including curing, drying, and aging processes. Controlling the humidity is crucial for achieving the desired texture, flavour, and shelf life of meat products [19].

pH sensors play a vital role in monitoring the acidity or alkalinity of food products. The pH value is a measure of the concentration of hydrogen ions in a solution, and it can provide valuable information about the quality, freshness, and safety of perishable food items [20]. In the context of fruits and vegetables, pH sensors are commonly used to assess their ripeness and determine their optimal storage conditions [21]. As fruits and vegetables ripen, their pH levels can change due to metabolic processes. Dairy products are also sensitive to pH changes, as alterations in acidity can affect their taste, texture, and shelf life. pH sensors are used to ensure that dairy products, such as milk, yogurt, and cheese, maintain the desired acidity levels throughout production and storage [22]. In addition to ripeness and fermentation processes, pH sensors are instrumental in detecting spoilage and microbial activity in various food products. Changes in pH levels can indicate the growth of harmful microorganisms, such as bacteria or fungi, which can lead to foodborne illnesses or product degradation.

Gas sensors are a type of chemical sensor that use different types of receptors and transducers to detect volatile organic compounds (VOC) emitted by the microorganisms. The data captured by the receptor is transformed into a quantifiable signal. One of the most researched gas sensors is Metal Oxide Semiconductor (MOS). It uses a coated electrode to vary the resistance of a sensor based on the amount of gas it is currently exposed to. Other sensors have been developed using several different technologies including optical sensors, surface acoustic wave sensors; and quartz microbalance sensors. Gas sensors have shown great potential in terms of assessing food quality. These sensors can provide fast assessments and physically they are small and relatively inexpensive, making them ideal for commercial development. Nonetheless, limitations do include poor selectivity, sensitivity and reproducibility.

Optical sensors are valuable tools in assessing and monitoring various aspects of food quality [23]. These sensors use light-based technologies to gather information about the physical and chemical properties of food products. By analysing the interaction of light with the sample, optical sensors can provide valuable insights into colour changes, composition, and overall quality [24], [25]. Colour sensors are commonly used in the food industry to measure and monitor colour changes in meat, fruits, and other products. Colour is an essential attribute of food quality and can indicate freshness, ripeness, and visual appeal. By using specific wavelengths of light, colour sensors can measure and quantify attributes such as hue, saturation, and brightness, providing objective data about the colour characteristics of the food [26]. This information is crucial for quality control and can help determine the optimal timing for harvesting or processing fruits, as well as identifying any undesirable colour changes in meat that may indicate spoilage.

In addition to sensing technologies, imaging technology (IMT) can measure the quality of a product. It has already been used successfully within food industry as it is fast, non-destructive and cost-efficient. There are various approaches of IMT that can be used to measure food quality attributes, these include: Computer Vision Systems (CVS), Near-Infrared Spectroscopy (NIRS), Raman Spectroscopy, Hyperspectral Imaging (HSI) and Ultrasonic Imaging.

CVS rely on image analysis and have become prevalent in the food industry for monitoring food quality [27]. These systems play a crucial role in enhancing the efficiency of food inspection, benefiting the industry as a whole. By capturing and analysing images, these systems can gather a range of information about food products, including size, dimensions, appearance, shape, and surface colour. This allows for precise and detailed monitoring of food processing, reducing the potential for human errors and improving overall accuracy.

NIRS is effective in monitoring product safety and quality within the food industry [28]. It simplifies sample preparation, provides rapid detection times, and offers non-destructive analysis in food monitoring. It saves time, reduces contamination risks, and enables real-time monitoring for timely decision-making in fast-paced food production. NIRS's non-destructive nature allows repeated measurements and sample retention, reducing waste. Handheld NIRS scanners enhance on-site monitoring throughout the food supply chain, facilitating timely interventions, traceability, and reliable results for food industry professionals [29].

In addition to NIRS, Raman Spectroscopy can also predict food quality and is widely used. It can be particularly helpful if the device is made portable and can be transported to different locations within the food processing facilities, enabling the collection of valuable information directly at various stages of production [6]. In addition, it can also be of benefit in a factory setting to detect changes at a molecular level to alert food owners of quality issues within the production stage and ultimately reduce food waste. This technology can also be applied at the transportation level to alert drivers and allow them to deliver food products to the nearest food outlet to avoid food loss.

HSI combines the advantages of image processing and spectral analysis technologies. Therefore, it has the capacity to extract 2-dimensional imaging and spectral details of each pixel of the product [30]. It can detect surface contamination, freshness, colour, pH, moisture, protein and fat. Overall, HSI technology is considered to be the most widely used technique for none-destructive food quality testing in recent years.

Ultrasonic Imaging can monitor power ultrasonic waves and detection ultrasonic waves. Ultrasonic techniques to detect the food quality is based on the analysis of changes in acoustic characteristic parameters for predicting food composition, integrity and quality. The detection ultrasonic wave is of high-frequency and low-energy and commonly used to analyse and detect food quality [30]. The power ultrasonic wave is typically utilised within food processing, such as homogenisation, food sterilisation, drying, thawing and filtration. Moreover, ultrasonic techniques can be employed to detect physical properties and defects in food products. For example, the presence of air pockets, voids, or cavities in foods can be detected by analysing the reflection or transmission of ultrasonic waves. This helps identify internal defects or irregularities that may impact the overall quality, texture, or structure of the food. Ultrasonic measurements can also provide insights into textural attributes like firmness or tenderness, which are crucial indicators of quality for certain food products.

And finally, one special category of monitoring devices is intelligent packaging, which is used to increase convenience by allowing the product to conform to shapes making it easier to handle. The packaging can be used as a marketing tool and it also protects the food from the external environment [31]. Three main types exist for intelligent packaging, these are packaging which is capable of monitoring quality characteristics and packaging which can monitor environmental conditions, such as temperature and humidity. The final type of intelligent packaging can store data, for example integrated with Radio Frequency Identification (RFID) tagging [32].

Intelligent packaging provides advantages across the different perspectives of the supply chain, if it does result in less food waste then it could save money for food producers, retailers and consumers. However, there are also disadvantages, most notable is the potential for increased cost for food producers in both the production and development of the new packaging [33]. On-package quality indicators may also drive consumers away from what may still be unspoiled food if the quality indicator has been activated. Installing sensors and other equipment into packaging may also increase the difficulty of recycling the packaging and could actually produce more non-food waste than conventional packaging [34].

Overall, the integration of sensing technologies, imaging technologies, and intelligent packaging in the food supply chain represents a significant step towards waste reduction and a more sustainable and efficient food system. By harnessing real-time data and leveraging advanced technologies, stakeholders gain valuable insights that enable informed decision-making, process optimisation, and improved operational efficiency. These advancements hold the potential to minimise food waste while ensuring the delivery of high-quality and safe food to consumers. Through continued innovation and adoption of these technologies, it is possible to work towards a more sustainable future, where the food supply chain operates with greater precision and responsibility.

1.3 Internet of Things Market Overview

The IoT market size will be valued at $925.2 billion in 2023 and is expected to grow at a compound annual growth rate (CAGR) of 13% during 2023-2026, as shown in Figure 1 [35]. The increasing demand for data connectivity at higher speeds will support the adoption of IoT. The rapid growth of the IoT sector can be attributed to several key factors. Firstly, advancements in connectivity, including high-speed internet and wireless communication technologies have made it easier to connect devices to the internet. Secondly, decreasing hardware costs have made IoT technology more affordable for businesses and consumers. Additionally, the miniaturisation of electronic components has allowed for the integration of IoT technology into various devices. The availability of cloud computing and scalable storage solutions has provided a cost-effective infrastructure for IoT applications. Data analytics and insights derived from IoT data have also played a significant role in driving adoption. The development of industry standards and protocols has facilitated interoperability among IoT devices, while increased awareness and adoption have fuelled the sector's growth across industries.

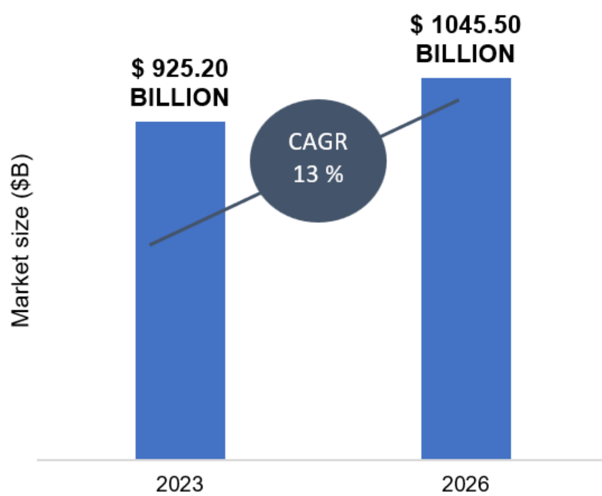


Figure 1. *IoT market outlook, 2023-2026 ($ billion).*

Asia Pacific account for 35.7% of worldwide IoT spending and is likely to show the highest CAGR during the projection period due to increasing smart city projects and rising initiatives, such as Smart Wellington (New Zealand) [36], Intelligent Disease Prediction Project (China) [37], and cloud spending in the region. Moreover, increased cloud spending in the region further fuels this growth. Communication service providers and manufacturers in the region, such as Nokia, Taiwan Mobile and Samsung Electronics, are actively expanding their portfolios to capitalise on opportunities in the smart device market [38], [39]. They are achieving this by developing information collection systems and integrating advanced analytics capabilities into their existing systems. These factors collectively contribute to Asia Pacific's strong potential for IoT growth.

North America holds the second largest market share in the IoT sector (27.3% of worldwide IoT spending), primarily driven by the rapid growth in healthcare, industrial, and automotive industries [40]. The region benefits from a substantial customer base for cloud-based platforms, which have gained widespread adoption. Factors contributing to this adoption include the expansion of IoT-enabled devices, increased research and development investments in the technology, and the presence of major market players like Google, Amazon Web Services (AWS), Microsoft, Cisco, and IBM. These factors collectively contribute to North America's dominant position in the IoT market, particularly in relation to cloud platforms. According to the Global Mobile Trends Report from GSMA [41], the total number of IoT connections is projected to reach 5.1 billion by 2025 in North America. The total number of connected devices in the region reached 2.9 billion in 2020.

Internet of Things Europe was responsible for 23% of global IoT spending. The spending was estimated to reach €184 billion in 2021 and it is expected to experience 10% growth through to 2025 [42]. One noteworthy industry in the region is healthcare, which is projected to hold a considerable market share. This sector is becoming increasingly linked to big databases as it can provide various insights, such as diagnostic analytics, descriptive analytics, predictive analytics and prescriptive analytics. The combination of connected devices and big data is expected to gain traction in Europe, driven by growing demand from enterprises in Germany, the U.K., France, Italy, Spain, and the Netherlands, bolstering the region's market growth. Additionally, Eastern European and Nordic countries display a notable adoption rate of advanced technologies. According to the Confederation of British Industry (CBI), European organisations are increasingly recognising the value and advantages of IoT technologies [42].

The agriculture IoT market is also predicted to grow at a fast CAGR (10.8% from 2021 to 2028 and to reach €20.4 billion by 2028 [43]. The growth of the agriculture IoT market is fuelled by the increasing understanding of the benefits that agriculture IoT can offer farmers. The benefits of implementing the IoT for farmers are two-fold. It has assisted them in lowering expenses while increasing yields by boosting farmer decision-making with precise data [44]. Some major applications of the technology in the agricultural sector are smart farming, precision farming, smart drones, among others. For example, smart farming enhances the entire agricultural system by monitoring the farm in real time and allowing farmers to produce food efficiently [45]. It uses IoT devices such as soil moisture sensors, weather stations, and livestock trackers enable real-time monitoring and data collection, providing farmers with valuable information for decision-making. Precision farming enables farmers to make informed decisions regarding irrigation, fertilisation, pest control, and overall crop management, leading to improved yields, reduced costs, and enhanced [46].

However, there are some significant restraining factors that need to be addressed in the agriculture IoT industry. One such challenge is the lack of connectivity and infrastructure in rural areas where farming is prevalent. Reliable internet connectivity and network coverage are essential for seamless data transmission between IoT devices and cloud platforms. Efforts are being made to expand connectivity in rural areas, but further infrastructure development is needed to fully unlock the potential of agriculture IoT [47], [48].

Other factors that may restrain the expansion of the IoT market is concern over the security, integrity, and privacy of data in connected devices [49], [50]. With the increasing number of connected devices, smart devices, mobile devices and platforms, the need for robust data protection and privacy measures becomes crucial. These connected devices have unique IP addresses that allow them to communicate and exchange information, but they also become potential targets for cyber attackers. The data transmitted and stored in these devices and networks may include sensitive and personal information, making them attractive targets for malicious actors.

The vulnerabilities and design flaws in connected devices can lead to data exploitation and privacy breaches if not properly addressed [51]. To overcome these challenges, it is crucial for IoT manufacturers, developers, and industry stakeholders to prioritise security and privacy measures. This includes implementing robust encryption, authentication and access control mechanisms to safeguard data in transit and at rest. Regular security audits and vulnerability assessments should be conducted to identify and address potential weaknesses. Additionally, industry standards and regulations can play a significant role in promoting secure IoT practices.

Another restraining factor is the limitations in battery life for IoT devices. Manufacturers face challenges in designing IoT products with extended battery life, as the demand for smaller and more lightweight devices increases. While computing power has been advancing, battery energy density improvements have been relatively slower. This limitation poses a challenge in achieving long-lasting, energy efficient IoT devices that can operate seamlessly without frequent battery replacements or recharging. The packaging and integration of small-sized chips with low power consumption remain areas of focus for manufacturers. Therefore, research and development efforts are needed to improve energy storage technologies and optimise power consumption in IoT devices. Innovations such as low-power wireless communication protocols, energy harvesting techniques, and more efficient battery technologies can help extend battery life and enhance the overall performance of IoT devices [52]–[54].

1.4 Assessing Market Demand for Sensor Technology in Agri-Food Supply Chains

Survey results can provide insights into the current state of the market, including the motivations, beliefs, and attitudes of potential customers and other stakeholders. This information can be used to inform the development of pilot trials, ensuring that they are designed to address the most pressing issues and meet the needs of the target audience. In light of this, a quantitative survey was conducted by the project REAMIT to gain a deeper understanding of the opinions held by agri-food businesses regarding the application of IoT technologies for monitoring environmental parameters to reduce food waste. The survey reached out to 315 agri-food businesses across the UK, yielding valuable data into company culture and future ambitions in this sphere. By delving into the survey results, actionable information can be gleaned to drive meaningful improvements and advancements in the agri-food industry.

Current use of IoT technology

In addition to investigating the external pressure and expectations surrounding IoT adoption, the survey also assessed the current use of technology in agri-food businesses. The findings indicated that (47.6%) of respondents are currently using some form of IoT technology in their business operations. This statistic demonstrates the recognition of the transformative potential that IoT offers in optimising processes, improving efficiency, and driving innovation.

Motivations

According to the survey results (Figure 2), reducing food waste is a significant business objective for agri-food businesses, with 72.4% of the respondents indicating so. Moreover, 69.2% recognised the potential of IoT technologies to assist them in achieving this objective. When focusing solely on businesses with food waste reduction as a priority, this percentage rises to 79.9%. These findings highlight the widespread recognition of IoT's efficacy in addressing this crucial challenge faced by the agri-food industry. Furthermore, it can also be observed that over two-thirds of all respondents (67.9%) believed that implementing IoT technologies could reduce costs in the long run, indicating that these technologies could be seen as a valuable investment for businesses. In addition to reducing costs and waste, implementing IoT technologies was also believed to have potential for attracting more customers, with 65.7% of respondents indicating so. This suggests that businesses see IoT technologies as a way to improve their operations and potentially increase their competitive edge.

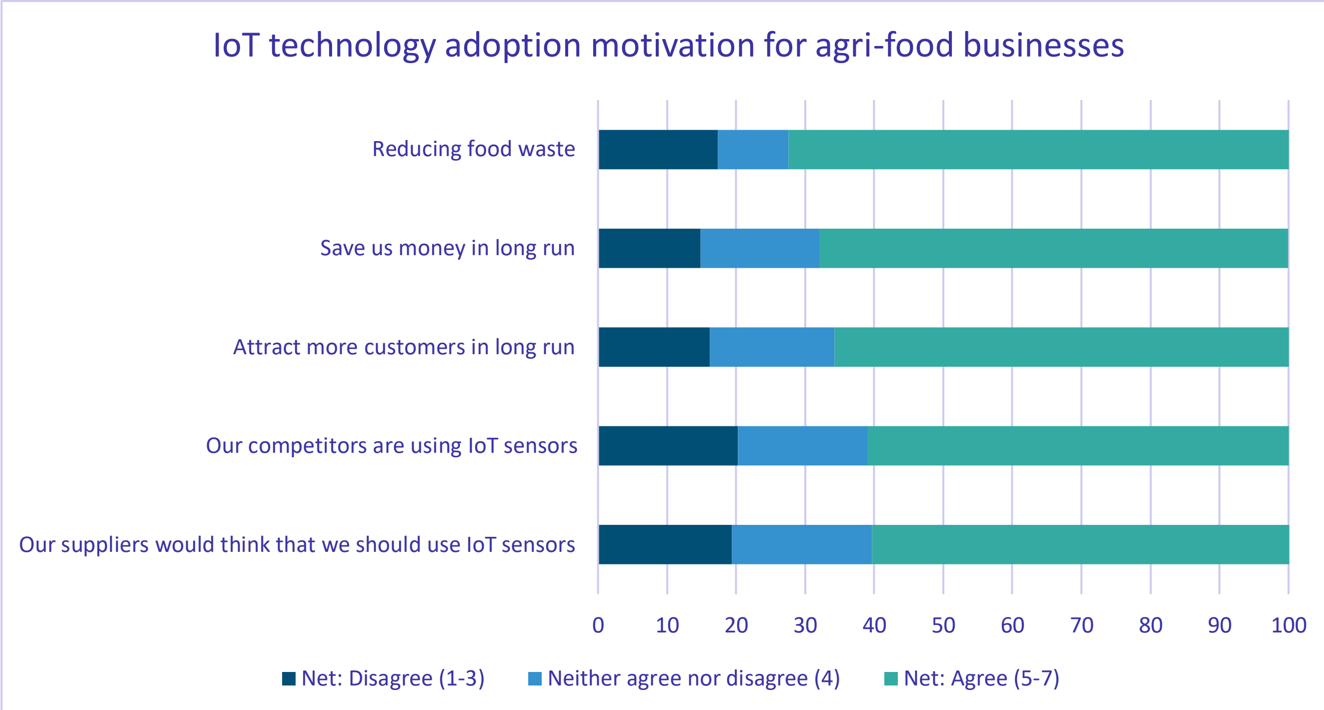


Figure 2. *Survey data exploring IoT technology adoption motivation.*

It is also noteworthy that a majority of respondents (61%) believed that their competitors are already using IoT technology. This indicates that businesses may feel pressure to adopt IoT technologies in order to keep up with their competition. By recognising the significance of IoT adoption for their competitiveness, agri-food businesses are motivated to explore and integrate IoT solutions into their operations to remain competitive and relevant in the evolving landscape of the industry. Additionally, 60.4% of respondents believed that their suppliers hold the expectation that they should be using IoT technology, suggesting that there may be external pressure from supply chain partners to adopt these technologies. The recognition of this external pressure implies that stakeholders within the supply chain, such as suppliers, are increasingly considering IoT adoption as a crucial factor for collaboration and efficiency. Consequently, agri-food businesses may feel compelled to adopt IoT technology not only to meet their own objectives but also to align with the expectations and demands of their suppliers.

Current status of monitoring and controlling food quality parameters

The survey findings presented in Figure 3 indicate the diverse state of monitoring and controlling food quality parameters in the food business, highlighting the need for improvement to prevent food waste. In this context, there is a significant market potential for devices that offer automated monitoring and control systems for temperature, humidity, lighting, and photos. These devices have the opportunity to address the current gaps identified in the survey and contribute to enhancing food quality management in the industry.

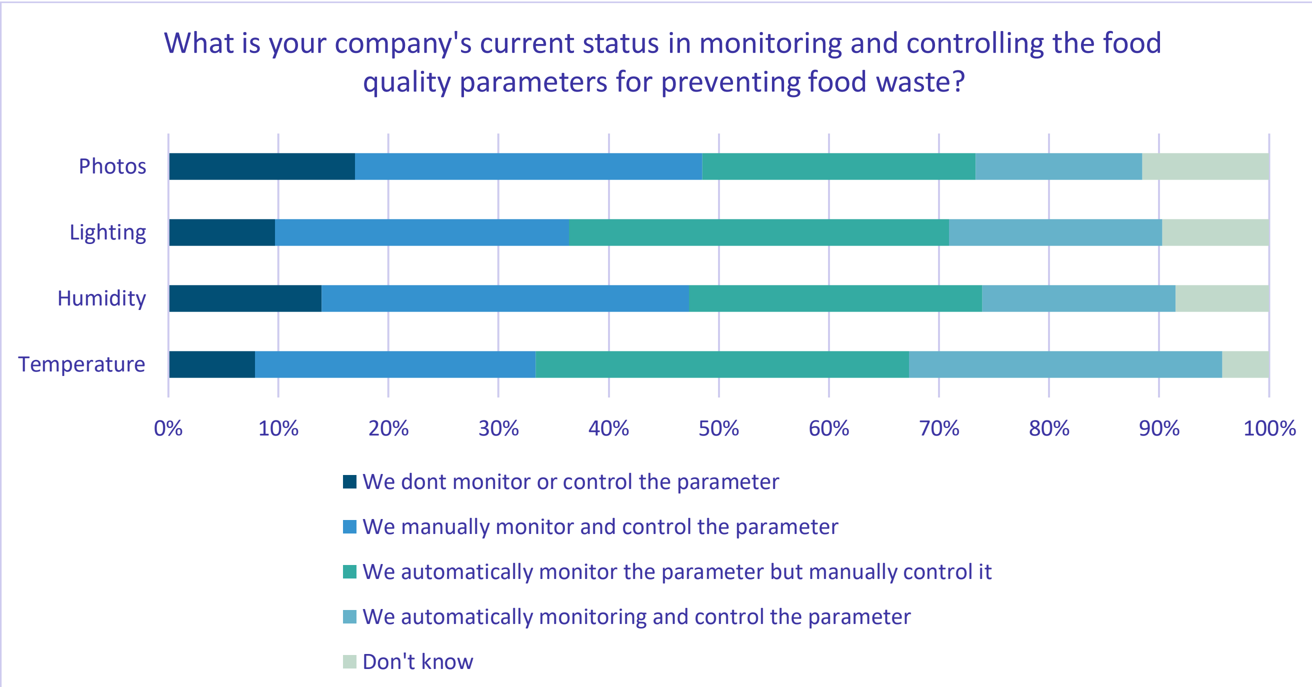


Figure 3. Current status of monitoring and controlling food quality parameters to prevent food waste.

Although a significant portion of companies still rely on manual monitoring and control of temperature parameters (25.5% manual monitoring and 33.9% automated monitoring but manual control), 28.5% of companies have already implemented both automatic monitoring and control systems for temperature. This indicates a growing trend towards adopting automated solutions in temperature management. Similar to temperature, there is room for improvement in the adoption of automated systems for humidity monitoring and control. Currently, only 17.6% of companies have implemented both automatic monitoring and control systems for humidity.

While a considerable portion of companies still rely on manual monitoring and control of lighting parameters (26.7% manual monitoring and 34.5% automated monitoring but manual control), there is an opportunity for growth in devices that provide automated monitoring and control systems for lighting. Currently, 19.4% of companies have implemented both automatic monitoring and control systems for lighting. The survey findings indicate that there is room for improvement in the adoption of automated monitoring and control systems for photo parameters. Only 15% of companies have implemented both automatic monitoring and control systems for photos. This presents a potential market opportunity for devices that offer automated solutions for photo management.

Low adoption rates and the capability of agri-food businesses to implement IoT technologies

Despite the positive attitudes perceived for agri-food businesses, the survey results also indicate relatively low adoption rates of IoT technologies, as 52.4% of the companies currently do not use any form of IoT technology in their business operations. This suggests that there may be barriers preventing widespread implementation. It is crucial to address these barriers and accelerate the adoption of IoT technologies in the agri-food industry. To understand the reasons behind the limited adoption of IoT in agri-food companies, the survey assessed the capability of these businesses to implement IoT technologies. One significant barrier identified was the lack of technical knowledge among respondents. Approximately 43% of participants who do not have IoT technologies implemented expressed their belief that they do not possess the necessary skills to effectively use it. This highlights the need for educational initiatives and training programs to enhance the technical skills of individuals within these companies, enabling them to leverage the potential benefits of IoT in their operations.

Another obstacle encountered by agri-food companies was the insufficient allocation of resources. The survey findings revealed that 52.1% of respondents cited a lack of adequate resources as a hindrance to IoT adoption. These resources could include financial investments, personnel, or equipment necessary for implementing IoT solutions. Overcoming this challenge would require a strategic approach from company management and collaborative efforts from various stakeholders, governments, and technology providers that play a crucial role in providing financial incentives.

Furthermore, the survey uncovered a significant gap in IT infrastructure readiness. Approximately 56.3% of respondents reported not having the required IT infrastructure to support the implementation of IoT technologies. This could include issues with network connectivity, data storage capacity, or outdated systems. Upgrading and modernising the IT infrastructure within these companies would be essential to unlock the potential of IoT solutions and enable seamless integration with existing systems.

Intention of companies to adopt IoT sensors in the future

Of those who did not currently use technology, 48.5% indicated that they were interested in implementing it in the future, which demonstrates a growing understanding of the benefits associated with IoT adoption among agri-food businesses and an openness to exploring and embracing new technological solutions to enhance their operations and overcome food waste challenges. With a clear intention to integrate IoT sensors, companies can proactively explore and capitalise on the potential applications of this technology, ensuring they remain at the forefront of industry trends and developments.

The need for piloting IoT technologies

Overall, the analysis highlights the significant benefits that agri-food businesses believe IoT technology can bring. The results suggest that businesses are motivated to reduce food waste and that they see IoT technology as a potential solution to this problem. They also believe that IoT technology can lead to cost savings and attract more customers. The analysis also identifies potential external pressures on businesses to adopt IoT technology. Respondents believe that their competitors are already using IoT technology, and many believe that their suppliers expect them to adopt it as well.

Despite that, low adoption rates have been observed, as the survey revealed that less than half of agri-food businesses currently have IoT solutions implemented. These findings highlight the need to accelerate the adoption of IoT technologies in the agri-food industry. One approach to accelerate the implementation and overcoming many barriers is through piloting IoT technologies, as demonstrated by the REAMIT project. By helping food supply chain businesses trial and implement IoT technologies, the project aims to increase efficiency and reduce food loss and waste, while providing added value to businesses. These pilot trials serve as real-world test cases, demonstrating the practical application and benefits of IoT technologies in various aspects of the agri-food supply chain. It is through these collective efforts, collaborative projects, and shared experiences that the agri-food industry can unlock the transformative potential of IoT technologies and pave the way for a more sustainable, efficient, and resilient future. In the next section, this document presents IoT technologies that have been piloted throughout the duration of the project.

2. Outline of REAMIT Pilot Trial Companies

2.1 WD Meats

Table 1 presents the Osterwalder Canvas to outline the pilot company, WD Meat’s, business model.

Table 1. WD Meats Osterwalder Canvas

<table>
<tr>
<td rowspan="2">Partners
- Francis Dillon (95%)
- Helen Dillon (5%)</td>
<td>Activities
- abattoir which handles all stages of process
-killing, prepping, dry ageing, cutting, packaging</td>
<td rowspan="2">Value Proposition
- WD Meats has been supplying quality assured beef and innovative beef products to retail customers throughout UK, Europe, Africa and Asia for 35 years
- Their commitment is to select only the best local beef that Northern Ireland has to offer.
- WD Meats has a philosophy of continual development and improvement, both in their infrastructure and in our professional skills.</td>
<td>Customer Relations
- Provide customers with high quality, technically advanced and innovative products at competitive prices.
-Total traceability of the livestock, their husbandry and welfare all form part of product specification at WD Meats.
-WD process and deliver it with the utmost care and attention to the animals, and to the highest standards that our customers demand.</td>
<td rowspan="2">Customer Segments
- UK and EU Supermarkets (both value and premium range), African and Asian Markets
- Restaurants
- Hotels
- Independent, Wholesale, and Catering Butchers</td>
</tr>
<tr>
<td>Key Resources
- 400+ Workers
- Plant
- Cattle provided by farmers</td>
<td>Channels
- Restaurants (McDonalds, etc.), supermarkets (Lidl NI)</td>
</tr>
<tr>
<td colspan="3">Cost Structure
1 - Rolling stock - cattle purchased from farmers
2 - Equipment and maintenance (factory based; transport based)
3 - Health and safety requirements (e.g. processing staff apparel)</td>
<td colspan="2">Revenue Streams
- Fresh meat product sales based on individual contracts with WD Meat customers</td>
</tr>
</table>

Table 2 presents the SWOT (Strengths (linked to business success factors), Weakness (Current problems with food waste/financial loss etc), Opportunities (potential to use technologies to overcome problems, Threats (no solutions will lead to continuing financial loss; customer loss; threat from competitors) analysis for the WD Meats pilot company.

Table 2. WD Meats SWOT analysis.Strengths	Weaknesses
- Experienced team of butchers who can expertly dry-age meat - State of the art dry-aging facilities at scale, allowing for fulfilment of large orders from local, national, and international customers - High-quality meat that is sought after by customers - Established reputation internationally	- Parameter optimisation of temperature and humidity control during the dry-ageing process unknown, resulting in some dark facing trim loss - Potential presence of Clostridium Esterthеticum on the production line
Opportunities	**Threats**
- Adopting temperature and humidity tracking IoT technologies and processes for dry-ageing to reduce waste and increase efficiency - Expanding the customer base by marketing the unique dry-aged meat products	- Potential damage to brand reputation due to food waste incidents - Competition from other abattoirs offering similar dry-aging service but with less waste - Economic downturns that could decrease demand for high-end meat products - Fluctuating costs of raw materials and other inputs.

Outline of Solutions implemented

The REAMIT solution selected for WD Meats was the Ursalink's UC11-T1 LoRa sensor. This sensor was chosen due to its long transmission range, even in noisy environments, and low power consumption. It offers extended battery life, with some sensors achieving >8 years use on one battery. Housed in a plastic container, this sensor includes an external/protected humidity probe that is ideal for monitoring humidity and temperature in enclosed and humid areas. To ensure accurate readings, the humidity probe is equipped with a foam exterior to prevent saturation. Additionally, the sensor is IP67 protected, offering durability and resistance against environmental factors.

Four LoRa sensors were installed at WD Meats in one dry-ageing chamber and integrated with the Multi-Tech Conduit (MTCDT-AEP) LoraWAN gateway. The gateway acts as a configurable and scalable cellular communications gateway for industrial IoT applications. It is registered on TheThingsNetwork (TTN), a global collaborative Internet of Things ecosystem that creates networks, devices and solutions using LoRaWAN. This setup enabled the transfer of data collected by the sensor to the cloud. The collected data was then processed, stored in a database, and visualised on the REAMIT dashboard, providing valuable insights to WD Meats.

At WD Meats, the focus was on optimising the dry-ageing process, which involves a 21-day cycle to enhance the tenderness and flavour of premium beef cuts. The REAMIT team attached sensors to each side of the 40ft refrigerated chamber using double-sided Velcro for easy removal after the ageing period. They monitored the conditions during the ageing process and compared them to the trim loss experienced. They aimed to identify "ideal" parameters that would reduce the weight loss during the process while avoiding the formation of "dark-face" meat, which occurs when excessive moisture is drawn from the hindquarter and must be cut off or trimmed before sale, resulting in food waste. To overcome signal attenuation caused by the heavily insulated container with large quantities of meat, which would undoubtedly absorb much of the signal, the LoRa gateway was positioned as close to the dry-age chamber as possible. As the chamber was a 40ft refrigerated trailer, the gateway was mounted outside, securely placed in a waterproof box mounted to the palisade fencing in the parking lot near the trailer. The box had drilled holes for cable entry and antenna protrusion, and a cover ensured its waterproof protection.

Another area of recurring concern at WD Meats is the potential presence of *Clostridium Estertheticum* on the production line. This anaerobic bacterium, commonly found in the digestive systems of animals, including cows, poses a significant risk of meat spoilage. This bacterium can contaminate large quantities of meat during processing or handling, as it easily spreads. When present, *Clostridium Estertheticum* produces a strong and unpleasant odour, often referred to as "sour meat," and causes discoloration of the meat. Vacuum-packed meat is particularly susceptible to the growth of this bacterium, which can result in a condition known as blown pack syndrome, causing the expansion of the meat's packaging. Due to its ease of transmission on the production line, undetected Clostridium can spoil a significant amount of meat.

Currently, WD Meats employs a detection method that involves sending qPCR swabs to an external laboratory twice a week, with a turnaround time of approximately 48 hours. Additionally, on-site acid washes are conducted twice a week to eliminate bacteria. However, if Clostridium is detected in the lab, production is halted, and an immediate acid wash is performed. Therefore, WD Meats was interested in potential solutions from the REAMIT team to reduce the 48-hour detection window, enabling WD Meats to respond more swiftly to the presence of *Clostridium* bacteria, thereby minimising its impact on production and meat loss. By implementing such solutions, WD Meats aims to enhance their ability to detect and respond promptly to the presence of *Clostridium Estertheticum*, mitigating its negative effects on production efficiency and minimising potential meat loss. In search of combatting the clostridium issue, during the project WD meats purchased their own Genesig qPCR machine, allowing them to perform on-the-fly measurements of clotridum from samples taken in the factory. The qPCR machine was able to provide results within 1 hour.

Ulster University's lab scientists assisted WD Meats in validating their *clostridium estertheticum* controls for the Genesig machine. They prepared positive strains of clostridium and conducted tests on both Ulster's lab-grade qPCR machine and WD Meat's Genesig machine. The results confirmed that WD Meats' in-house equipment accurately detected the presence of clostridium, enabling on-the-spot site testing in the factory. This expert knowledge, support, and validation from Ulster's lab scientists empowered WD Meats to conduct their testing confidently.

Trial data

The correlation between dry-age chamber temperature and weight loss during the dry-age process was analysed using Matlab 2021b. Before and after weight measurements were taken on a set of hindquarters, alongside the corresponding dry-ageing temperatures. Figure 4 depicts the 14-day dry-age process.

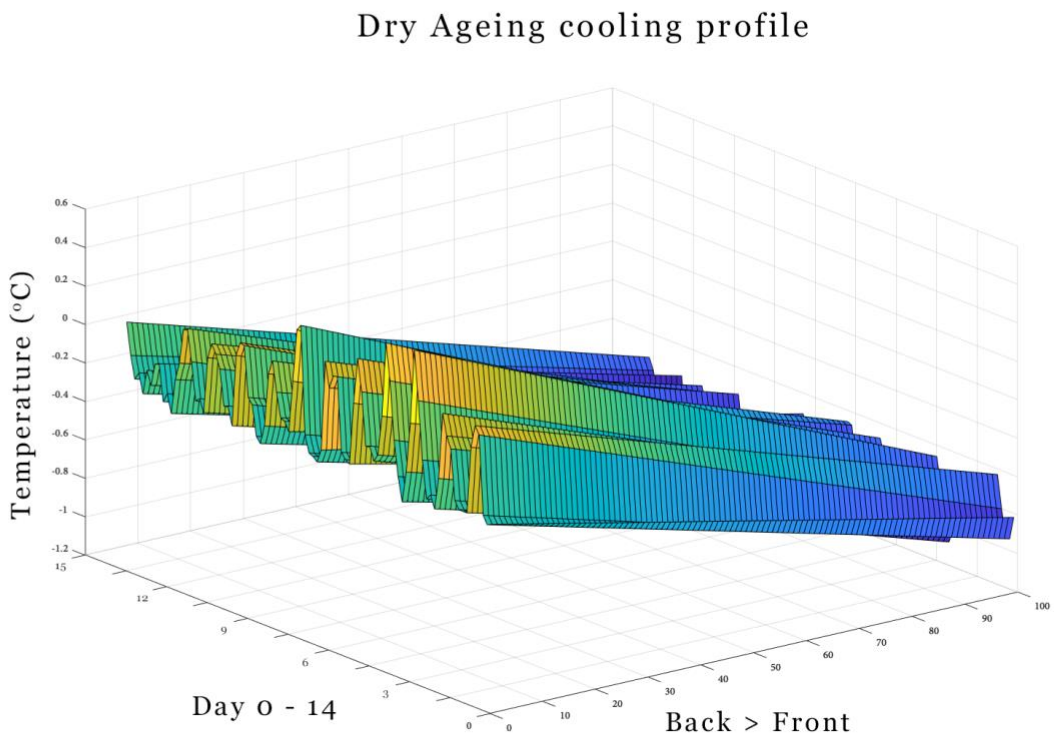


Figure 4. Dry ageing profile over a 14- day period.

The analysis revealed that there existed a distinct temperature gradient within the chamber. This gradient manifested as lower temperatures situated in proximity to the front of the chamber, where the refrigeration unit was positioned, as opposed to the rear. Delving into the specifics, the mean temperature recorded at the point nearest to the refrigerator was measured at -0.7954 (std 0.3274). In contrast, the mean temperature documented at the furthest point from the refrigerator, located at the rear of the chamber, was 0.0164 (std 0.3459).

The observed temperature differences between the front and rear of the chamber could be attributed to several factors inherent to the design and operation of the dry-ageing process and the chamber itself. One set of reasons centers on the chamber's design and operation, such as the positioning of the refrigeration unit at the front and the resulting temperature gradient as cooling systems tend to be more effective near their source. Additionally, airflow patterns, insulation discrepancies, and variations in thermal mass within the chamber may contribute to uneven temperature distribution. Frequent door opening and closing can also introduce fluctuations, impacting the front area due to its proximity to the entrance. These factors collectively create a complex interplay of cooling and heat transfer mechanisms. The second set of reasons pertains to the specifics of the cooling system and the chamber's geometry. Elements like the cooling system's capacity, design, and distribution, as well as the chamber's shape and dimensions, can influence how air circulates and heat is transferred. These variables may lead to localised cooling effects, resulting in temperature disparities.

The next step of the analysis was to compare the weights of the hindquarters located in the front half of the chamber with those in the rear half. Following the 14-day dry ageing period, results revealed that hindquarters situated in the cooler front section (adjacent to the refrigerator unit) exhibited a total weight reduction of 3.87%, whereas hindquarters located in the warmer rear portion experienced a total weight loss of 4.33%. The proximity to the refrigeration unit in the cooler front section aids in maintaining controlled temperatures and moisture retention, resulting in a lower weight loss percentage. Conversely, the warmer rear section experiences accelerated moisture evaporation due to higher temperatures, leading to a comparatively higher weight reduction. Additionally, airflow patterns and humidity levels, influenced by chamber design, impact moisture content. The interplay of temperature's effects on protein and fat structures, along with insulation properties, further contribute to the observed differences. Positioning of the meat within the chamber and the inherent characteristics of the dry-ageing process also play a role in shaping these weight loss behaviors.

Employing an ANOVA test to assess the statistical significance of weight variations between these storage areas, the test yielded a significance level of $P<0.05$, indicating that the distinctions in weight loss between the front and rear segments were statistically meaningful.

After establishing that there was a statistical difference between the weights and the temperature parameters during the dry age process, regression modelling was undertaken on the full dataset. Linear regression and tree models were tested, and 10-fold cross validation was used to validate the models. The best performing model used all the independent variables in the dataset, i.e. the statistical description of the temperature and humidity parameters and the zonal information relating to where the hindquarter was stored in the chamber. The linear regression performed best achieving an R-squared of 0.99 and an RMSE of 1.0534. The Predicted vs Actual plot of the linear regression is show in figure 8.

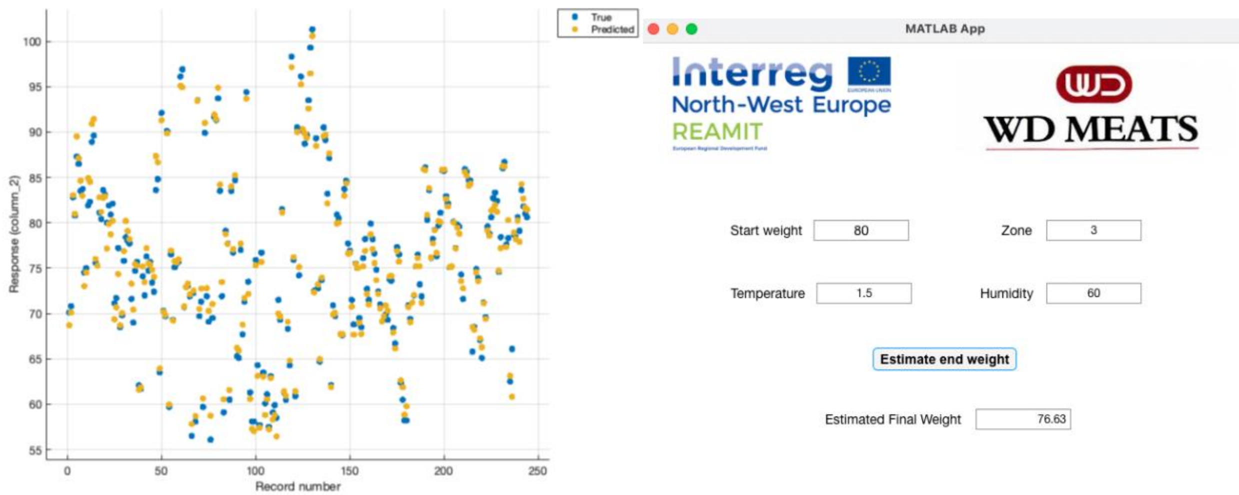


Figure 5. (left) Linear regression dry age weight loss; (right) regression model deployed as a predictive application.

Lessons learned

The pilot test at WD Meats yielded valuable insights and lessons for optimising the dry-ageing process. The sensor's selection was driven by its long transmission range, low power consumption, and extended battery life, making it suitable for monitoring temperature and humidity even in challenging environments. The integration of four LoRa sensors with the LoraWAN gateway facilitated data transfer to the cloud, enabling real-time monitoring and analysis through the REAMIT dashboard.

The correlation between dry-age chamber temperature and weight loss was analysed, revealing a significant temperature gradient from the front to the rear of the chamber. This discrepancy was attributed to a combination of factors, including the positioning of the refrigeration unit, airflow patterns, and insulation differences. Further analysis compared hindquarters' weights between the front and rear sections of the chamber. The results indicated notable weight differences, with hindquarters near the front experiencing lower weight loss than those at the rear. Then, using regression modelling, a prediction model was developed and deployed as a matlab application, allowing WD Meats to estimate the amount of weight loss which would occur given the start weight, temperature and humidity parameter the fridge was configured for, and the zone in which the hindquarter was stored. This knowledge opens avenues for refining the chamber's temperature distribution and crafting protocols that align with the commercial goals of WD Meats.

Overall, the pilot test demonstrated the effectiveness of the LoRa sensor-based solution in providing actionable data to optimise the dry-ageing process, offering potential benefits for minimising food waste and improving product quality. However, to gain statistical significance to any prediction tool created, more edge-case data would need collected by WD Meats including results from different configurations of the temperature and humidity parameters of the refrigeration unit.

2.2 Musgrave

Table 3 presents the Osterwalder Canvas to outline the pilot company, Musgrave's, business model.

Table 3. Musgrave Osterwalder Canvas

<table>
<tr>
<td rowspan="2">Partners
- 6th generation family-owned Irish business group</td>
<td>Activities
- Supporting hundreds of family businesses and local entrepreneurs through their supply chain and franchises.</td>
<td rowspan="2">Value Proposition
- Musgrave is Ireland's leading provider of food retail and wholesale brands, feeding 1 in 3 people across the island of Ireland every day.
- Sustainability is at the centre of their business strategy. Since its launch in 2017, Taking Care of Our World, has set out their People, Planet, Prosperity agenda and ambitions to be Ireland's most sustainable business.
- In 2019, the Irish government appointed Musgrave as a UN SDG Champion.</td>
<td>Customer Relations
- Provide customers with good quality food at a good price that is going to last a full shelf life.
- Working with B2B customers on quality issues, to reduce food waste and partnering with local charities for food donations to prevent wastage (e.g. FoodCloud).
- Local community focused and promoting social responsibly to drive change and initiatives to show the local communities it is important, why they're doing it and how it's going to impact everyone's future</td>
<td rowspan="2">Customer Segments
- ROI, NI & Spanish retail stores/ supermarkets

Food Service Customers:
- Restaurants
- Hotels
- Bars</td>
</tr>
<tr>
<td>Key Resources
- Own 11 market-leading and award-winning food retail and wholesale brands across ROI, NI & Spain
- Over 40,000 peoples employed in the group's business & brands
- Ireland's largest private sector employer</td>
<td>Channels
- Their own brands (SuperValu, Centra, Musgrave Market Place, Drinks Inc, MACE, Centra etc)
- Bars & Restaurants (6500 food service customers)</td>
</tr>
<tr>
<td colspan="3">Cost Structure
1 - Upgrading retail stores (€26 invested in Centra revamps)
2 - Staff Costs (€346.5m in 2019)</td>
<td colspan="2">Revenue Streams
- 11 owned brands in ROI, NI & Spanish markets and over 6500 food service customers</td>
</tr>
</table>

Table 4 presents the SWOT analysis for the Musgrave pilot company.

Table 4. Musgrave SWOT analysis.

Strengths	Weaknesses
-Strong reputation for high-quality, fresh produce -Established relationships with suppliers and customers -Experienced logistics team and infrastructure to manage transportation efficiently	-Breakdowns in refrigeration units during last mile cold chain transportation leading to food waste -Currently, no way of detecting if a breakdown has occurred during transportation -High volume of perishable goods increases the risk of spoilage and waste
Opportunities	**Threats**
-Leverage IoT temperature monitoring systems to provide real time monitoring and alerting to drivers and logistics staff if refrigeration failure occurs during deliveries	-Potential damage to brand reputation due to food waste incidents -Increasing competition in the market -Changing consumer preferences and demands for sustainable and low-waste products -Regulatory changes and stricter food safety standards

Outline of solution

The REAMIT solution for Musgrave relied on the Eagle datalogger (Digital Matter, South Africa). This logger stands out for its rugged design, boasting an IP67 rating and cellular IoT capabilities. It offers a versatile range of inputs, making it suitable for various IoT applications. The Eagle runs on either 4 x C Alkaline or Lithium Thionyl Chloride (LTC) batteries, or can be wired to permanent power (6-16 V DC). With I2C, SDI-12 and RS-485 interfaces, as well as 2 x analogue inputs, 3 x digital inputs, 2 x switched ground inputs, and 2 x 4-20 mA inputs, it supports seamless connectivity with a wide range of sensors.

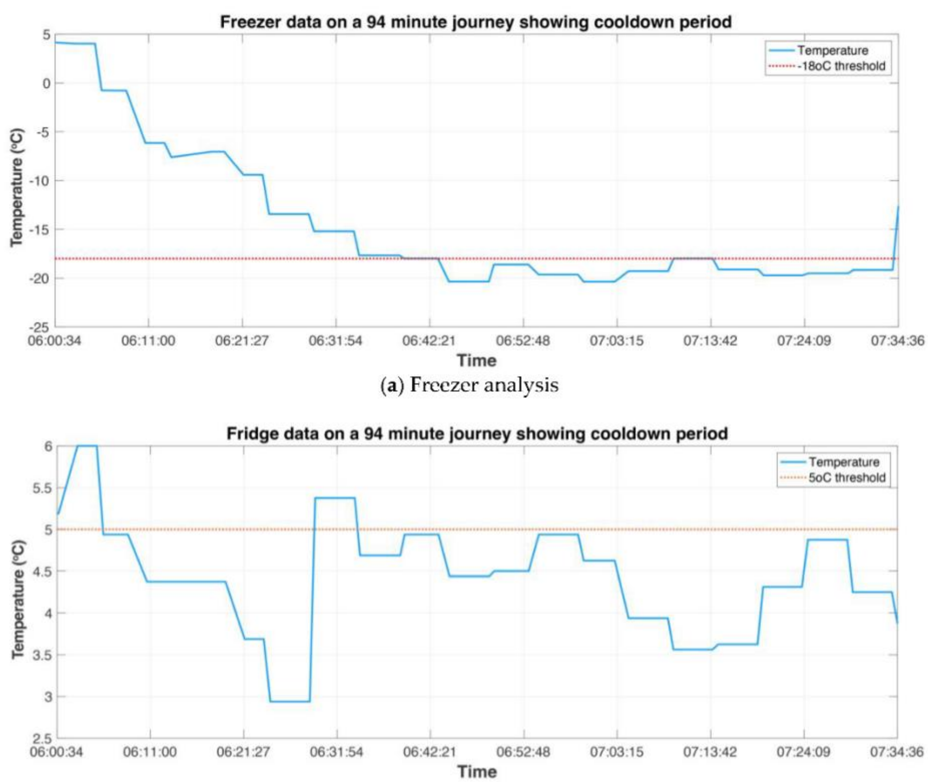
Additionally, the Eagle features an onboard GPS module and an accelerometer, enabling functionalities such as geofencing and movement detection. Its SIM card allows for connectivity to the IoT low power LTE-M (CAT-M1) network. The Eagle also offers third party cloud integration via HTTPS webhook, allowing for the convenient retrieval of recorded data for visualisation and analytics.

The Eagle was equipped with a T9602 temperature/humidity sensor and a DS18B20 temperature sensor allowing Musgrave to monitor both the chill and freeze compartments of their vans. The eagle had trip detection enabled, allowing the logger to enter sleep mode to reduce power consumption when the vehicle was not being driven. A web dashboard to Musgrave personnel was provided to allow for real time data monitoring, and text alerts were enabled to alert staff if temperature abuse was detected. The system was deployed in three last mile delivery vans at Musgrave NI, ensuring prompt identification of any anomaly.

Trial data

After 179 days of continuous operation, the three IoT loggers had cumulatively recorded 49,839 datapoints monitoring the chill and freeze zone conditions of the last mile delivery vans operated by Musgrave. To effectively deploy an alerting system that notified the company of refrigeration anomalies in the delivery vehicles, it was necessary to evaluate the cool-down period of the refrigerators, i.e., the amount of time that it took for the vans to reach the desired temperature. The reason for this was to avoid alerting during periods where no anomaly or malfunctioning was occurring, and the refrigeration units were merely cooling from ambient temperature to chill/freezing temperatures.

Using the data recorded by Musgrave during deliveries, a preliminary analysis was carried out to estimate the cool-down period length of the delivery vans. The desired temperatures the vans were to operate at were 5 °C in the fridge compartment and −18 °C in the freezer compartment. Analysis from the recorded data showed that it took approximately 35 min for the vans to appropriately cool down (Figure 6); thus, alerts should be configured in such a way that they were only sent after this initial period had passed. To do so, an alerting algorithm was implemented that only triggered the alerting system after 35 min.



(**a**) Freezer analysis

(**b**) Fridge analysis

Figure 6. Musgrave fridge and freezer cooldown period.

Lessons Learned

When monitoring ambient temperature within vans, careful consideration should be given to the chosen sensor's location. It's important to note that the chosen installation spot for the temperature probe can significantly affect the recorded ambient temperature, with fluctuations of up to +10°C. Through experimentation, it was found that the most accurate representation of ambient temperature within the van is at the 'air on' site of the refrigerator. This location is where the air is drawn back into the compressor after circulating throughout the entire van, providing a true reflection of the van's ambient temperature. By closely monitoring temperature conditions during food transportation, the company has gained a clearer understanding of the environment within the vehicles, ensuring that perishable goods are maintained within safe temperature ranges.

Additionally, the trip detection algorithm played a pivotal role in refining the accuracy of temperature alerts. By identifying when the vans were truly in transit, the algorithm helped eliminate false alarms that might have been triggered by the opening and closing of doors or temporary stops. It is also worth noting the sensitivity of the trip detection algorithm. The sensitivity is configurable by adjusting the time out between GPS readings. For Musgrave NI, the detection window was set at every 5 minutes, meaning this was the time between GPS location checks to detect if the van was in motion. This feature not only reduced unnecessary operational disruptions but also bolstered the company's confidence in the reliability of temperature alerts. However, if the system was deployed in a densely populated city with heavy traffic, it may be advisable for users to increase this parameter accordingly. By extending the window between trip checking, the system can ensure the accuracy of trip status even in the event of a traffic jam or congestion.

In addition, trip detection has increased battery performance significantly, extending the sensor's lifespan to approximately 6 months. However, its maintenance is still an issue especially when working with a large logistics company. To address this, we recommend considering the addition of external power sources to the loggers whenever possible. By incorporating external power, the maintenance window can be further reduced, alleviating the burden of frequent sensor maintenance.

2.3 Picnic

Table 5 presents the Osterwalder Canvas to outline the pilot company, Picnic's, business model.

Table 5. Picnic Osterwalder Canvas

<table>
<tr>
<td rowspan="2">Partners
- Joris Beckers and Frederik Nieuwenhuys (owners of fredhopper, software for webshops), Michiel Muller (entrepreneur), Bouke van der Wal (owner of Boni supermarkets), Gerard Scheij (retail entrepreneur)
- Edeka (german supermarket)</td>
<td>Activities
- Online only supermarket in Netherlands
-Developing and improving the mobile app and website
- Sourcing and purchasing high-quality groceries from suppliers
- Managing and maintaining a fleet of delivery vehicles and drivers</td>
<td rowspan="2">Value Proposition
- Convenient and affordable online-only grocery shopping delivered to your door
- Environmentally-friendly and sustainable grocery shopping practices
- Ability to choose your delivery time and location
- Quality customer service and easy-to-use mobile app</td>
<td>Customer Relations
- Personalised customer service through the mobile app and website</td>
<td rowspan="2">Customer Segments
- Customers looking for convenient and affordable grocery shopping options delivered to their door
- People who value sustainable and environmentally-friendly grocery shopping practices
- Customers who prioritise convenience over a wide selection of products</td>
</tr>
<tr>
<td>Key Resources
- Warehousing, distribution, and fulfilment centres
- Fleet of delivery vehicles and drivers
- A mobile app and website for customers to place orders and manage deliveries</td>
<td>Channels
- Mobile app and website for ordering and scheduling deliveries
- Direct mail and email marketing campaigns to reach target customers
- Word-of-mouth referrals and customer loyalty programs</td>
</tr>
<tr>
<td colspan="3">Cost Structure
1 - Maintenance and upkeep of delivery vehicles and equipment
2 - Warehousing, distribution, and fulfilment centres rental
3 - Website and mobile app maintenance costs; technology development costs</td>
<td colspan="2">Revenue Streams
- Sales of groceries and other products on the platform
- Delivery fees and other service charges</td>
</tr>
</table>

Table 6 presents the SWOT analysis for the Musgrave pilot company.

Table 6. Musgrave SWOT analysis.

Strengths	Weaknesses
- Picnic's focus on technology and innovation make them well suited for IoT trialling - Strong reputation for high-quality, fresh produce -Established relationships with suppliers and customers -Experienced logistics team and infrastructure to manage transportation efficiently	-Unknown optimal number of icepacks required to ensure perishable goods stay fresh, resulting in unnecessary amounts of ice being used for cooling. This is costing the company money. -High volume of perishable goods increases the risk of spoilage and waste
Opportunities	**Threats**
-Leverage IoT temperature monitoring systems to provide real time monitoring and alerting to drivers and logistics staff	-Potential damage to brand reputation due to food waste incidents -Increasing competition in the market -Changing consumer preferences and demands for sustainable and low-waste products -Regulatory changes and stricter food safety standards

Outline of Solutions implemented

To facilitate real-time data upload while the sensors were in motion in Picnic's trucks, REAMIT sought a suitable solution with LoRaWan connectivity as the Netherlands had a reliable network provided by KPN that covered the entire country. Elsys, a Swedish company, emerged as a suitable solution with their indoor LoRaWan room sensor (EMS), originally designed for measuring the indoor environment. The EMS sensor proved to be compact and well-suited for deployment in smaller spaces like cooling boxes within the trucks. It includes a comprehensive set of internal sensors for measuring temperature, humidity, acceleration, opening activity, and detecting water leaks. These capabilities ensured that a range of critical environmental factors could be monitored effectively.

Powered by a single 3.6 V AA Lithium battery, the EMS sensor has an expected battery life of up to 10 years, depending on configuration and environmental conditions. This extended battery life minimises the need for frequent battery replacements, contributing to cost savings and operational efficiency. The Elsys EMS sensor was available at an approximate cost of €65 / £57, while the 3.6 V AA Lithium batteries cost around €4 / £3.50. Elsys had previously collaborated with Whysor, a known supplier, for similar use cases, which further instilled confidence in their expertise and the suitability of their solution. The sensors work in partnership with the REAMIT cloud to ensure the recorded values are securely stored at periodic intervals. To conserve battery life, the sensors were configured to transmit data every 10 minutes at lower transmission speeds, striking a balance between real-time data capture and energy efficiency.

Trial data

The variation of temperature from Picnic cooling boxes are shown in Figure 7 for the period from 1st April 2022 until 9th August 2022. It was noted that there were much larger fluctuations in temperature in April compared to August (summer).

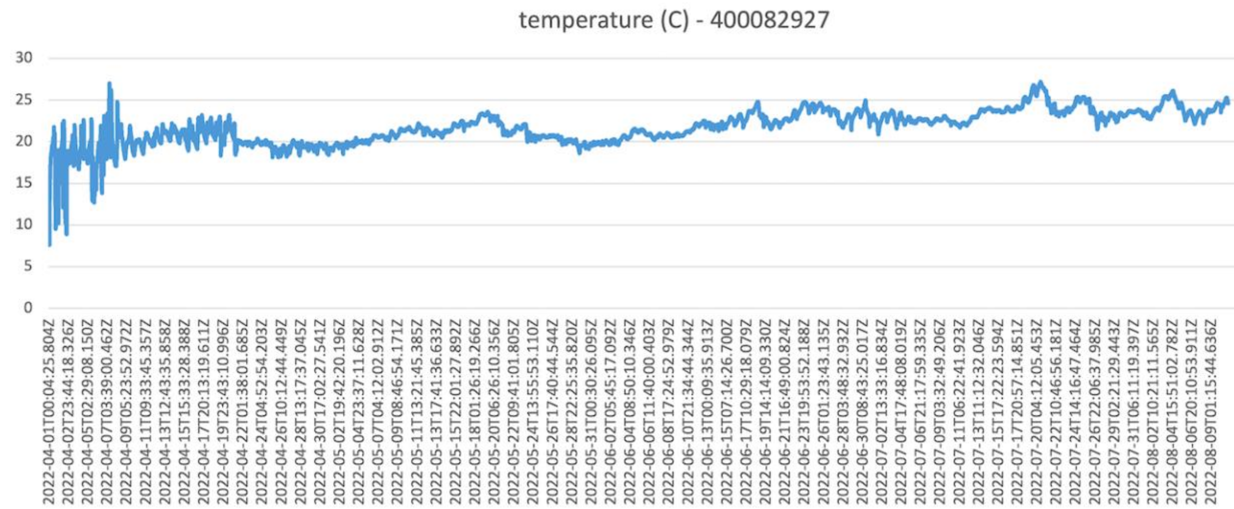


Figure 7. Musgrave fridge and freezer cooldown period.

To understand the main reasons behind this result a Statistical Process Control (SPC) and Process Capability Analysis (PCA) was performed based on the temperature data inside the vehicle. It was observed that the process capability has improved significantly between April 2022 (Avg. Cp = 1.24) and August 2022 (Avg. Cp = 7.9), indicating that the temperature control practices employed by Picnic have evidently been refined, facilitating a more adept alignment with requisite standards and specifications. The real-time monitoring systems employed by REAMIT might have enabled prompt interventions during temperature anomalies and contributed to the observed enhancement. Those interventions could include optimised packing arrangements to facilitate better airflow and heat distribution within the cooling boxes. Calibration and fine-tuning of cooling mechanisms, such as refrigeration units. Furthermore, the cultivation of a culture of continuous improvement, possibly involving feedback loops from drivers, quality control teams, could have played a role in driving these improvements.

This progress not only fortifies their ability to safeguard the quality and integrity of transported goods but also resonates with their commitment to elevating customer satisfaction. Through a blend of data-driven insights and diligent improvements, Picnic's pursuit of operational refinement continues to elevate their standing in ensuring the optimal journey of goods within their cooling boxes.

Lessons learned

Incorporating real-time monitoring analysis, such as the one implemented by REAMIT, into the operational framework of like Picnic offers a valuable means to assess and uphold the dependability of the cooling process. This analysis, combined with alerting mechanisms, constitute a robust toolkit for Picnic's operations. This deployment entails several significant benefits for the company, including enhanced monitoring capabilities, heightened responsiveness, augmentation of customer satisfaction and trust, reduction in costs, improved planning, adherence to legal and regulatory requirements, and the creation of new business opportunities.

In this example, the analysis was limited to local (offline) calculations, however frameworks exist to integrate and automate SPC analysis with real-time sensor readings. Future work could examine developing online SPC analysis as a feature of the Whysor platform.

2.4 Yumchop

Table 7 presents the Osterwalder Canvas to outline the pilot company, Yumchop's, business model.

Table 7. Yumchop Osterwalder Canvas

<table>
<tr>
<td rowspan="2">Partners
- Co-owned by Abi and Michael Adefisan</td>
<td>Activities
- Creating home styled frozen ready meals that are authentic and bursting with African flavours</td>
<td rowspan="2">Value Proposition
- Home styled ready meals with no added preservatives, flavourings, or colours, bursting with African flavour
- All products are Halal compliant
- Flash frozen to preserve taste, texture, and quality</td>
<td>Customer Relations
- Comes with easy-to-follow instructions, pre-portioned meals ensuring a stress-free mealtime for you.
-Customer is in control of the subscription, allowing changes to meals from month to month, pausing or cancelling for free</td>
<td rowspan="2">Customer Segments
- Geographic market within 15 miles of Milton Keynes for subscription delivery
- General public based close to vending machine locations
- Mass market – Sainsburys supermarket</td>
</tr>
<tr>
<td>Key Resources
- 10 Workers
- Production facility in Towcester UK
-Vending machines located in high-density areas</td>
<td>Channels
- Vending machines located in high-density areas (Imperial college London, NHS)
-Online sales (subscription-based plan)
- Supermarkets (Sainsburys UK)
- Local shops (university of Essex).</td>
</tr>
<tr>
<td colspan="3">Cost Structure
1 – Rolling stock – cost of raw materials to produce meals
2 – Equipment and maintenance (factory based; transport based)
3 – Health and safety requirements (eg processing staff apparel)</td>
<td colspan="2">Revenue Streams
- Direct sales to customers through vending machines in high density areas and supermarkets
- Subscription sales of home-delivery ready meals</td>
</tr>
</table>

Table 8 presents the SWOT analysis for the Yumchop pilot company.

Table 8. Yumchop SWOT analysis.

Strengths	Weaknesses
-Unique flavoured range of African themed ready meals -High-quality ingredients used in the ready meals -Established relationships with suppliers and customers -Efficient production process that allows for quick turnaround times	-Breakdowns in refrigeration units during storage leading to food waste -Currently, no way of detecting if a breakdown has occurred -High volume of perishable goods increases the risk of spoilage and waste
Opportunities	**Threats**
-Leverage IoT temperature monitoring systems to provide real time monitoring and alerting to staff if refrigeration failure occurs at production site	-Potential damage to brand reputation due to food waste incidents -Increasing competition in the market -Changing consumer preferences and demands for sustainable and low-waste products -Regulatory changes and stricter food safety standards

Outline of Solutions implemented

The challenge at Yumchop Foods revolves around the need to monitor temperature and humidity in real time across 10 different zones within their factory. To address this, the REAMIT team proposed using traditional temperature sensors to help ensure proper storage of frozen food, gather data on the conditions in which the food is stored and transported, and maintain the optimal temperature in Yumchop Food's vending machine at Victoria Coach Station in London. Whysor, the technical partner, assessed the company's needs and recommended the implementation of 10 ELT Lite loggers and 10 digital temperature sensors from ELSYS in Sweden, along with a Multitech LoRaWAN gateway for communication.

The equipment was purchased by BED and delivered to Whysor's office for configuration in mid-June 2021. In September 2021, during a visit to Yumchop Foods' factory, Whysor installed the 10 sensors and a gateway in various locations, including freezers, fridges, and other relevant zones. To meet the specific needs of the company's owners, thresholds values were set on all sensors, specifying the desired temperature ranges and triggering alerts in case of any deviations.

In addition to the hardware installation, Whysor also created a dashboard for Yumchop Foods, accessible to key staff members. The dashboard provides real-time temperature information through visualisations such as gauges, line charts, and bar graphs. This intuitive interface allows for easy monitoring and quick identification of any anomalies in the 10 zones where the REAMIT sensors have been deployed.

Trial data

In this pilot test, despite that anomalies had been identifyed, none of them yielded significant interpretability. Therefore, the focus shifted towards designing tools to effectively describe the data and explore recurring patterns and atypical occurrences using the matrix profile algorithm. Figure 8 presents the resulting output of this analysis, capturing the data patterns for each sensor and highlight any deviations from those patterns, hence being useful for exploratory data analysis.

Figure 8. Yumchop temperature fluctuations.

For sensors placed in refrigerators, the motif that typically appears as the second pattern in the matrix profile is likely indicative of a defrost operation. In other words, this recurring pattern in the data could be a sign that the refrigerator's defrosting mechanism is activated during those instances, leading to certain changes in temperature or other parameters that can be detected and interpreted through the analysis of the collected sensor data. Figure 9 presents instances of this motif.

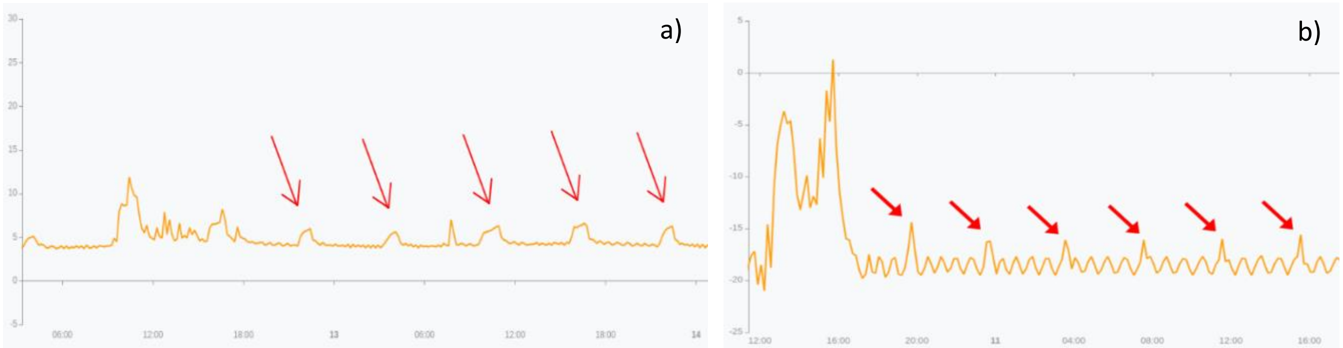


Figure 9. Examples of recurring patterns found in Yumchop sensors data at (a) fridges, (b) freezers.

The consistent occurrence pattern observed in Figure 9 (a) indicates that a defrost operation typically takes place every 6 hours under normal circumstances. In essence, this enables the company to predict the timing of the next defrost operation unless any external event disrupts this pattern. Likewise, when considering sensors placed in cold room freezers (b), the consistent motifs observed likely reflect the effects of defrost operations on temperature, but in this particular context, these motifs tend to occur approximately every 4 hours.

Additionally, it is worth noting that occasionally, atypical discordant patterns like the one observed at the beginning can be found in the data. These patterns are likely a result of significant movements within the cold room and prolonged instances of open doors. These instances underscore the sensitivity of the analysis to external events that influence temperature variations.

Lessons learned

The analysis conducted in this pilot test has yielded several valuable lessons. The matrix profile algorithm emerged as a powerful tool for the identification of anomalies and recurring patterns, capturing data for each sensor and highlighting deviations.

In particular, the recurring pattern indicating the activation of the refrigerator's defrosting mechanism provides crucial insights into the temporal aspects of defrost cycles. For instance, the pattern's recurrence every 6 hours in one case, and approximately every 4 hours in another, enables predictive capability and empowers the company to anticipate and manage defrost operations more effectively.

In essence, this pilot test has underscored the potency of the matrix profile algorithm in uncovering hidden patterns and regularities within sensor data, thereby enhancing the company's ability to predict and manage crucial operations such as defrost cycles and the increase in temperature that can be harmful to the maintenance of food quality. The insights derived not only refine operational strategies but also emphasise the potential for advanced data-driven decision-making in maintaining optimal conditions and ensuring quality across various settings within the company's operational landscape.

2.5 Human Milk Foundation (HMF)

Table 9 presents the Osterwalder Canvas to outline the pilot company, HMF's, business model.

Table 9. HMF Osterwalder Canvas

<table>
<tr>
<td rowspan="2">Partners
- Charity co-founded by Natalie Shenker and Gillian Weaver</td>
<td>Activities
- Human milk bank which arranges the collection, transportation, treatment, storage and delivery of donor milk to hospitals and neonatal care units following the highest safety and quality standards.</td>
<td rowspan="2">Value Proposition
- Provide safe, pasteurised donor human milk to premature infants and babies with medical conditions who are unable to receive their mother's milk.</td>
<td>Customer Relations
- Providing a safe, convenient way for mothers to donate their excess milk
- Building trust with NICUs, hospitals, and birthing centres by providing safe, pasteurised donor milk
- Continuing to communicate the importance of donor milk to recipient families</td>
<td rowspan="2">Customer Segments
- Neonatal intensive care units (NICUs)
- Hospitals and birthing centres
- Mothers with excess milk production
- Donor milk recipients (babies and families)</td>
</tr>
<tr>
<td>Key Resources
- Access to donated human milk
-Qualified and trained staff for milk processing and distribution
-Medical-grade milk pasteurisation equipment
-Transportation and storage facilities for donor milk</td>
<td>Channels
- NICU and hospital partnerships
- Outreach programs to mothers with excess milk production
- Online presence and social media to reach potential donors and recipients</td>
</tr>
<tr>
<td colspan="3">Cost Structure
1 - Milk processing and distribution equipment and supplies
2 - Staff salaries and training costs
3 - Storage and transportation expenses
4 - Operational costs such as marketing and outreach</td>
<td colspan="2">Revenue Streams
- Donations from individuals, foundations, and corporations</td>
</tr>
</table>

Table 10 presents the SWOT analysis for the HMF pilot company.

Table 10. HMF SWOT analysis.

Strengths	Weaknesses
- High demand for human milk products due to their benefits for premature babies and infants with medical conditions -Strong relationships with healthcare providers and hospitals that refer customers to the facility -Robust quality control measures in place to ensure safe and high-quality products -Experienced and knowledgeable staff with expertise in milk production and handling	-No indication if temperature during transportation is close to broaching safety thresholds at present, thus caution is exercised in transport -Maximum transportation distance unknown as no temperature logging is performed during transport -Some customers having to be turned down based on location because milk freshness cannot be guaranteed at present -Limited production capacity due to the nature of the product and sourcing of donor milk -Potential for regulatory challenges and changes in the industry
Opportunities	**Threats**
-Leverage IoT temperature monitoring systems to provide real time monitoring and alerting to drivers and logistics staff if temperature abuse occurs during deliveries -Produce ML model based on transport temperature data to estimate maximum journey time	-Potential damage to brand reputation due to food waste incidents -Increasing competition in the market -Changing consumer preferences and demands for sustainable and low-waste products -Regulatory changes and stricter food safety standards

Outline of Solution implemented

After analysing the current business operations at HMF, the REAMIT team recognised the need to implement a system to record temperature data inside human milk bags during transportation. The objective was to minimise milk waste and ensure that the transportation conditions were conducive to maintaining the quality and safety of the milk. With this goal in mind, the REAMIT technical partners selected 10 cellular Digital Matter Eagle loggers for deployment at HMF. Each logger was equipped with a temperature and humidity sensor (Amphenol T9602 T/RH) for monitoring the real-time transportation conditions. Additionally, a binary sensor was incorporated into each logger to monitor the status of the milk bags. The equipment was assembled and connected to the internet, becoming visible in the Whysor dashboard for the Human Milk Foundation.

In May 2022, the loggers, temperature sensors, and binary sensors were installed at the Human Milk Foundation. Initially, the loggers were programmed to report temperature data every 5 minutes. However, it was determined that taking measurements while stationary was unnessararily drawing battery power. The sensors were reconfigured to record data every 5 minutes while in motion (performing a delivery), and upload a ‘heartbeat’ signal of one sensor reading to the cloud every 12 hours when there was no motion detected. Real-time monitoring and alerting mechanisms were implemented to ensure that timely information on the status of the bags were received whenever motion was detected, enabling proactive measures to be taken to preserve the quality and safety of the milk. This system not only helped minimise milk waste but also contributed to the overall mission of the Human Milk Foundation to ensure that human milk is delivered to infants in the best possible condition.

Trial data

Various modelling approaches were employed to develop the predictive models, namely, linear regression, decision trees, random forest, and neural networks. Each model was trained using the prepared dataset, and their predictive performance was evaluated using the test dataset. The performance was quantified with several statistical measures, such as R2 and Root Mean Squared Error (RMSE). For the linear model, Variance Inflation Factor (VIF), Durbin Watson Test, F score, and P value were also checked. Table 11 presents the results from each of these models.

Table 11. HMF pilot test statistical analysis.

	R2	RMSE (°C)	VIF	Durbin Watson	F-score	p-value
Linear regression	0.7396	0.7242	Time: 1.3760 Temp. Outside 1.5497 Quantity of milk 1.7531 Car: 1.3778 Size of bag (big): 1.4931 Size of bag (small): 1.4466		550.5	< 2.2e-16
Decision trees	0.8721	0.5332	Not applicable			
Random forest	0.9673	0.3585	Not applicable/ Non-linear			
Neural networks	0.9514	0.3099	Not applicable/ Non-linear			

According to the results, random forest and neural network based models provided the best accuracies. Placing a preference on the R-squared value, the random foest model was chosen for the final prediction task. An application was designed (Figure 10) based on the data collected from the temperature sensors installed by the project. The app can be used to predict the maximum trip duration and the maximum distance the human milk can be transported. The user needs to input the value of external parameters for the journey, such as the temperature outside (°C), the quantity of milk (L), the type of vehicle (car or bike), the average speed of the vehicle (km/h), and the size of the bag.

The app was created using R Shiny, a web application framework for R programming language. The codebase includes an app.R script, which is responsible for creating the user interface and establishing the connection with the trained prediction model in the backend.

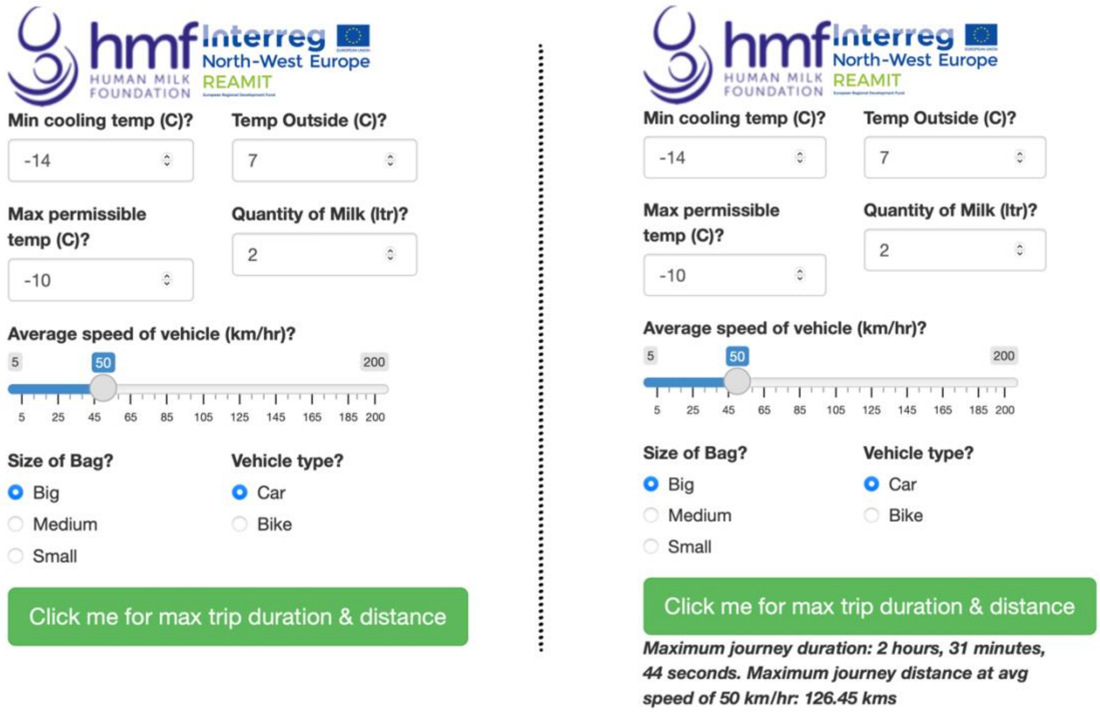


Figure 10. REAMIT app for human milk transportation prediction.

Lessons learned

The development of the application stands as a transformative innovation with profound implications for the operations of a human milk banks that can expanded to different food products in the future. This pioneering application is specifically tailored to address a critical need within the context of human milk transportation, offering predictive insights that streamline decision-making processes and increase the overall efficacy and impact of the pilot company.

The application's core function revolves around predicting two parameters with a high degree of accuracy: the maximum trip duration and the maximum distance for human milk transportation. Through this predictive lens, the company gains the ability to strategise its transportation endeavors with an acute awareness of the operational limitations and potential challenges associated with each journey.

Moreover, the application’s role extends beyond mere logistical planning. It directly contributes to the preservation of the vital properties of human milk. By accurately estimating the maximum trip duration and distance, the application plays a pivotal role in maintaining the integrity of the milk’s temperature-sensitive composition. This, in turn, ensures that the milk reaches its destination in the best possible condition, retaining its nourishing properties and minimising any potential compromise to its quality.

Beyond operational and quality considerations, this application holds the potential to significantly optimise resource allocation. The predictive insights it offers empower the human milk bank to allocate resources judiciously, ensuring that transportation efforts are not just efficient but also aligned with sustainability and cost-effectiveness. It marries cutting-edge technology with a deep understanding of the operational intricacies, safeguarding both the efficiency of transportation and the quality of the milk itself. As an invaluable tool, it not only streamlines decision-making but also upholds the organization’s mission of delivering the highest quality nourishment to those who need it most.

2.6 Burns Farm Meats (BFM)

Table 12 presents the Osterwalder Canvas to outline the pilot company, BFM's business model.

Table 12. BFM Osterwalder Canvas

<table>
<tr>
<td rowspan="2">Partners
- Burns family (100%)</td>
<td>Activities
- Abattoir which handles all stages of process
- Killing, prepping, dry ageing, cutting, packaging
- Customer facing butcher shop
- Delivers to local shops, restaurants, customers in 35km radius</td>
<td rowspan="2">Value Proposition
- Proximity meat products from locally raised and cared for animals.
- Dry-ageing of meat that enhances the quality and tenderness of beef.</td>
<td>Customer Relations
- Long-established family business that has grown its reputation and reliability locally by customer's word of mouth over the years - both for the quality of the meat and their abattoir services.
- Emphasis on the proximity of meat and good care of animals raised on their farm.
- Sale and delivery of high-quality meat products at competitive prices to the public, restaurants and retail.</td>
<td rowspan="2">Customer Segments
-Farmers (dry ageing service)
-Irish shops
- Restaurants
- Hotels
- Burns Meat butchery</td>
</tr>
<tr>
<td>Key Resources
- 5-10 Workers
- Plant
- Cattle provided by farmers
- Cattle direct from Burns Farm</td>
<td>Channels
- Burns Farm customer-facing butcher shop
- Local restaurants, hotels, and shops</td>
</tr>
<tr>
<td colspan="3">Cost Structure
1 - Rolling stock - cattle purchased from farmers
2 - Equipment and maintenance (factory based; transport based)
3 - Health and safety requirements (e.g. processing staff apparel)</td>
<td colspan="2">Revenue Streams
- Fresh meat product sales based on:
- Individual contracts with Burns Meat customers
- Public facing butcher shop</td>
</tr>
</table>

Table 13 presents the SWOT analysis for the BFM pilot company.

Table 13. BFM SWOT analysis.

Strengths	Weaknesses
-Experienced team of butchers who can expertly dry-age meat -High-quality meat that is sought after by customers -Established reputation in the local community -On site parameter controlled dry-aging chambers	-Inadequate temperature and humidity control during the dry-ageing process resulting in a high-percentage dark facing trim loss
Opportunities	**Threats**
-Adopting new IoT monitoring technologies for dry-ageing to reduce waste and increase efficiency -Expanding the customer base by marketing the unique dry-aged meat products	-Potential damage to brand reputation due to food waste incidents - Competition from other abattoirs offering similar dry-aging service but with less waste -Economic downturns that could decrease demand for high-end meat products -Fluctuating costs of raw materials and other inputs.

Outline of solution

For the pilot project with Burns Farm Meats, traditional sensor technology was chosen to monitor temperature and humidity in their two refrigeration chambers used for dry aging beef. Considering the requirements of the company, the REAMIT team opted for the Ursalink UC11-T1 sensor previously used for a similar purpose. However, due to its unavailability at the time, an alternative sensor, the Elsys ELT-2 Internal Antenna sensor, was selected. The ELT-2 had integrated temperature and humidity sensors and transmitted data via LoRa signal to a Kona Micro IoT Gateway (Tektelic, Canada) installed on-site. The decision to opt for the Elsys ELT-2 sensor was based on several factors. Firstly, its installation and configuration processes were straightforward, ensuring a smooth implementation. Additionally, its compact size and waterproof design made it suitable for the refrigeration chamber environment. Furthermore, Whysor already had experience working with Elsys sensors, which streamlined the integration process and reduced potential complications.

The Kona Micro IoT Gateway played a critical role in the data communication process. It served as the intermediary device that collected the sensor data and transmitted it to the processing layer for analytics and alerting. To provide convenient access to real-time data and enable effective monitoring, a user-friendly application was developed for real-time data access. This application allows Burns Farm Meats personnel to access the temperature and humidity data, receives alerts via SMS or email, and generates reports for documentation. In terms of sensor placement, six sensors were deployed in the larger chill room, strategically positioned at the front, middle, and back, while four sensors were placed in the smaller chill room. Careful consideration was given to the height of the sensors to avoid any interference with the meat or other objects in the chamber.

Trial data

Following sensor installation, by continuously collecting data, the deployed sensors were able to identify potential issues or deviations that could lead to food spoilage by comparing each newly acquired environmental reading to a predefined safety threshold value. This way, real-time monitoring enables swift corrective actions, ensuring the quality and safety of food products.

In the context of this pilot test, and to best adapt to Burns Farm Meats operations and procedures, the alerting system had to be such that it would not send alerts repeatedly at times when they were aware that the chambers were not at their adequate temperature, e.g., they were carrying out cleaning, loading or unloading procedures and the door of the chamber would remain open, leading to an increase of temperature inside. In some instances, it could also be that the refrigerator had been turned off as the chamber was not in use – this mainly concerned the smaller chamber.

For this reason, the REAMIT team decided to install door contact switch sensors on the doors with the purpose of refining the logic of the alerting system. The first of the two alerts that was pilot tested was designed to alert of anomalies while the door of the chamber was closed (Figure 11a). In this case, the temperature threshold selected was 5°C and it had to be recorded consecutively 6 times by 3 different sensors. By implementing an "AND" logic, the team would avoid alerting if the selected sensor was malfunctioning. While that could also lead to not alerting. A second alert was also designed to signal potential issues while the door remained open (Figure 11b).

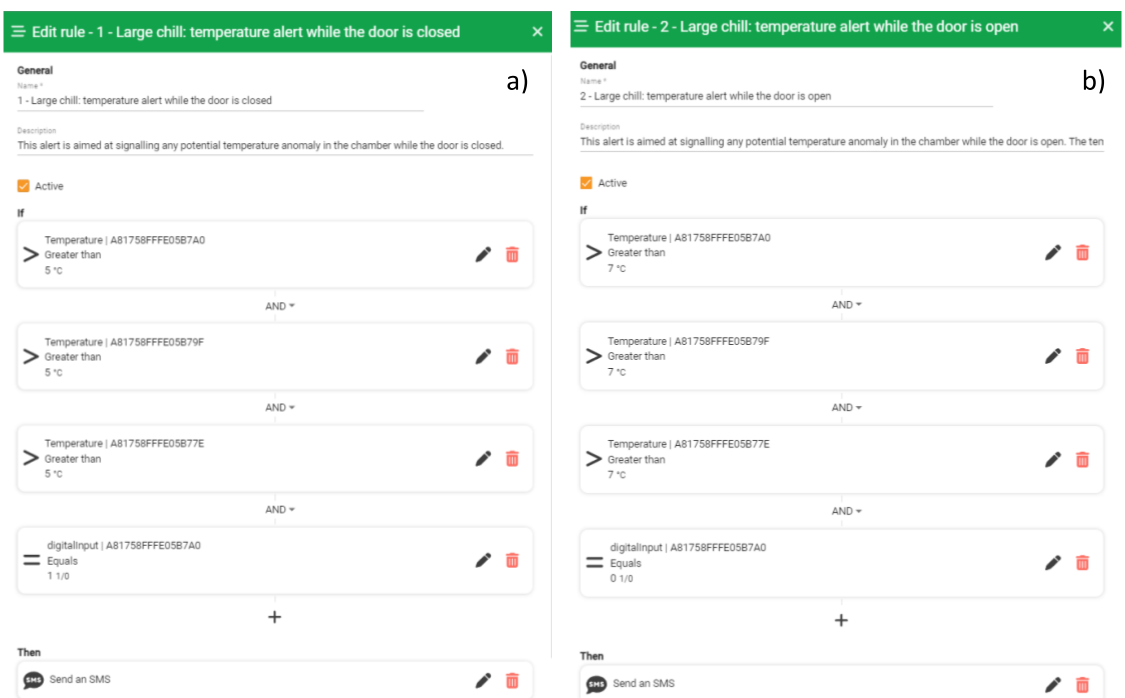


Figure 11. Temperature alert while the door is (a) closed, (b) open.

Lessons Learned

During the implementation of the sensor system at Burns Farm Meats, the REAMIT team encountered two main challenges that required attention and innovative solutions. The first challenge was related to the alerting system, as staff had to open the refrigeration chamber doors for loading/unloading meat or cleaning. This led to unnecessary notifications and made it difficult for staff to differentiate between genuine environmental anomalies and routine door operations. To address this, an external magnetic switch was added to one of the sensors. This switch was strategically placed near the door of the refrigeration chamber and detected whether the door was open for a certain duration before sending alerts. Through the addition of this switch, the system could distinguish between routine door openings and actual temperature or humidity deviations that required attention. This improvement ensured that staff members were only alerted when there was a genuine concern, reducing the number of false alarms and improving the efficiency of the alerting system.

The second challenge was faced during the data analytics phase of the project. The REAMIT team realised that to gain deeper insights into food loss and refrigeration unit performance, additional data, such as weights, were needed to link temperature and humidity recordings to food loss and refrigeration unit performance. This data would provide valuable context and enable more accurate analysis of the environmental conditions during different stages of the meat storage process. Discussions were held with Burns Farm Meats to explore the possibility of collecting weight data alongside the monitoring dashboard. This information would be instrumental in identifying any correlations between environmental conditions and potential food loss, as well as evaluating the performance of the refrigeration units.

In addition, concerns were raised about the accuracy of humidity readings from the internal probes of the ELT-2 sensors. It was suggested that future work would be needed to validate the humidity readings and explore alternative sensors or external probes for more accurate humidity monitoring. Moving forward, the team's commitment to validating humidity readings and exploring alternative sensors will further enhance the accuracy and reliability of the data collected, ensuring the system's effectiveness in monitoring and preserving the quality of the stored meat at Burns Farm Meats.

2.7 Biogros

Table 14 presents the Osterwalder Canvas to outline the pilot company, Biogros's business model.

Table 14. Biogros Osterwalder Canvas

<table>
<tr>
<td rowspan="2">Partners
- Local organic farmers</td>
<td>Activities
- Sourcing and purchasing organic products from local farmers
- Quality control and product testing
- Inventory management and warehousing
- Distribution of products to retail locations (a Biogros subsidiary) and wholesale customers
- Marketing and promotion of organic products</td>
<td rowspan="2">Value Proposition
- High-quality organic products
- Support for local farmers and sustainable agriculture
- Reliable and efficient distribution to retail locations and wholesale customers</td>
<td>Customer Relations
- Collaborating closely with local organic farmers to maintain a transparent and mutually beneficial partnership, ensuring a consistent supply of high-quality organic products.</td>
<td rowspan="2">Customer Segments
- Retail grocery stores
- Wholesale buyers such as restaurants, cafes, and hotels
- Health food stores and specialty markets
- Individual consumers interested in organic and sustainable products</td>
</tr>
<tr>
<td>Key Resources
- Warehouse and storage facilities
- Transportation fleet for delivery of products
- Skilled workforce for quality control, product testing, and distribution</td>
<td>Channels
- Direct sales to retail locations and wholesale customers
- Online ordering and delivery</td>
</tr>
<tr>
<td colspan="3">Cost Structure
1 - Sourcing and purchasing organic products
2 - Quality control and product testing
3 - Warehouse and storage facilities
4 - Transportation and delivery costs</td>
<td colspan="2">Revenue Streams
- Sales of organic products to retail locations and wholesale customers</td>
</tr>
</table>

Table 15 presents the SWOT analysis for the Biogros pilot company.

Table 15. Biogros SWOT analysis.

Strengths	Weaknesses
-Strong reputation for high-quality, fresh produce -Established relationships with suppliers and customers -Experienced logistics team and infrastructure to manage transportation efficiently	-Breakdowns in refrigeration units during last mile cold chain transportation leading to food waste -Currently, no way of detecting if a breakdown has occurred during transportation -High volume of perishable goods increases the risk of spoilage and waste
Opportunities	**Threats**
-Leverage IoT temperature monitoring systems to provide real time monitoring and alerting to drivers and logistics staff if refrigeration failure occurs during deliveries	-Potential damage to brand reputation due to food waste incidents -Increasing competition in the market -Changing consumer preferences and demands for sustainable and low-waste products -Regulatory changes and stricter food safety standards

Outline of Solutions implemented

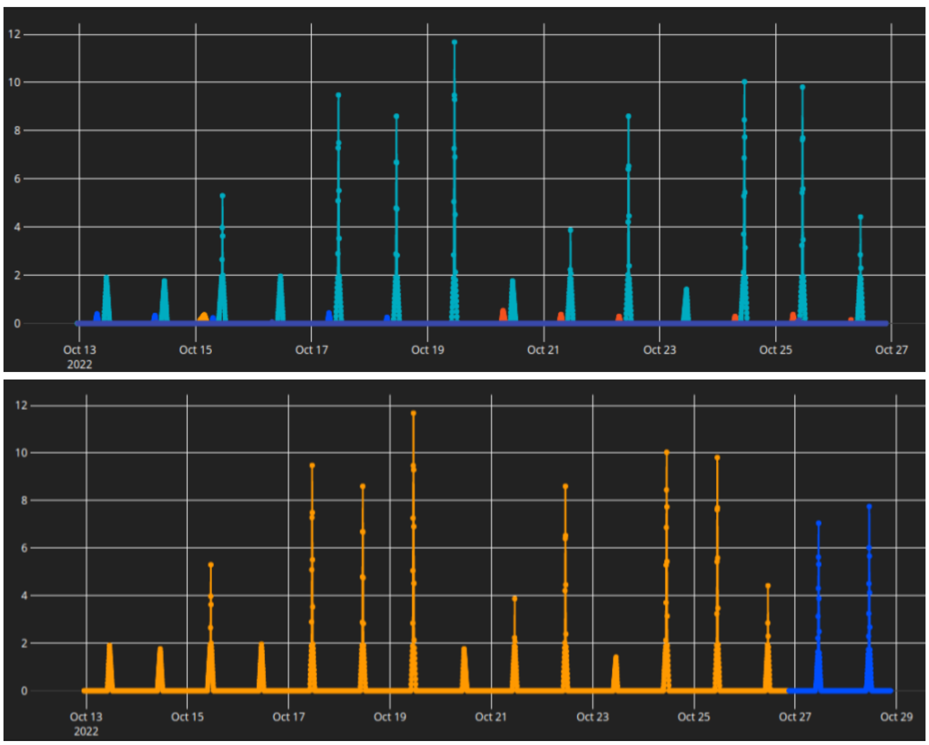
The implementation of the real-time monitoring and alerting system for Biogros' supply chain by the REAMIT team involved the selection of suitable devices and sensors to ensure accurate data collection and effective communication. The Whysor team opted for cellular loggers from Digital Matter (South Africa), specifically the Eagle device, which uploads data to the cloud using a 4G connection much like a mobile phone. These loggers detect whether a truck is moving or stationary (trip-detection) and adjust the sending and measuring frequency accordingly, conserving battery life and optimising data transmission efficiency. The loggers store measurements locally and periodically transmit the collected data to the REAMIT cloud. Temperature and humidity sensors (1.8m T9602 T/RH I2C probe) from Amphenol (USA) were fitted into the loggers for monitoring ambient and chilled zones.

The data is stored in the REAMIT cloud and made available for analysis and visualisation through the Whysor dashboard. To ensure comprehensive monitoring and effective management of the supply chain, 5 dashboards were created to provide real-time insights and visibility. These dashboards catered to different stakeholders, including trucks, the Biogros warehouse, and individual farmers. Alerts were set up based on temperature thresholds, notifying relevant personnel in case of any temperature anomalies that could potentially compromise the quality or safety of the transported goods. To reduce the number of unnecessary alerts, trip detection was added as an additional condition for truck alerts. This condition ensured that alerts were only triggered when temperature deviations occurred during active transportation, further enhancing the accuracy and relevance of the alerts.

The REAMIT-analytics team analysed the data and developed an anomaly prediction model to aid the company's efforts in reducing food waste. This model leveraged algorithms to identify patterns and anomalies in the temperature and humidity data. By predicting potential issues in advance, Biogros could take proactive measures to mitigate risks, optimise their supply chain operations, and reduce food waste.

Trial data

Figure 12 (a) illustrates the plotting of data captured by temperature sensors in selected warehouses over a specific time period. The anomaly score is computed for each temperature time series by utilizing the logical ranges provided in the metadata of the time series. These scores effectively curate the time series data, enhancing the applicability of machine learning models. An example of this is depicted in Figure 12 (b), showcasing the plotting of the results generated by a forecasting model. Notably, this model demonstrates a clear seasonal forecasting pattern.



a)

b)

Figure 12. Data captured (a) by temperature sensors in selected warehouses, (b) by a forecasting model.

The analysis has revealed seasonal forecast patterns in the anomaly score for certain static sensors, indicating cyclical instances where the temperature exceeded the recommended threshold. These results were communicated to Biogros.

The mean anomaly scores showed in Table 16 depict the quality of chilling conditions during product transportation. A score close to 0 indicates optimal chilling, meaning that the products were transported under suitable cooling conditions. If the score exceeds 1, it suggests that the chilling was acceptable but not ideal, indicating a need to slightly increase the cooling power. However, if the score surpasses 10, it usually indicates a lack of proper cooling throughout the transportation process.

Table 16. Mean anomaly scores.

Sensor	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	Trip 7	Trip 8	Trip 9	Trip 10	Trip 11	Trip 12	Trip 13	Trip 14	Trip 15	Trip 16	Trip 17
1	0.4	0.77															
2	0.05	1.54	0.74	4.78	2.46	13.86	12.9	75.07	2.68	3.2	0.47	2.36	2.7	2.07	4.0	1.9	0.29
3	55.46	0.39	0.18	1.7	5.03	0.56	15.13	0.59	0.13	0.59	0.03	0.98					
4	0.01	0.51	0.52	0.15	18.02	45.08	55.73	0.6	0.01	0.12	0.52						
5	0.01	1.16	0.45	1.92	13.84	0.73	1.58	1.88	0.14	2.9	2.07						
6	2.17	1.84	1.92	0.72	0.0	0.7	0.02	0.14	0.49								
7	0.0	0.1	1.52	0.87	0.53	0.15	12.57	0.12	0.01								
8	0.55	0.84	4.1	1.5	2.5	0.76	1.85	3.77	0.39	11.19							

Lessons learned

In early 2023, Biogros received a notification from their own operating system indicating a cooling system failure on a Sunday. Typically, the operating system would also notify an external service company for off-hours malfunctions. However, thanks to the REAMIT system, an alert was sent to the Biogros technician that detected an anomaly in the warehouse temperature. Upon receiving the alert from the REAMIT system, the technician took immediate action and visited the warehouse on Sunday evening. It was discovered that the cooling system issue had not been resolved during the day and the notification to the external service company failed. Fortunately, due to the alert from the REAMIT system, no fresh food products were lost, and the cooling system problem was resolved in time, preventing any further deterioration of temperature-sensitive goods.

This incident highlighted the effectiveness and reliability of the REAMIT system in providing real-time alerts and preventing potential food losses. By integrating the REAMIT monitoring system into their operations, Biogros gained an additional layer of protection and timely intervention in cases of critical failures or anomalies. The system's ability to detect and alert the relevant personnel in such situations significantly minimises the risk of product spoilage and financial losses, ensuring the quality and safety of the stored goods.

2.8 Raman Spectroscopy at University of Nantes

University of Nantes (UoN) has put forward a new strategy for swiftly evaluating the quality of food by utilising an advanced spectroscopic method known as Raman spectroscopy. This innovative technique enables the non-invasive analysis of food samples, spanning from raw to extensively processed items, delivering a prompt and precise assessment of their quality.

Raman spectroscopy is a highly effective analytical approach that employs laser light to identify and examine the chemical makeup of substances. It relies on the interaction between light and molecular vibrations, generating a distinct spectral pattern that can be utilised to identify and measure various constituents within a sample.

When applied to the analysis of food quality, Raman spectroscopy imparts valuable insights into the chemical composition, structure, and functional properties of food ingredients and products. It provides information regarding the presence of nutrients, contaminants, additives, and other chemical elements that impact the sensory attributes and nutritional value of food. The benefits are presented below:

- Non-invasive method that allows for the analysis of food samples without compromising their quality or safety.
- Swift and accurate assessment of food quality and composition, facilitating the rapid screening of large quantities of food products.
- Enables the identification and measurement of diverse chemical components in food samples, including nutrients, contaminants, additives, and functional ingredients.
- Applicable to a wide range of food products, spanning from raw to extensively processed items.
- Requires minimal sample preparation, resulting in a cost-effective and time-efficient approach.
- Enables the identification and characterisation of food ingredients and products, contributing to enhanced quality, consistency, and traceability.

Outline of solution implemented

The portable Raman sensor was developed and updated in the GEPEA lab at the university of Nantes and below are the stages needed to adapt the portable Raman sensor for pilot testing:

1. Installation and assembly of equipment
2. Implementation of the analysis protocol (experimental setup)
3. Setting up the data transmission to servers
4. Data exploration and statistical scripts
5. Validation of the approach at lab scale
6. Automation of the analysis process

7. Validation of the approach in real semi-real conditions in a cold room (preparing the system for field analysis).
8. Search and find interested companies.
9. Integration of the system in a refrigerated food truck
10. Validation of the sensor in the field

Challenges were encountered going through each stage and below are some:

Table 17. Raman Spectroscopy pilot challenges.

Stage	Challenges
Installation and assembly of equipment	Shipment delays caused by the impact of the COVID pandemic, resulting in a one-year delay.
Setting up data transmission to servers	Connectivity issues with the BED server and connections between computers from different institutions.
Data exploration and statistical scripts	The need to develop scripts and data processing models, which consumed a significant amount of time.
Automation of the analysis process	More work is required to automate the adjustment of focal length or the distance between the laser and the sample (Z).
Validation of the approach in semi-real conditions (preparing for field analysis)	The laser source failed to work at temperatures below 10°C.
Integration of the system in a refrigerated food truck	The sensitivity of the Raman signal can be affected by speed bumps on the road.
Validation of the sensor in the field	Challenges in finding companies willing to test the Raman sensor in their transportation trucks.

Trial data

After successfully addressing the majority of the previously mentioned challenges, the portable Raman system was tested. Over a span of 30 days, the portable Raman system collected 30 spectra in the morning and another 30 in the evening, resulting in a total of 60 spectra per day. Simultaneously, temperature measurements (at 4°C) were recorded throughout the entire process. Following the conclusion of this monitoring period, the collected data underwent analysis.

Upon analysing the acquired data from the portable Raman system over the 30-day period, several noteworthy results were obtained. Figure 4 demonstrates that the system effectively distinguished between fresh and spoiled samples, enabling the monitoring of quality deterioration from day zero to day 30.

Moreover, the system identified the specific molecules affected, particularly highlighting the impact on amide I (a major protein in chicken) and Tyrosine (an indicator of quality deterioration) (Figure 13). The system also successfully determined the day on which the initial shift in quality occurred. Figure 14 illustrates that the first shift transpired on day 6, followed by another on day 12. Notably, on day 21, a significant decline in quality was observed, signifying the commencement of the spoilage process (Figure 14).

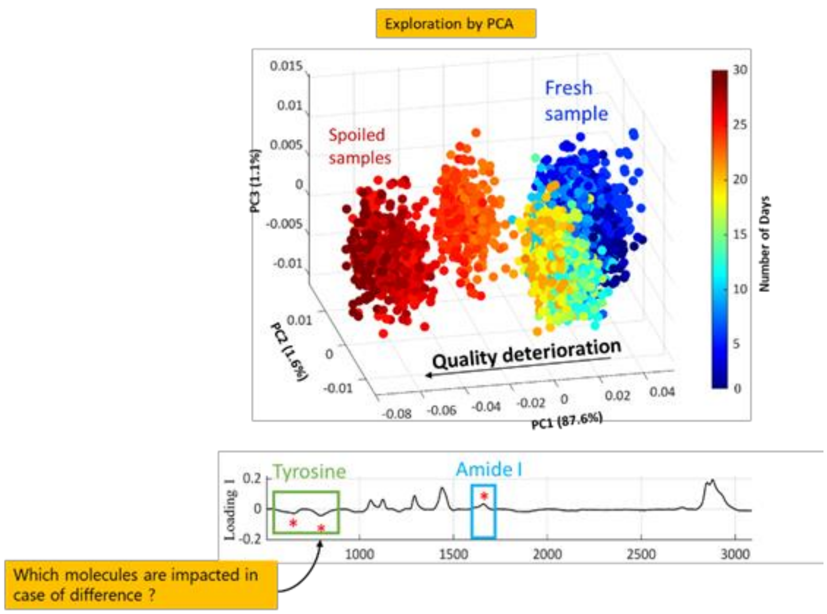


__Figure 13.__ Raman system capabilities on observing the quality change and detecting the molecules behind this change.

For further details, additional information can be found in the article titled "Raman Spectroscopy Application in Food Waste: A Step towards a Portable Food Quality-Warning System," published in the Sustainability Journal, MDPI.

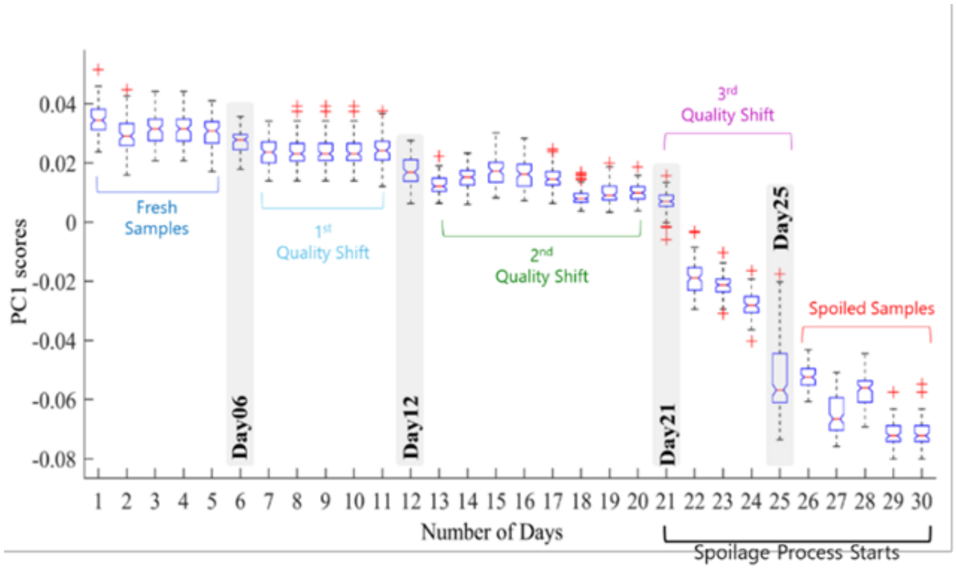


Figure 14. *Detecting the day on which the quality deterioration started.*

Lessons Learned

Based on our test results, Raman spectroscopy proves to be a valuable tool for monitoring changes in the quality and chemical composition of chicken products. However, it's important to note that these changes require a certain duration to occur, typically a minimum of four days for chicken products. Consequently, there is no need for continuous Raman spectroscopy during transportation. Instead, it is advisable to conduct Raman spectroscopy analysis two to three times per day when the truck is stationary, to eliminate any vibrations caused by road bumps that could affect result accuracy. This approach ensures the acquisition of high-quality spectra, enabling an accurate evaluation of product quality and chemical composition while minimising electrical consumption. However, for the system to recognise to run in stationary phase, two components are needed.

The first component is a raspberry Pi kit, which will help initiate the scan remotely without the need for physical proximity. Also, the kit possesses an LTE-M GMS shield, ensuring the transmission of the Raman data to the server to be analysed can be achieved regardless of the location of the spectrometer. This has, in turn, turned the Raman setup into a location agnostic analysis tool as it does not rely on any other infrastructure to operate. This component was added to the system recently with the help of our REAMIT partners from University of Ulster.

The second component is an accelerometer. This device can detect any type of movement or change in velocity. By integrating the accelerometer into the portable Raman system, it ensures that the scanning process is done in the stationary phase, thereby enhancing the accuracy and reliability of the results. The installation of this device is part of our ongoing plans for future improvements. It is currently being considered for implementation as we continue to develop and enhance our system.

2.9 3D Fluorescence Spectroscopy with FreshDetect

FreshDetect GmhH manufacture the FreshDetect BFD-100, a handheld non-invasive fluorescence spectrometer device that operates at an emission wavelength of 405nm. The FreshDetect device was initially designed for monitoring the quality of meat products by determining bacterial contamination through the estimation of the total viable count, which refers to the number of viable microorganisms present in a sample. However, in the REAMIT project the FreshDetect device has been the subject of exploration to determine its applicability in assessing the freshness of other household food items that are prone to spoilage.

In this pilot, the goal was to expand the application of FreshDetect beyond meat products and evaluate its effectiveness in determining the freshness of whole milk (2%). The motivation behind this was fuelled by the removal of use-by dates on milk by some UK supermarkets, promoting alternative methods like the "sniff test" for determining milk spoilage. This pilot sought to explore the potential of utilising the portable handheld spectroscopy device as a quantitative tool for measuring milk quality. By doing so, it aimed to reduce the reliance on subjective olfaction techniques and potentially pave the way for the introduction of handheld spectrometers as a commonplace tool in households, in turn offering consumers a more reliable and convenient method for assessing the freshness of their milk. The objective was to examine the relationship between the fluorescence signals emitted by milk and attempt to correlate it to its freshness status.

Outline of solution implemented

Since the collaboration was with FreshDetect GmbH, the selection of sensors was limited to the handheld device they offered. This was the FreshDetect BFD-100, a handheld non-invasive fluorescence spectrometer device that operates at an emission wavelength of 405nm.

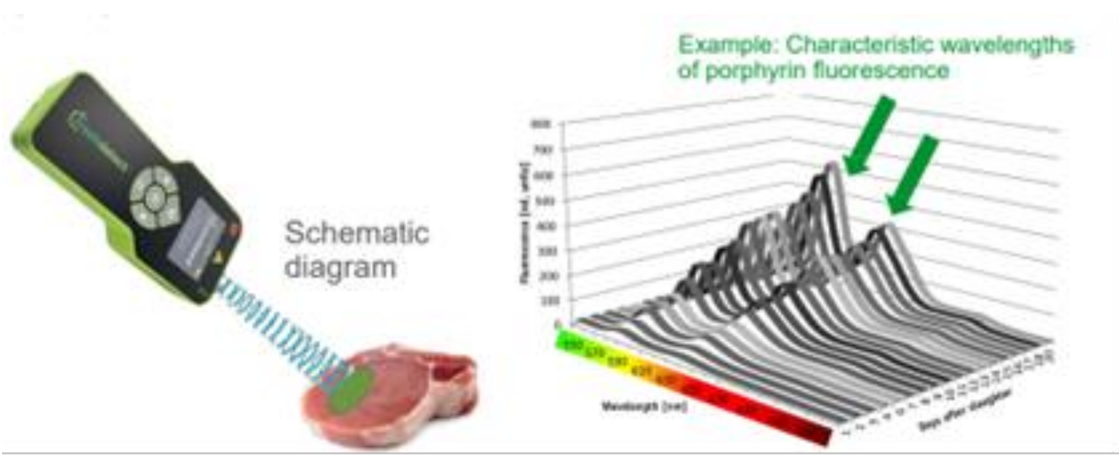


Figure 15. *FreshDetect BFD-100.*

The decrease in pH is one of the indicators of milk spoilage. Fresh milk typically has a pH of around 6.6 to 6.8, which is slightly acidic. As spoilage progresses, the pH can drop significantly below this range, indicating that the milk has become more acidic. The increased acidity not only affects the taste and sensory qualities of the milk but also creates an environment that is unfavourable for the growth of other microorganisms. The acidic conditions help to inhibit the growth of spoilage-causing bacteria and may contribute to the characteristic sour taste and odour associated with spoiled milk.

Since it is known that lower pH levels are associated with milk spoilage, researchers sought to link the spectra obtained by the FreshDetect to a measurement of pH. In order to obtain accurate and consistent pH measurements, the Thermo scientific Orion Star A215 pH meter was chosen. This laboratory grade pH meter offered the ability to log pH measurements using a provided user specified time increment, ensuring that the milk quality degradation could accurately be monitored. The device offered USB communication allowing the measurements to easily be exported and transferred to a computer, enabling the researchers to map the pH data to spectra obtained by the FreshDetect at the same timestamp.

Trial data

The results of the spectra were discussed with analytical chemist partners at University of Nantes, where it was discovered that the main spectra peak produced by the FreshDetect was Riboflavin, a water-soluble vitamin which is a key component of milk.

Figure 16 presents the initial results, which show that as the milk ages, both the pH of the milk and Riboflavin levels obtained from the FreshDetect spectra decline. This is thought to be primarily due to the chemical instability of riboflavin under acidic conditions. Riboflavin is sensitive to pH changes, and its stability is influenced by the acidity or alkalinity of the environment.

With the POC complete, researchers collected a larger milk dataset consisting of 15 different batches of milk, each left to degrade over a 48 hour period. Regression and classification modelling were both performed on the milk dataset collected. Employing a pH threshold of 6.4 to indicate spoilage, classification modelling performed to assess whether the milk was fresh or gone off. The best performing model was a Support Vector Machine (SVM), able to achieve a 95% accuracy on determining the status of the milk.

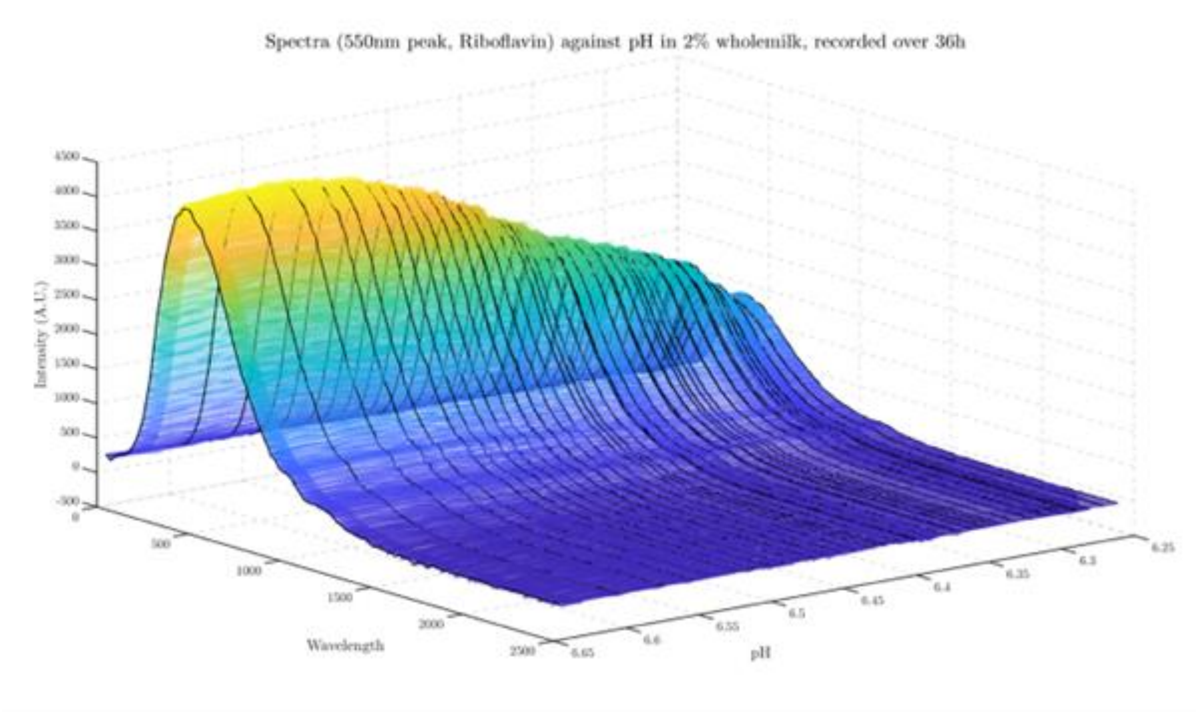


Figure 16. *Spectra (550 nm peak, Riboflavin) against pH in wholemilk, recorded over 36h.*

Lessons Learned

To ensure consistency and obtain a reliable spectra training set, it is crucial to maintain a consistent distance between the FreshDetect device and the sample during each scan. In order to facilitate this, a custom 3D printed casing was specifically designed, providing a fixed and replicable scan distance for the FreshDetect device. By using the custom casing, researchers can maintain a standardised scanning procedure, which improves the accuracy and reliability of the spectra obtained for training and analysis.

The laser integrated into FreshDetect has a narrow emission range centred at 405nm, which was suitable for its initial purpose of determining total viable count (TVC) in meat products. However, this limited range poses challenges when expanding the device's use to other applications. Specifically, at 405nm, the laser can only excite Riboflavin in milk, while other chemical properties undergo changes during spoilage that cannot be detected within this spectral range. Gaining insights into these additional properties could provide researchers with a deeper understanding of the factors contributing to milk spoilage and potentially lead to the development of a more informative model. To capture information about these properties, it may be beneficial to replace the laser with a broader range LED, allowing for a wider range of chemical analyses in milk samples.

3. Future Market Scalability (Readiness)

3.1 Feasibility of the REAMIT technologies

By implementing Action Research within REAMIT, it provided researchers and practitioners with the opportunity to apply and test their research of modern IoT technologies and Big Data analytics in a practical business setting. This is a valuable method of collaboration as it increases the authenticity and trustworthiness of results [55]. Researchers within REAMIT demonstrated their technology in multiple food businesses across Europe, focusing primarily on food production, transportation and storage stages of the supply chains.

Initially, it was identified that whilst food companies recognised the need for food waste reduction and to improve their carbon footprint, not all of them were prepared to engage in using modern digital technologies for this purpose [2]. Regardless of food waste being recognised as being a significant threat to food security, the economy, and the environment [12]. This was due to no prior experience of using such technologies, as IoT sensors and big data for real-time information on the quality parameters [12]. However, whilst some companies have been using thermometers and refrigerated trucks to transport food, they did not attempt to track quality parameters in real-time. This method can cause food waste issues especially if the system does not work properly and it is not flagged until the truck has reached its destination. After discovering how IoT sensors could reduce food waste by monitoring quality parameters in real-time, the companies then valued the use of such technologies to allow for demonstrations to be deployed and motivations to be gleaned.

After providing demonstrations of IoT sensors in action within real world settings, there were several motivators that would encourage companies to integrate them to assist with food waste reduction, including food quality, reliability, legal, green image, pressures from stakeholders, economic factors and survival [2]. Continuously monitoring food can reduce waste and improve on quality whilst tracking its performance in real-time, this can assist a business in increasing their revenue via higher prices. Businesses have also experienced increasing reliability of their food processing systems due to the continuous monitoring of quality parameters in real-time. This method helps to predict and reduce potential failures within the system that could lead to food waste.

The use of modern technologies allows businesses to comply with food safety regulations by monitoring food quality to be compliant and ultimately to prevent food waste, which has proved to be one of the main reasons why companies are integrating the use of IoT sensors. In addition, businesses are also interested in promoting a green image by showcasing sustainability and donating to food charities. However, as with all businesses there can also be pressure from stakeholders to incorporate the use of modern digital technologies to provide a stable image to the media and general public. This can also have an economic impact and overall survival rate of the business which is an important motivator to implement such technologies.

However, whilst these motivators assisted in reaching out and working with additional companies some challenges did emerge. These challenges revolved primarily around the collection of sensitive data using IoT sensors, namely data security, data sharing, threat from hackers, privacy, technology challenges and trust issues [2]. Data security is a very important factor and can influence businesses adopting such technologies. It was identified that businesses find data sharing and security issues could prevent them from using such technologies as there is a threat from hackers and if attacked this could ultimately impact their brand image.

In addition, privacy was another concern especially from truck drivers when installing a gateway device in their cabins, this also raised issues pertaining to the exposure of radioactivity and the continuous monitoring of their location. Other technological challenges became apparent, such as a business wanting to monitor the temperature of fruit during international flights. Unfortunately, this could not be completed cost-effectively with the current technologies available in the market. However, a general negative perception from some companies on any IT projects are overpromising and under-delivering, this was apparent during early stages. However, as successful demonstrations were performed over time, trust issues become more positive.

By tackling these challenges head-on, businesses can harness the full potential of IoT solutions to transform their operations, reduce waste, and deliver better products and services to their customers. The integration of REAMIT technologies into the different sectors offers significant opportunities for businesses to enhance efficiency, sustainability, and safety throughout the entire chain. IoT-based solutions can revolutionise how businesses and industries operate and provide real-time solutions to their challenges. The potential for innovation and positive impact is vast, with IoT serving as a catalyst for digital transformation and sustainable growth across industries.

Overall, by taking both the motivators and challenges into consideration, there is potential for such modern technologies to be implemented easily to help businesses create value by reducing waste via timely alerts and improve overall food quality.

3.2 Market Readiness in the Industry Sector

A qualitative survey was conducted with six out of the seven pilot companies, including WD Meats, Musgrave, Yumchop, HMF, BFM, and Biogros to gain a comprehensive understanding of their company culture regarding their goals related to food waste reduction, and their experiences with IoT technologies. The interview sought to understand the impact of the REAMIT project on these companies and identify valuable lessons learned from the pilot phase.

Product's Relevance: Is the product or service solving a real need?

The interviews underscored the relevance of REAMIT's IoT technology in addressing real needs, such as reducing food waste, improving product quality, cutting costs, complying with regulations, and enhancing operational efficiency. BFM emphasised the financial impact of food waste, stating, "food waste for us is money in the bin, we are losing money on our bottom line, and then we are also having to pay to get the waste taken away". They expressed the need for improved chilling systems to reduce waste, enhance product quality, decrease utility bills, and minimise their carbon footprint.

Biogros highlighted the dual benefits of reducing costs and waste, aligning with their objective of maintaining a closed temperature supply chain system, as mandated by legislation. The implementation of REAMIT IoT technology facilitates meeting regulatory requirements while minimising waste. Yumchop expressed the desire for real-time monitoring and control of freezer temperatures to prevent food waste. They acknowledged the administrative burden and risks associated with manual data capture, emphasising the potential efficiency gains and waste reduction through IoT sensors.

HMF emphasised the emotional and financial implications of milk wastage, stating, "there's obviously emotional pain caused. Also, there's obviously a financial waste when donor milk isn't able to be used". By reducing milk wastage, HMF aims to minimise grief for donors and increase their operational efficiency, striving to bring down their failure rate from 16% to below 10%. WD Meats highlighted the benefits of real-time monitoring and automation, citing the need for improved visibility into their processes. They mentioned the financial motivation and the shift toward online and automated systems, emphasising the value of live data to identify and address issues promptly.

The insights gathered from these companies provide valuable evidence of the positive impact that IoT technology can have on addressing critical challenges in the food industry.

Market readiness: Is it the right time to bring the solution to market?

It is apparent that the market conditions are favourable for introducing the REAMIT IoT solutions. Musgrave's strong focus on sustainability, environmental initiatives, and their targets for becoming net neutral by 2040 indicate an opportune moment to bring the IoT technologies to their business. By implementing IoT sensors, they can optimise their supply chain, enhance temperature control, track assets, and reduce waste, aligning with their sustainability goals. BFM's recent adoption of environmentally sustainable policies and positive customer response to changes suggest that their efforts to improve sustainability align with current market trends and consumer preferences, though further progress in data-driven decision-making and waste reduction targets would be beneficial.

Biogros has already implemented IoT technologies for temperature monitoring in their supply chain to comply with EU regulations. It can be inferred from the interview, that the implementation of IoT technologies for temperature monitoring contributes to maintaining product quality and reducing potential food waste caused by temperature fluctuations. Yumchop's commitment to sustainability, evident in their use of biodegradable packaging, food waste reduction strategies, and real-time sales data monitoring, indicates their readiness to adopt IoT solutions. Their actions demonstrate a dedication to incorporating sustainability practices into their business strategy. HMF's strong commitment to sustainability and food waste reduction, as well as their utilisation of IoT technologies for real-time tracking, suggests that it is the right time to bring the IoT solutions to market. Their goal of reducing failure rates and making data-driven decisions aligns well with the capabilities of IoT technology.

The overall conclusion is that the market is ripe for introducing the REAMIT IoT solution. The companies' commitment to sustainability, environmental initiatives, waste reduction targets, and the utilisation of data-driven approaches indicate a readiness to embrace IoT technologies to address their needs effectively. By launching the REAMIT solution now, companies can further enhance their sustainability efforts, optimise operations, reduce waste, and meet evolving market demands.

Companies current strategy: How are the companies currently solving the food problem?

The companies are employing a range of approaches to tackle the food problem. While some rely on manual checks and basic monitoring systems, others utilise limited IoT solutions or external support for specific aspects of their operations. Musgrave relies on trackers installed in vans to monitor temperature during food deliveries to smaller establishments. They use of real-time alerts to notify staff of any temperature fluctuations, allowing them to take immediate action to rescue the products. Additionally, they employ messaging and email systems for effective communication when issues arise. BFM acknowledges their limited technology infrastructure and currently relies on manual checks for monitoring temperature. They have implemented a basic fridge monitor, but the interviewee emphasises their need for additional technological advancements, such as those provided by the REAMIT IoT solution.

Biogros has an existing system that alerts them when their cooling system fails. This alert is sent to an external company, indicating a reliance on external support for monitoring and addressing cooling system issues. Yumchop currently handles monitoring manually but mentions the potential to integrate their data into their Enterprise Resource Planning (ERP) system. This integration would offer a more streamlined and efficient approach to data management.

HMF captures data through two systems: a human milk tracking and tracing system and a concurrent tracking system using Google Sheets. These systems enable them to maintain comprehensive records and perform interactive data analysis. However, the interviewee acknowledges the need for further improvements in data collection and analysis. WD Meats has been implementing various technologies, such as sensors and monitoring devices, to identify bottlenecks and improve efficiency. They have invested in equipment like X-ray machines and near-infrared machines for quality testing, storing and managing the collected data in their own systems.

These current strategies highlight the potential for the REAMIT IoT solutions to provide more comprehensive and advanced approaches to monitoring, data analysis, and proactive problem-solving in the food industry.

Adoption Potential: Will they be willing to adopt the REAMIT IoT solution?

There is a general openness and willingness to consider adopting the REAMIT IoT service in the future. The companies express a range of motivations, including sustainability goals, data-driven decision-making, cost savings, and operational efficiency. Musgrave has already recognised the importance of IoT technology for monitoring various aspects of their supply chain. They have expressed interest in using IoT to track parameters like temperature, fill rate, and moisture contents of their plastic crates. This demonstrates their willingness to explore new technologies and indicates a potential openness to adopting the REAMIT IoT service. BFM, a company starting from scratch in terms of technology adoption, has recently implemented a fridge monitor for temperature, air pressure, and humidity. They acknowledge their limited technological capabilities and express a strong interest in improving their chill operation and reducing food waste. Their receptiveness to data-driven solutions and their focus on sustainability suggest that they would likely be open to considering the REAMIT IoT service to further their environmental goals.

Yumchop, with its existing utilisation of real-time data from vending kiosks and their IT background, is well-positioned to embrace IoT technologies. They emphasise their commitment to using information technology and data for maximising efficiency. Given their data-driven approach and interest in further enhancing their sustainability efforts, it is likely that Yumchop would be willing to adopt the REAMIT IoT service. HMF has already integrated IoT technologies into their operations. They capture and analyse data using a human milk tracking system and have achieved positive results through the

REAMIT project. Despite challenges encountered during integration, they express a willingness to continue using the implemented technologies.

WD Meats has already made investments in handheld systems and is exploring the integration of robot arms. Their proactive approach to incorporating technology suggests a readiness to adopt IoT solutions. Although challenges may arise, such as implementation costs, the company recognises the potential benefits of IoT technology, making the REAMIT IoT technology a promising opportunity for the company. In general, the interviews showed companies' receptiveness to explore and implement IoT technologies. With careful consideration of their specific needs and challenges, the REAMIT IoT service has the potential to continue helping these companies to enhance their operations, sustainability efforts, and overall business performance.

Consumer Willingness to Invest: Is there a willingness from consumers to pay to solve the food problem?

The interviews reveal that cost is not a significant barrier for many companies when it comes to implementing innovative technologies and approaches. Instead, their focus is on driving change, achieving proof of concept, and seeking continuous improvement. Musgrave, for example, expresses strong support for reducing waste and driving change. The company is willing to invest in solutions as proof of concept and wants to expand its efforts to achieve even greater impact. They demonstrate a desire to explore how technologies like IoT can track additional parameters impacting quality and waste, highlighting their readiness to pay for the benefits of such solutions. Similarly, BFM shares that they did not face significant challenges in terms of cost when adopting technology for their fridges. Their positive experience with implementing solutions indicates a willingness to invest in solving the food problem.

Biogros stands out as a company with a clear willingness to pay and invest in sustainability solutions. They have already taken several initiatives, including transitioning to electric trucks, using biodegradable packaging, and implementing IoT technologies for temperature monitoring. These actions demonstrate their commitment to investing in technologies that align with their environmental goals. Yumchop also demonstrates a strong commitment to sustainability and actively seeks ways to reduce food waste. Their willingness to integrate IoT technologies for data-driven decision-making indicates a readiness to invest in the necessary tools and solutions.

HMF have implemented various measures and projects to reduce their environmental footprint and are actively working towards becoming a net zero milk bank. Their willingness to pay to solve the waste problem is evident in their efforts to incorporate sustainability considerations into their supply chain and their projects aimed at finding alternative uses for unused milk. While cost considerations are present for companies like WD Meats, they acknowledge the importance of investing in solutions to address the food problem. They highlight the need for free trials and proofs of concept to ensure that the solutions align with their specific business requirements and provide long-term value.

Therefore, while cost is a consideration, it is not a significant barrier when companies see the potential value, positive impact, and alignment with their goals. The readiness to invest in innovative technologies and approaches reflects a collective commitment to driving change and finding sustainable solutions for the food problem.

REAMIT's strengths and expertise in providing innovative solutions

The strengths of REAMIT, as evident from the pilot projects, include their expertise in selecting appropriate sensors, their ability to integrate sensors with gateways for data transfer to the cloud, and their development of user-friendly dashboards for data visualisation and analysis. The project also demonstrate proficiency in setting up alerting mechanisms based on threshold values and implementing real-time monitoring systems.

The project offered a range of sensors and devices suitable for monitoring temperature, humidity, and other relevant conditions in various food-related environments. Partners have experience working with different types of sensors, including those from Ursalink, Digital Matter, Elsys, and Amphenol. Additionally, they have expertise in implementing LoRaWAN gateways for data communication and cloud integration.

REAMIT has carefully chosen sensors based on the specific requirements of each pilot company. They consider factors such as durability, power consumption, communication range, and environmental resistance to ensure accurate and reliable data collection. In addition, REAMIT integrates their sensors with LoRaWAN gateways and uses cellular IoT capabilities for seamless connectivity. This enables efficient data transfer to the cloud and facilitates real-time monitoring and analysis.

REAMIT provided intuitive dashboards and analytics tools that allow companies to access and interpret the collected data easily. The dashboards offer visualisations such as gauges, line charts, and bar graphs for quick identification of anomalies and actionable insights. The partners tailored the solutions to meet the specific needs of each company. They configure the sensors with threshold values and alerts to notify personnel in case of deviations from desired conditions, enabling timely intervention and waste reduction. In addition, REAMIT took proactive measures to mitigate risks and reduce food waste. They develop anomaly prediction models leveraging advanced algorithms to identify patterns and potential issues in advance, allowing companies to optimise their operations and minimise waste. REAMIT demonstrated a strong understanding of the challenges related to food waste reduction and provides comprehensive solutions by combining suitable sensors, connectivity options, data visualiaation, and analytics capabilities.

Market opportunity and potential market share for REAMIT Solutions

The REAMIT solutions have demonstrated their potential for sustainability and market growth through its successful implementations and the value it brings to various industries. The solution's ability to optimise the dry-ageing process, monitor temperature and humidity, and reduce food waste at WD Meats and BFM showcases its efficiency and effectiveness in improving operational processes. This addresses a critical need in the food industry, making it a viable solution with significant market opportunity.

Furthermore, the inclusion of IoT technology, such as LoRa sensors and LoraWAN gateway, in monitoring temperature in delivery vans for Musgrave highlights the solution's adaptability and relevance to food safety during transportation. This application opens up possibilities for wider adoption in the food delivery industry, indicating a substantial market potential. The real-time monitoring and alerting system implemented for Biogros' supply chain management further emphasises the versatility of the REAMIT solution. By utilising trip detection, temperature sensors, and cloud-based analytics, the solution optimises logistics and reduces food waste. This successful implementation showcases the solution's ability to address critical pain points in supply chain management, making it valuable to stakeholders involved in the process.

Expanding on the market potential, the REAMIT solution has proven its relevance in various contexts. For example, the implementation at Yumchop Foods, where temperature and humidity sensors were used to ensure optimal conditions for food storage and vending machines, demonstrates the solution's applicability to similar businesses. This showcases its scalability potential within the food industry and highlights its ability to contribute to product quality and customer satisfaction.

Additionally, the implementation of a system to monitor temperature and motion during the transportation of human milk bags to address specific needs of a foundation indicates the solution's adaptability to niche markets. While the market size may be relatively small in this context, the REAMIT solution can still achieve a substantial market share by targeting and catering to specific industry requirements. Therefore, the REAMIT solutions have showcased their potential for sustainability and growth through successful implementations in various industries. Its ability to address critical pain points, reduce waste, optimise processes, and leverage IoT technology positions it well for scalability and wider adoption. While some applications may be niche, the solutions’ adaptability and value make them a viable contender for achieving a substantial market share.

3.3 MRL, TRL & MTRL assessment

In the dynamic landscape of technology and innovation, the successful development and deployment of new products, technologies, and solutions require careful evaluation and assessment at various stages of their evolution. This is where concepts like Technical Readiness Level (TRL), Market Readiness Level (MRL), and the combined Market and Technical Readiness Level (MTRL) come into play. These frameworks serve as crucial tools for gauging the maturity, viability, and potential impact of innovations, guiding stakeholders in making informed decisions and allocating resources effectively.
Technology Readiness Levels (TRL) are a type of measurement system used to assess the maturity level of a particular technology, initially defined by NASA [56]. There are nine technology readiness levels that reflect the advancement from basic research to practical application, from TRL 1 being the lowest to TRL 9 that is the highest. Using the NASA definition as a starting point, the European Commission (EC) in the H2020 general annexes G11 provides the description of the TRL that applies for EC projects [57]. The method proposed by the CloudWATCH2 project [58] added a new category with several objectives to simplify the TRL scale in order to keep a limited number of categories. In this approach, each level represents a specific milestone, such as prototype, validation and production (Annex A1), which helps stakeholders assess the risks, challenges, and potential benefits associated with the technology's development.

While TRL focuses on the technical aspects of innovation, MRL shifts the emphasis towards the readiness of a technology for commercialization and market adoption. To bring the results of a project to the market, it is not enough to complete the technological developments, but rather a set of support activities is necessary. This support includes business strategy, business modelling, marketing, sales, after-sales support, etc. And this set of activities must be also measured to accurately determine the readiness level of a project outcome. The MRL approach from CloudWATCH2 offers a systematic framework for understanding a product's potential to succeed in the market (Annex A2). The MRL scale typically ranges from MRL 1 (hunch) to MRL 9 (proof of stability), providing decision-makers with insights into the commercial viability and risks associated with introducing a technology to consumers.
Recognizing the interconnectedness of technical advancement and market acceptance, the combined concept of MTRL provides a holistic view of innovation's overall maturity. It takes into account both the technical development and the market dynamics to provide a comprehensive assessment of a technology's potential for success. By integrating TRL and MRL, MTRL offers a more nuanced understanding of the innovation's readiness across multiple dimensions. This integrated approach assists stakeholders in making well-informed decisions about investment, resource allocation, and strategic planning.

3.3.1 Methodology

The CloudWATCH2 approach gives a complete vision of a project both from a technical and nontechnical point of view. The score obtained by a project according to this methodology is called MTRL Score and it is a pair (TRL, MRL) that can be graphically presented to display the status of the project. This representation can be used both to assess the current situation of a project and to design a plan for the future of the project, that is, where we are and where we want to go.

The approach consists of 9 questions regarding Product Maturity, Product Development, Product Definition/Design, Competitive Landscape, Team, Documentation, Intellectual Property Management, Go-To-Market and Manufacturing / Supply Chain. The first two questions are focused on obtaining a value for the TRL and the rest for the MRL. For each question, 5 possible answers are shown, ordered from less developed (answer number 1) to more developed (answer number 5). The project representative selects the answer that best fits their project. Annex A3 shows the content of the questionnaire. To obtain the TRL score, the mathematical Equation 1 was used.

$$\boldsymbol{TRLscore} = \begin{cases} \boldsymbol{q_2 + 4}, & \boldsymbol{(q_2 \geq 2)} \\ \boldsymbol{q_1}, & \boldsymbol{otherwise} \end{cases} \tag{1}$$

where *q1* is the value selected for the Project Maturity question and *q2* the value selected for the Product Development question. The value selected for *q1* determines the TRL between levels 1 – 5 and the value selected for *q2* determines the TRL between levels 6 – 9 (Annex A4). To be more specific when the value of Product Development is between 2 and 5, the TRL value is obtained proportionally to this value, regardless of the value of Project Maturity. When Product Development is 1, the value of Project Maturity coincides with the TRL value.

To get the MRL score, each question is assigned a weight (Annex A5), so that the response selected by the user is weighted according to that weight and calculated using Equation 2.

$$\boldsymbol{MRLscore} = \frac{\boldsymbol{9 \times \sum (q_i \times w_i)}}{\boldsymbol{5 \times \sum w_i}} \tag{2}$$

where *qi* is the value of the answer to question *i* and *wi* the weight of that question (for *i* from 3 to 9). The MTRL matrix of identified technologies and services is the result of crossing the data obtained in the two previous steps (Annex A6). This result helps to determine which projects are less mature, both in the technology readiness and the closeness to the market.

3.3.2 Results

Table 18 shows the questionnaire answers to the four overarching solutions developed under the REAMIT project, along with their corresponding TRL, MRL, and MTRL outcomes.

Table 18: Response to the questionnaire and MRL, TRL and MTRL results.

Levels	Solutions			
	Intelligent alerting based on trip detection for perishable food transportation clients	Intelligent alerting with anomaly detection for perishable food storage clients	Real-time Raman spectra analysis for perishable food transportation clients	Handheld spectrometer for consumer level quality monitoring
1. PROJECT MATURITY	★★★★★	★★★★★	★★★★	★★★★
2. PRODUCT DEVELOPMENT	★★★★★	★★★★★	★★	★★
3. PRODUCT DEFINITION/DESIGN	★★★	★★★	★★	★★★★★
4. COMPETITIVE LANDSCAPE	★★★★★	★★★★★	★★★★	★★★★
5. TEAM	★★★★	★★★★	★★★★	★★★★
6. DOCUMENTATION	★★★★★	★★★★★	★★★★	★★
7. INTELLECTUAL PROPERTY MANAGEMENT	★	★	★	★★★★★
8. GO-TO-MARKET	★★★★	★★★★	★★★	★★★
9. MANUFACTURING/ SUPPLY CHAIN	★★★★★	★★★★★	★★	★★★★
TRL	9	9	6	6
MRL	7	7	5	7
MTRL	63	63	30	42

Solution 1 was was employed for the pilot tests at Musgrave, Biogros and HMF. The results for this solution, which focuses on intelligent alerting based on trip detection for perishable food transportation clients, indicate a high level of project maturity and robust product development. The product's definition and design have reached a commendable rating, while the competitive landscape analysis also receives a strong rating, reflecting its favourable positioning. The project benefits from a proficient team, and well-documented processes. However, intellectual property management shows room for improvement. The go-to-market strategy is well-formed, and the manufacturing/supply chain aspect is also well-structured. The solution demonstrates a TRL of 9, indicating a Full commercial application, while the MRL stands at 7, signifying advanced market testing and validation. The combined MTRL score of 63 highlights the substantial progress and readiness of Solution 1 for both market introduction and technical deployment. Solution 2, employed by WD Meats, Burns Farm Meats, Yumchop, and Picnic is paralleled in its maturity, both in technical development and its acumen within the dynamic market landscape.

Solution 3, tested at the University of Nantes, was centred around real-time Raman spectra analysis for perishable food transportation clients. The project has attained a substantial level of maturity. However, the product development stage suggests room for further enhancement in this aspect. Similarly, the product's definition and design indicate potential for refinement. The competitive landscape analysis, on the other hand reflects a solid understanding of market positioning. The solution benefits from a competent team, and effective documentation practices. Intellectual property management is an area identified for improvement. The go-to-market strategy is well-considered, while the manufacturing/supply chain element demonstrates a low rating. The TRL of 6 implies that Solution 3 is still under the validation phase, while the MRL stands at 5, signifying that market testing has been initiated at a large-scale early adopter campaign. The MTRL of 30 means Solution 3 is ready to be commercialised, but there is still room for enhancement and some aspects should be improved.

Solution 4, tested at Ulster University, introduces an innovative handheld spectrometer tailored for consumer-level quality monitoring, showcasing significant strengths across various evaluation criteria. The project has attained a good level of maturity, indicative of a well-established foundation. In terms of product development, there is potential for further refinement and advancement. The product's definition and design, on the other hand, have achieved a high rating, underscoring the solution's meticulous planning. The competitive landscape analysis also reveals a strong rating, highlighting a comprehensive understanding of the market dynamics. A capable team has been assembled, while improvements could enhance the documentation level. Intellectual property management is a particular strength, indicating a robust strategy in place. The go-to-market strategy demonstrates a thoughtful approach, while manufacturing and supply chain aspects have been thoughtfully structured. In terms of technical maturity, the solution registers a TRL of 6, showcasing significant testing and development in relevant environments. The MRL is 7, implying that substantial market testing and validation have taken place. The combined MTRL stands at 42, highlighting the notable progress achieved across technical and market-oriented dimensions. Solution 4 is positioned favourably for further development and potential market introduction, leveraging its robust foundation and innovative design.

In conclusion, the assessment of the four solutions, each addressing distinct challenges in the ambit of perishable food monitoring, provides valuable insights into their varying levels of readiness. Solution 1 and 2 presented advanced project maturity and well-established product development, reinforced by commendable ratings for its definition, design, and competitive positioning. Solution 3 showcases some degree of maturity, although room for enhancement remains in the product development stage. Noteworthy strengths lie in the understanding of market positioning and the capability of the team, supported by effective documentation. Similarly, Solution 4 exhibits strong attributes across various evaluation criteria. Its level of maturity and product design are counterbalanced by opportunities for refinement in product development. A strategic understanding of the competitive landscape and intellectual property management underscore Solution 4's potential. With a well-considered go-to-market strategy and structured manufacturing/supply chain elements, the solution is well-poised for future development and potential market entry, as reflected by its TRL, MRL, and MTRL scores.

The evaluations underscore the progress achieved by each solution, presenting a dynamic landscape of innovation where technological advancement and market readiness intersect. As these solutions continue their journeys towards further enhancements and strategic refinements hold the promise of transforming these concepts into impactful realities within the perishable food transportation domain.

3.4 Forthcoming opportunities for REAMIT technologies

The market potential for technologies aimed at reducing food waste and improving quality is significant and growing [59]. With increasing global concerns about sustainability, environmental impact, and resource efficiency, businesses and consumers are actively seeking innovative solutions to address these challenges [60]. Technologies that offer food waste reduction and quality improvement have the potential to not only meet these demands but also create new market opportunities [61].

The technologies employed in REAMIT have wider applications and scalability potential within and across various business sectors. These technologies, which include sensor-based monitoring systems, data analytics, real-time alerting, and cloud-based platforms, offer valuable solutions for waste reduction, quality improvement, and operational optimisation. Some examples of areas identified by the project during its execution were presented below.

- Farming [62], [63]: The application of REAMIT technologies in the farming sector can contribute to sustainable practices and improve yield and product quality. Sensor-based monitoring systems can provide valuable insights into soil conditions, temperature, moisture levels, and crop health, enabling farmers to make data-driven decisions for irrigation, fertilisation, and pest control. This can lead to optimised resource usage, reduced waste, and increased productivity.

- Greenhouses and Controlled Environments [64], [65]: REAMIT technologies can be applied in greenhouse farming and controlled environment agriculture to monitor and regulate temperature, humidity, and lighting conditions. This enables precise control over plant growth, optimising crop yields and resource utilisation.

- Wine and Beverage Production [66], [67]: REAMIT technologies can be employed in wineries and beverage production facilities to monitor and control fermentation processes, storage conditions, and aging environments. This ensures product consistency, quality, and preservation of desirable flavors.

- Manufacturing and Industrial Processes [68]–[70]: The technologies employed in REAMIT can be scaled and applied to manufacturing and industrial processes for quality control, waste reduction, and operational optimisation. Real-time monitoring of critical parameters such as temperature, pressure, and humidity can help identify deviations, prevent defects, and enhance product quality. Data analytics can provide insights for process optimisation, predictive maintenance, and waste reduction, resulting in improved efficiency and cost savings.

- Logistics and Transportation [71], [72]: The logistics and transportation industry can benefit from the application of REAMIT technologies to monitor and track goods during transit. Sensor-based monitoring systems can provide real-time visibility into several parameters to ensure the safe transportation of sensitive products such as pharmaceuticals, chemicals, and perishable goods. This can help mitigate quality issues, and enable interventions in case of deviations from desired conditions.

- E-commerce [73]–[76]: In the retail and e-commerce sector, the technologies used in REAMIT can be used to monitor and optimise the storage and transportation of perishable goods. Real-time monitoring of temperature, humidity, and other environmental conditions can ensure product quality, reduce waste, and prevent losses due to improper handling or storage. Additionally, these technologies can enable retailers to implement predictive analytics to anticipate demand, optimise inventory management, and improve overall supply chain efficiency.

- Hospitality and Hotels [77]–[80]: The application of REAMIT technologies in the hospitality industry can enhance guest experiences and operational efficiency. Monitoring systems can track room conditions, such as temperature and air quality, to ensure comfort for guests while optimising energy usage in unoccupied rooms.

- Healthcare and Pharmaceuticals [81]–[83]: In the healthcare and pharmaceutical sectors, the technologies used in REAMIT can be leveraged for precise monitoring and quality control. Real-time monitoring of temperature, humidity, and other environmental factors can ensure the integrity of medicines, vaccines, and biological samples. This can enhance patient safety, regulatory compliance, and operational efficiency in healthcare facilities and pharmaceutical manufacturing.

- Energy and Utilities [84]–[86]: The technologies employed in REAMIT can be extended to the energy and utilities sector to optimise resource management. Real-time monitoring and data analytics can help identify areas of energy inefficiency, detect anomalies in consumption patterns, and enable proactive maintenance to prevent equipment failures. This can result in energy savings, improved operational efficiency, and reduced environmental impact.

- Chemical and Petrochemical Industry [87]–[89]: The technologies employed in REAMIT can play a significant role in the chemical and petrochemical industry by monitoring and controlling critical parameters such as temperature, pressure, and gas levels. Real-time data analytics can help identify potential hazards, improve safety protocols, and optimise process efficiency.

- Construction Industry [90]–[92]: Real-time monitoring of environmental conditions, such as temperature and humidity, can aid in construction projects, ensuring optimal curing of concrete, minimising material degradation, and maintaining safe working conditions.

- Smart Vending Machines [93], [94]: Vending machines equipped with REAMIT technology can offer personalised information, real-time inventory tracking, and remote management capabilities. These machines enhance customer experiences and enable targeted marketing campaigns.

These examples demonstrate the wide-ranging scalability and applicability of the technologies employed in REAMIT across various business sectors. By leveraging sensor-based monitoring, data analytics, and real-time alerting, organisations can optimise their operations, reduce waste, improve product quality, and achieve sustainability goals. As these technologies continue to evolve and advance, their potential for scalability and cross-sector adoption is expected to grow, providing immense value to businesses across industries.

4. Conclusions and Future Research

Food waste is a global challenge amounting to 88 million tons or €143B per year, with approximately one-third occurring in agri-food supply chains. To address this issue, the EU is committed to halving food waste by 2030 across all stages of the supply chain. The integration of Internet of Things (IoT) technologies in the food industry presents an opportunity to revolutionise operations, enhance efficiency, sustainability, and safety throughout the supply chain. IoT enables real-time monitoring, tracking, and management of various processes, making it a potential game-changer for reducing food waste and environmental impacts. The Interreg NWE REAMIT project focused on applying innovative IoT technology to assist in combating the wastage in fruits, vegetables, meat, and fish within interconnected supply chains in Ireland, Germany, France, UK, Luxembourg, and the Netherlands.

Survey results of agri-food businesses demonstrate that while IoT's potential to slash food waste and improve operations is recognised, challenges like skills gaps, limited resources, and lack of IT infrastructure slow down the adoption. To mitigate these challenges, REAMIT partnered with pilot companies to deploy and test innovative IoT solutions in the agri-food supply chain and assess their effectiveness at reducing food waste. This report focused on presenting the solutions implemented for each company and assessing the market readiness level of these tested IoT technologies based on the lessons learned from each pilot.

Four solutions were proposed and tested in 10 pilot companies, namely (i) intelligent alerting based on trip detection for perishable food transportation clients, (ii) intelligent alerting with anomaly detection for perishable food storage clients, (iii) real-time Raman spectra analysis for perishable food transportation clients, and (iv) handheld spectrometer for consumer level quality monitoring. The pilot tests were conducted utilising the proposed REAMIT technology across different stages and products in the agri-food supply chain. After a minimum of 1 year of system testing, quantitative analysis and qualitative interviews were performed with each company.

An assessment of the piloted technologies show that a majority of those tested reached the maximum Technology Readiness Level (TRL) of 9, accompanied by an impressive Market Readiness Level (MRL) of 7. This attests to the advanced stage of development and the proximity of these technologies to full-scale implementation. Equally significant were the accomplishments of the remaining technologies, both based on spectral capture and analysis, which reached a commendable TRL of 6 and an MRL of 5 and 7 repsectively. These strides, although slightly earlier in their developmental journey, still mark substantial progress, indicating promising potential for further maturation and successful integration.

The findings and experiences gained from the implementation of REAMIT technologies provide valuable insights and pave the way for future research in several areas. These research opportunities can further enhance the effectiveness and application of IoT solutions in various industries. The analysis of data collected through REAMIT technologies can be further explored to develop advanced data analytics techniques and predictive models. Researchers can investigate machine learning algorithms and artificial intelligence approaches to identify patterns, trends, and anomalies in the data. This can enable proactive decision-making, predictive maintenance, and optimisation of operational processes.

While IoT technologies offer numerous benefits, their energy consumption and environmental impact require attention. Future research can focus on developing energy-efficient IoT devices, optimising energy consumption in IoT networks, and exploring renewable energy sources to power IoT deployments. Additionally, investigating sustainable practices and circular economy approaches within IoT ecosystems can contribute to overall environmental sustainability.

Enhancing the usability and user experience of IoT systems is crucial for widespread adoption. Future research can explore novel interaction techniques, intuitive interfaces, and intelligent user interfaces to facilitate seamless human-computer interaction in IoT environments. User-centered design methodologies and usability studies can provide insights into designing user-friendly IoT applications and improving user satisfaction.

Future research can also explore the societal impact of IoT deployments, including issues related to privacy, surveillance, data ownership, and algorithmic bias. Ethical frameworks and guidelines can be developed to ensure responsible and ethical use of IoT technologies. In addition, understanding the economic impact and developing sustainable business models around IoT deployments is crucial for long-term success. Future research can explore the economic implications of IoT technologies, including cost-effectiveness, return on investment, and value creation. Examining new revenue models, monetisation strategies, and economic frameworks can guide businesses in leveraging IoT for sustainable growth.

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6. Annex

A1. Technology Readiness Levels

TRL	Description	Phase
0	Idea Unproven concept, no testing has been performed	Idea
1	Basic Research Principles postulated and observed but no experimental proof available	
2	Technology formulation Concept and application have been formulated	
3	Applied research First laboratory environment (early prototype)	
4	Small scale prototype Built in a laboratory environment (early prototype)	Prototype
5	Large scale prototype Tested in intended environment	
6	Prototype system Tested in intended environment close to expected performance	Validation
7	Demonstration system Operating in operation environment at pre-commercial scale	
8	First of a king commercial system Manufacturing issues solved	Production
9	Full commercial application Technology generally available for all consumers	

A2. Market Readiness Levels

MRL	Description	Phase
0	Hunch You perceive a need within a market and something ignites	Ideation
1	Basic Research You can now describe the need(s) but have no evidence	
2	Needs formulation You articulate the need(s) using a customer/user story	
3	Needs validation You have an initial “offering”; stakeholders like your slideware	
4	Small scale stakeholder campaign Run a campaign with stakeholders (“closed” beta – 50 friendly stakeholders)	Testing
5	Large scale early adopter campaign Run a campaign with early adopters (“open beta – 100 intended customers).	
6	Proof of traction Sales match 100 paying customers	Traction
7	Proof of satisfaction A happy team and happy customers give evidence to progress	
8	Proof of scalability A stable sales pipeline and strong understanding of the market allow revenue projections	Scaling
9	Proof of stability KPIs surpassed an predictable growth	

A3. MTRL Questionnaire

1. PROJECT MATURITY
1. Project work is beyond basic research and technology concept has been defined. Principles postulated and observed but no experimental proof available. 2. Applied research has begun and practical applications have been formulated. 3. Preliminary testing of technology components has begun in a laboratory environment. Proof of concept. 4. Initial testing of integrated product has been completed in a laboratory environment. Early prototype. 5. Integrated product demonstrates performance in the intended environment. Large scale prototype.
2. PRODUCT DEVELOPMENT
1. Initial product/market fit has been defined. 2. Pilot scale product has been tested in the intended environment close to the expected performance. Prototype System. 3. Demonstration of a full scale product prototype has been completed in operation environment at pre-commercial scale. 4. The manufacturing issues has been solved and you have a first commercial product/service. 5. Product/service is available for all consumers
3. PRODUCT DEFINITION/DESIGN
1. One or more initial product hypotheses have been defined. 2. Mapping product attributes against customer needs has highlighted a clear value proposition. 3. The product has been scaled from laboratory to pilot scale and issues that may affect achieving full scale have been identified. 4. Comprehensive customer value proposition model has been developed, including a detailed understanding of product design specifications, required certifications, and trade-offs. 5. Product final design optimization has been completed, required certifications have been obtained and product has incorporated detailed customer and product requirements.
4. COMPETITIVE LANDSCAPE
1. Market research has been performed and basic knowledge of potential applications and competitive landscape have been identified. 2. Primary market research to prove the product commercial feasibility has been completed and basic understanding of competitive products has been demonstrated. 3. Comprehensive market research to prove the product commercial feasibility has been completed and intermediate understanding of competitive products has been demonstrated. 4. Competitive analysis to illustrate unique features and advantages of the product compared to competitive products has been completed. 5. Full and complete understanding of the competitive landscape, target applications, competitive products and market has been achieved.
5. TEAM
1. No team or organization (single individual, no legal entity). 2. Solely technical or non-technical founders running the organization with no outside assistance.

3. Solely technical or non-technical founders running the organization with assistance from outside (advisors, mentors, incubator, accelerator, etc.). 4. Balanced team with technical and business experience running the organization. 5. Balanced team with all capabilities onboard (technical, sales, marketing, customer service, operations, etc.) running the organization.
6. DOCUMENTATION
1. Solely technical descriptions have been elaborated, i.e., software documentation, architecture diagrams, etc. 2. User-oriented documentation has been created, such as user manual, installation guides, reference manual, etc. 3. Live demonstration resources have been developed (recorded videos, website with link to demo, etc.). 4. Position papers, press releases, posters, etc. have been elaborated for the dissemination of the project. 5. Marketing documentation has been created, such as a Business Model Canvas, etc.
7. INTELLECTUAL PROPERTY MANAGEMENT
1. No IPR have been defined. 2. Initial means of protection have been considered. 3. A proper and clear definition of shares has been elaborated. 4. An assignation of exploitation rights has been developed. 5. A contractual obligation regarding IPR has been established.
8. GO-TO-MARKET
1. Initial business model and value proposition have been defined. 2. Customers have been interviewed to understand their needs and business model and value proposition have been redefined based on customer feedback. 3. Market and customer needs and how those translate to product requirements have been defined, and initial relationships have been developed with key stakeholders across the value chain. 4. Partnerships have been formed with key stakeholders across the value chain (suppliers, partners, service providers, customers). 5. Supply agreements with suppliers and partners are in place and initial purchase orders from customers have been received.
9. MANUFACTURING/SUPPLY CHAIN
1. Potential suppliers, partners and customers have been identified and mapped in an initial value chain analysis. 2. Relationships have been established with potential suppliers, partners, service providers and customers and the have provided input on product and manufacturability requirements. 3. Manufacturing process qualifications have been defined and are in progress. 4. Products have been pilot manufactured and sold to initial customers. 5. Full scale manufacturing and widespread deployment of product to customers has been achieved.

A4. TRL Score

1. PROJECT MATURITY	2. PRODUCT DEVELOPMENT	TRL
-	5	9
-	4	8
-	3	7
-	2	6
5	1	5
4	1	4
3	1	3
2	1	2
1	1	1

A5. Weight of the MRL questions

QUESTION	WEIGHT
3. PRODUCT DEFINITION/DESIGN	4
4. COMPETITIVE LANDSCAPE	3
5. TEAM	7
6. DOCUMENTATION	2
7. INTELLECTUAL PROPERTY MANAGEMENT	1
8. GO-TO-MARKET	5
9. MANUFACTURING/SUPPLY CHAIN	6

A6. MTRL Matrix.

PRODUCT/ CUSTOM THRESHOLDS		TRL								
		1	2	3	4	5	6	7	8	9
MRL	1	1	2	3	4	5	6	7	8	9
	2	2	4	6	8	10	12	14	16	18
	3	3	6	9	12	15	18	21	24	27
	4	4	8	12	16	20	24	28	32	36
	5	5	10	15	20	25	30	35	40	45
	6	6	12	18	24	30	36	42	48	54
	7	7	14	21	28	35	42	49	56	63
	8	8	16	24	32	40	48	56	64	72
	9	9	18	27	36	45	54	63	72	81

Insufficiently prepared	It seems almost impossible that the result/s can be introduced into the market successfully
Fairly prepared	The results are ready to be commercialized, but there is still room for enhancement and some aspects should be improved
Greatly prepared	The sales are going well, and the product/service is stable

Disclaimer: *This document was prepared by James Gillespie, Tamíris da Costa, Elaine Ramsey, Trevor Cadden, and Joan Condell (j.gillespie1@ulster.ac.uk; tamiris.dacosta@ucd.ie) to the best of their knowledge, in association with REAMIT project team. All information provided in this document are verified and found correct at the time of publication – June 2023.*