WP T3 - Deliverable 1.2

Life Cycle Assessment of REAMIT Technologies

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

Executive summary

The REAMIT project aims to tackle the significant issue of food waste by leveraging cutting-edge technologies and data-driven approaches. By deploying Internet of Things (IoT) technologies and harnessing Big Data analytics, the project seeks to optimise resource utilisation, improve supply chain efficiency, and ultimately reduce waste throughout the agribusiness sector. The waste reduction framework, integrated with the IoT sensors, enabled real-time monitoring and data collection on food quality. Key findings and outcomes of deliverable 1.2 of the REAMIT project are presented in this report.

In this deliverable, the focus was placed on conducting a Life Cycle Assessment (LCA) to evaluate and understand the environmental implications of the REAMIT project's interventions. The LCA tool developed specifically for this project was used to estimate the environmental impacts associated with the food supply chains, which was subsequently applied to analyse four pilot cases within the REAMIT project: Yumchop, Human Milk Foundation (HMF), Burns Farm Meats, and WD Meats.

The results of the LCA assessments indicated reductions in food waste, which directly translated into environmental benefits. The findings highlight the project's effectiveness in reducing food waste through the use of IoT technologies and its significant potential for transforming agribusiness supply chains towards a more sustainable and resource-efficient future. The insights gained from the analysis of the four pilot cases provide valuable guidance for replicating the positive outcomes through the entire food supply chain and will inform decision-makers, stakeholders, and industry leaders in their efforts to mitigate food waste and enhance environmental performance across the agribusiness sector.

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1. Introduction

Around 10% of food made available to EU consumers (at retail, food services and households) may be wasted [1]. These losses occurred at different stages of the food supply chain (FSC) i.e. in companies converting the raw agricultural materials into final products feasible for direct consumption [2]. Literature suggests that issues within FSC management leading to food waste are numerous, including inadequate processing and packaging, lack of transportation and distribution systems and inadequate storage facilities and techniques [3,4], and call for targeted action.

In particular, in the EU, nearly 57 million tonnes of food waste (127 kg/inhabitant) are generated annually, with an associated market value estimated at 130 billion euros [1]. By preventing food waste, companies can sell more food and create more revenue. However, the importance of reducing food waste has been recognised worldwide not only because food waste causes serious economic impacts but also due to environmental and social consequences [5]. Due to the amount of resources (water, nutrients, fertilisers, etc.) consumed during food production and distribution, food waste saved is much more than the face value of the waste itself for society [6]. Regarding environmental effects, the food sector accounts for over 30 % of global greenhouse gas (GHG) emissions [2]. Significant carbon emissions result from the production of food that is wasted, and the wasted food will emit more GHG in landfill, causing significant environmental impacts. To reduce carbon emissions, various companies have been seeking ways to reduce their own emissions [7].

Recent research supports the importance of using smart technology such as the Internet of Things (IoT), machine learning and blockchain to advance and improve FSC management [5,8–12] and thus help reduce food waste. The IoT is a growing network of objects that communicate between themselves and other internet-enabled devices over the Internet and allows users to monitor and control the physical world remotely [13]. In the supply chain context, Abdel-Basset et al. [14] defined IoT as a set of digitally connected physical objects for sensing and monitoring supply chain interaction, agility, visibility and information sharing to facilitate the plan, control, and coordination of supply chain processes within an organisation. In addition, adopting IoT is a potential opportunity to upgrade and reshape the FSC [12], and help data-driven decision-making in supply chain management [15].

Several areas in the field of IoT implementation in the FSC were discussed in the literature, including implementation models and frameworks [16–18], managing risks and revenues [9,19], platform design [16], usefulness [20], supply chain sustainability [21], supply chain coordination and information sharing [19]. Even though IoT and FSC applications were discussed in the literature, there is a lack of studies on tools assessing the environmental performance of different food products, food supply chain stages and technologies used to reduce food waste in FSC [22].

Life cycle assessment (LCA) is a methodology that can analyse the environmental impacts of products or processes by inventorying all the inputs and outputs throughout the product's life cycle, from raw material production to end-of-life [23–25]. This methodology determines where the most significant impacts occur and where the most relevant improvements can be made while identifying potential trade-offs [26,27]. It allows companies to investigate areas where they might improve [28,29]. Despite a protracted theoretical discussion on the simplification of LCA, few approaches and tools have been developed and proposed for the agri-food sector. Food products are not part of the scope of a significant part of the tools found in the literature, which are focused on the building [30–33] and energy [34–36] sectors. Only a few tools have been developed to conduct LCAs in agriculture [37,38]. However, these tools have a limited scope and does not allow the understanding of the environmental impacts of different stages of the food supply chain or implementing IoT technologies to save food waste. Therefore, such a tool will be invaluable given the increasing trend in the food industry for using new technologies.

Therefore, this deliverable fills this gap and contributes to the knowledge regarding the trade-offs between the environmental impacts of IoT technologies and the reduction of food waste. A new adaptable open-source tool (REAMIT-LCA Tool) was developed to conduct an extensive environmental evaluation of food supply chains in compliance with International Standard Organization's (ISO) 14040/14044 guidelines [39,40]. It is publicly available online, has a user-friendly framework and can run in Microsoft Excel. Furthermore, it can be applied in different countries of North West Europe.

Unlike previous tools developed for LCA, the REAMIT-LCA tool includes other impact categories besides global warming, such as fossil scarcity, land use, human toxicity and water consumption. The tool is used to compute the contribution of each stage of the food supply chain to support food producers, food supply chain companies (processing and logistics), local authorities, academics and digital technology providers in conducting LCA and exploring the problem of food waste and the solutions to achieve more sustainable food systems. Additionally, developing a complete LCA can be difficult and time-consuming, particularly discouraging to non-experts. Therefore, it also aims to reduce the computational time and processing, which the other LCA tools have not yet resolved.

The report is organised as follows. The REAMIT-LCA tool scope is discussed in section 2, along with the modelling methods and data sources, Yumchop is discussed in section 3, Human Milk Foundation in section 4, Burns Farm Meats in section 5, WD Meats in section 6 and Musgrave in section 7. Results are presented and discussed in Section 8. Conclusions are shown in the last section.

2. REAMIT-LCA tool

This tool has been developed based on the work performed in the REAMIT project. This project was launched to support food companies in North-West Europe (NWE) to reduce food waste by applying existing innovative technologies, such as the Internet of Things (IoT) and Big Data [41]. IoT technologies have been identified as a potential breakthrough class of technologies to reduce food waste this decade [42–44]. Through testing and adaptation, these technologies enabled the continuous monitoring and recording of food quality and potential issues [8,45]. Through analytics, owners of 'food to be at risk of becoming waste' are provided with decision support options to minimise food waste, including redistribution to nearby customers [46,47]. The project focused on fruits, vegetables, meat and fish, which are wasted in large quantities. The supply chain included farms, packaging sites, food processors, distribution, logistics, wholesalers and retailers. The project was carried out in Ireland, Germany, France, Luxembourg, the UK and the Netherlands due to the interconnected food supply chains and massive food waste in these countries [41].

The REAMIT project observed that there was demand among its partners, food product manufacturers, for a tool providing insight into the environmental performance of their products. This demand arose from a desire to improve the environmental profile of products across the product chain. The food supply chain is a very diverse sector comprising manufacturers specialised in a wide range of complex food products [48,49]. In many cases, the results of existing generic LCAs tools cannot be translated into the food supply chain practice [22]. Therefore, it was essential for the tool to be adaptable, allowing the users to model and analyse their specific product system. The tool, which was named the REAMIT-LCA tool, was developed as a joint venture by researchers from a variety of organisations and food companies and is available to companies without fees.

It contains LCA information on the processes in each phase of the food production chain and provides a life cycle framework to help evaluate diverse categories of food products in a consistent manner. The user constructs a product's life cycle by selecting the relevant food materials and, subsequently, the appropriate production process(es) per life cycle phase. The tool focuses on 12 different impact categories to offer a comprehensive view of the potential environmental impacts of the organisation under analysis. With the tool, the company can gain insight into its products' life cycles and the contribution of company-specific production processes within the entire life cycle. It can also be used to develop strategies to reduce the environmental impacts associated with food waste production and for food companies to evaluate their processes and make necessary improvements at an early stage of development.

The REAMIT-LCA tool is a spreadsheet-based, stand-alone model operating in Microsoft Excel through which the user can navigate, and it is compatible with both PC and Mac versions of Excel. The tool is available at da Costa et al [50]. Before starting, for security reasons, the "Trust Center" settings in Microsoft Excel must be set to allow needed Visual Basic for Applications (VBA) code to execute. Click the "Enable Content" button next to the security warning message to open the tool's main Menu dialogue box. The tool is organised in separate sheets where users can check and adjust the data to fit their own processes. It follows the four phases of the LCA methodology, according to ISO 14040/14044 [39,40]. The LCA tool's general structure, including the life cycle stages of the food supply chain, can be seen in Figure 1. The methodological framework and the Excel-based tool will be described in the sections below.

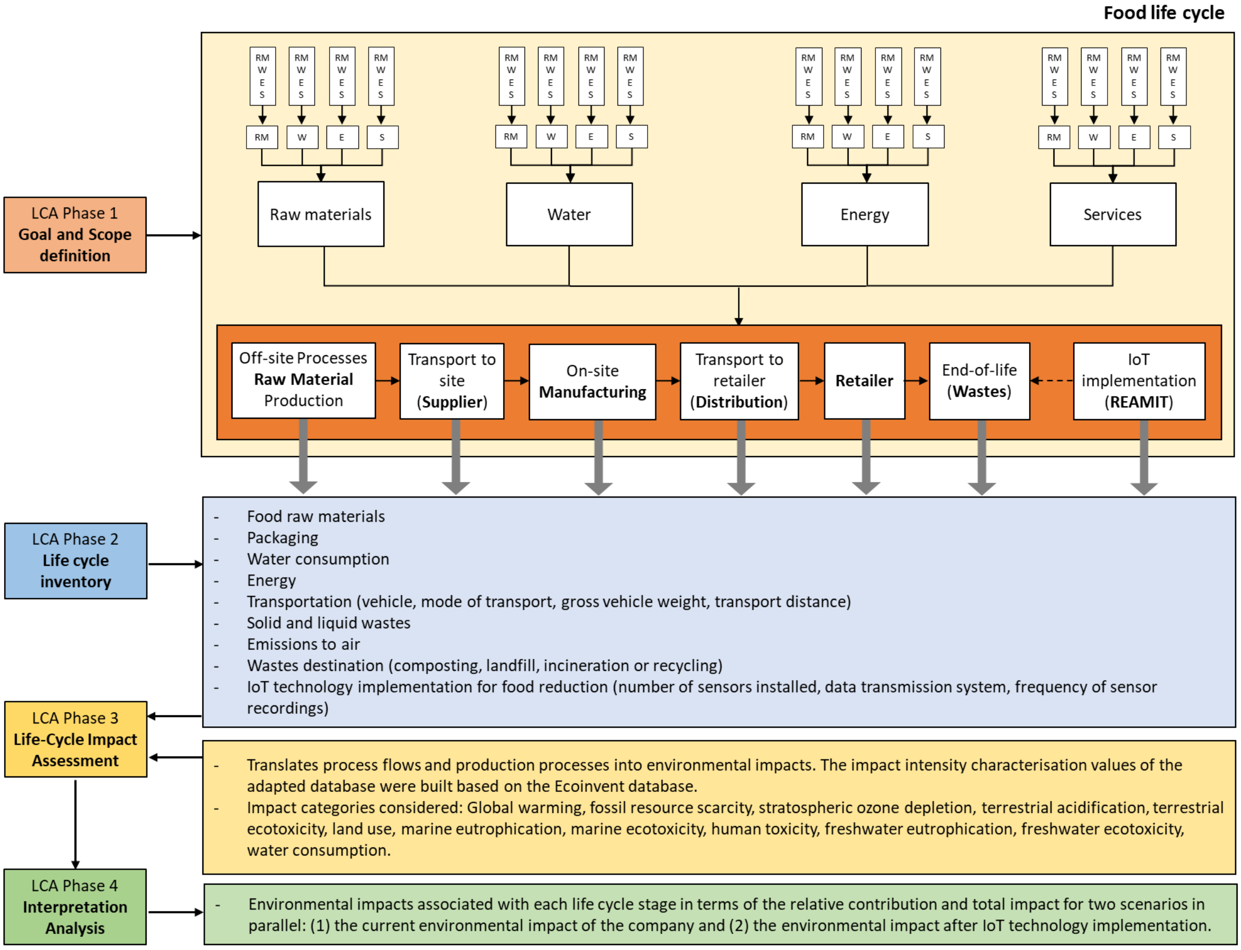

Figure 1. General structure of the LCA tool, including the life cycle stages of the food supply chain.

2.1 Goal and scope

The tool is recommended for food producers, food supply chain companies (processing and logistics), local authorities, academics and digital technology providers to explore the problem of food waste and the solutions to achieve more sustainable food systems. In addition, it captures the entire food supply chain (from cradle-to-grave) and contains information on a wide range of materials, production processes of various food manufacturing phases, packaging materials, end-of-life treatments and transportation modes. The user can construct the entire life cycle by selecting the appropriate processes per life cycle stage. The life cycle stages considered by the tool are shown in Figure 2.

Figure 2. Life-cycle stages considered in the REAMIT-LCA tool.

The system boundary encompasses seven stages: raw materials, supplier, manufacturing, distribution, retail, wastes and REAMIT technology. The raw material's general scope includes acquiring an initial set of food products. More than 60 food products were included in the tool database and were organised into four categories: (i) cereals, leguminous crops and oil seeds, (ii) vegetables, roots and tubers, (iii) fruits, and (iv) animal products. The supplier stage includes raw materials transportation from the supplier to the food company under analysis. It allows the user to select between different types of vehicles, modes of transport and gross weight.

In the manufacturing stage, it is possible to include some inputs from the food manufacturing process, such as water consumption, energy (including electricity and fuels), and packaging materials. Some output emissions to air and water are also included in this stage. Solid waste generation, including packaging materials and food waste, were organised in a specific stage. The distribution consists of product transportation from the food company to retail. The inputs included in the retail consist of energy consumed during food storage.

The tool is general and should be adapted to each food company, i.e., each company can fill the stages present in their life cycle and disregard the unnecessary stages. The functional unit of the reporting results will refer to the amount and nature of food products provided by the food company over the reporting interval. In this case, the functional unit is the sum of all products included in the distribution stage and allocation between products is not available in this tool. The reporting interval is recommended to be one operation cycle of the food company, i.e., one year is the preferred option.

In the tool, the goal and scope worksheets include: 1) the menu with the links for all the stages of the food chain that can be analysed using this tool and 2) a more information worksheet that provides the author list, a brief user guide containing the purpose of the project and some specifications of the tool, the terms of use and a tutorial video.

2.2 Life cycle inventory

The food supply chain life cycle inventory worksheets include all essential inputs and outputs that need to be filled to run the tool and generate results. General and pathway-specific assumptions may be changed on this worksheet. Since the REAMIT-LCA tool is designed for food companies, users can either complete the product's entire life cycle (seven stages) or investigate one specific production phase (e.g. distribution).

Users start selecting the food raw material item of interest and the appropriate weight. By changing the values of consumption, the figures on the results worksheets will update automatically. The tool does not calculate any material quantities. The user should perform calculations before modelling the food materials in the tool. It should be noted that quality data is crucial in the life cycle assessment methodology. In this sense, the highest possible level of detail is required. In addition, the user should document any assumptions that go into the calculations.

If the user intends to evaluate the transportation performance in the distribution stage, additional information should be provided using the drop-down lists included in the tool. In this stage, the user must select the appropriate transportation specifications under three forms – train, ship, and road vehicle (lorry). In addition, the transportation distances (in km between origin and destination) associated with the food materials used by the company should be provided, as well as the mode of transport (freezing, cooling, or none) and, if applicable, gross lorry weight.

In the manufacturing stage, all inputs consumed for food production must be added, including consumption of water, energy and packaging materials. Some inputs have regionalised characterisation factors, such as electricity consumption; therefore, the user must select in which country the consumption is made. Data selected for inclusion in the tool reflect national averages and do not reflect regional variation in practice. A list of outputs that may occur during the manufacturing step is also provided, such as emissions to air and water. Solid waste was organised in a different worksheet, including all solid waste produced in the previous stages. In this stage, it is necessary to define the final destination of each solid waste using the drop-down menu, for example, composting, landfill, incineration or recycling. Some final destination options are limited to specific scenarios due to database limitations.

The REAMIT stage is treated as a sensitivity analysis case of the LCA methodology, where temperature and humidity sensors and a Big Data server are hypothetically implemented in the company to monitor food quality and prevent its degradation along the supply chain. In this stage, it is possible to simulate the incorporation of temperature sensors in the company's system, selecting the number of sensors planned, the data transmission system (GSM-based or LoRa) and the frequency of sensor recordings per hour, which will influence the amount of data stored in the Big Data cloud server and consequently the electricity allocation. Credit is given to the system for avoiding additional food production to cover the losses and all related upstream activities avoided, according to the amount and type of food avoided.

The sensors considered in the REAMIT-LCA tool are composed of a printed circuit board (PCB), flexible copper cables, a temperature/humidity probe, lithium batteries, stainless steel screws and a housing top and bottom made with plastic. Installation of the sensor is performed manually, and no environmental burden was assumed. The life span of the sensor considered in this study is 10 years [51]. The sensors transmit the temperature/humidity information to a Big Data Server, and the user can select the mode of transmission, i.e. via a GSM-based (4G) or LoRa network. In this study, sensors operating through a GSM-based mode are composed of four lithium batteries that provide energy to support temperature/humidity analysis and data transmission. Therefore, no other electricity or power is required during the use phase of this type of sensor. According to the supplier, the batteries last about 4 years, considering one recording every 20 minutes. However, the field testing showed that the lifetime is 87% lower. The complete inventory data of raw materials, manufacturing, use, and end-of-life were described in da Costa et al. [52].

On the other hand, sensors operating through a LoRa network have a lower power consumption and require only two batteries. According to the supplier, LoRa sensors batteries last around 4-6 years, considering one measurement every 20 minutes. In this case, additional digital technology is required to transmit the data to the Big Data Server, as many countries still do not have a countrywide LoRa network. Therefore, it is necessary to integrate a gateway connecting two networks with different transmission protocols. In this scenario, it was considered that the gateway operates 24h per day and has a power consumption of 7W. The only exception is the sensor that operates in the Netherlands, as KPN deploys the LoRa IoT network across this country and sensors work without an additional gateway.

The sensors used in this study were manufactured in South Africa, but most of the electronic components of the PCB were produced in China as well. The sensors were transported to the UK in a container ship as a whole component, and the batteries were also included. A freight lorry was used for transportation within the UK. Transport distances were calculated based on the distance from the production site to the HMB. The air emissions due to the combustion of diesel and heavy fuel oil during the sensor transportation were taken from Ecoinvent [53]. The electricity consumed during the manufacturing phase for mounting the PCBs and the sensors was taken from Chiew and Brunklaus [51]

The sensors were installed inside the bag of each volunteer blood biker making regular journeys. Installation of the sensor is performed manually, and no environmental burden was assumed. The life span of the sensor is around 10 years, depending on the environmental conditions [51]. According to the supplier, the batteries last about 4 years, considering one measurement every 20 minutes. However, in this study, the sensors measure the conditions every 2 min; therefore, it is estimated that the batteries will last about 5 months each.

For the end-of-life phase of the sensor's components, it was considered that the sensor housing, the copper cables, and the screws were recycled, while the PCB was reused, and the batteries and the antenna were sent to a landfill, as they cannot be recycled at this time. It was considered that 100% of the solid wastes reach the final disposal (regardless of the technique used). The sensors components were weighted, and the complete inventory data of raw materials, manufacturing, use, and end-of-life were described in Table 1.

Table 1. Life cycle inventory of sensor manufacturing, transportation and use per single unit working one year.

Unit Process	Value	Unit
Inputs		
Raw materials		
Printed circuit board	1.576	g
Copper flexible cable	1.114	g
Antenna with ceramic tip metal probe	0.530	g
Alkaline batteries	219.2	g
Stainless steel screws	0.384	g
Housing top and bottom	6.746	g
Manufacturing		
Electricity	0.0044	kWh
Transportation		
Heavy fuel oil (container ship)	0.00062	L
Diesel (freight, lorry)	0.00024	L
Outputs		
Products		
Sensor	1	unit
Solid wastes		
Printed circuit board	1.576	g
Copper flexible cable	1.114	g
Antenna with ceramic tip metal probe	0.530	g
Alkaline batteries	219.2	g
Stainless steel screws	0.384	g
Housing top and bottom	6.746	g
Air emissions (transportation)		
CO_2, fossil	2.617	g
CO, fossil	0.002	g
CH_4, fossil	0.034	mg
NMVOCs	0.002	g
N_2O	0.134	mg
NO_x	0.047	g
SO_2	0.028	g
Particulates	0.004	g

The data is transmitted to the server, and alerts are sent when the temperature exceeds an acceptable limit. This alert helps the company fix any malfunctioning of the fridge/freezer before the stored items go to waste due to temperature fluctuations. The Big Data Server comprises one unit of computer equipment, a redundant power supply, processors and storage drives with a total capacity of 3.7 TB. The estimated electricity consumption of the server is 1152 kWh per month. To allocate the electricity consumption, it was considered that each row of data generated per recording occupies around 87 bytes in the server.

The database worksheet contains a list of materials used in the food supply chain (e.g., food products, packaging, water, fuels, electricity, etc.) and associated characterisation factors used to perform the environmental impact estimation, as well as a list with acronyms. The inventory data of raw materials production, water, energy and emissions due to transportation were taken from the Ecoinvent database [53]. Environmental impact data are specified for the unit database items. Therefore, the user cannot edit or delete default database items in this worksheet since it may affect the reference and the code in the model's background. For each input and output, there is a specific cell with calculations in the worksheet life cycle impact assessment (LCIA); the methodology will be explained in the section below.

2.3 Life cycle impact assessment methodology applied in the tool

This section provides a summary of the LCIA methodology structure to give the user a quick overview of the model's main features used in the REAMIT-LCA tool. It follows the computational structure of the life cycle assessment proposed by Heijungs and Sangwon [54]. In short, the LCA principle can be presented with three matrix equations. Equation 1 is used to translate process data into a production system.

$$\boldsymbol{s} = \boldsymbol{A}^{-1}.\boldsymbol{f} \tag{1}$$

where s is the scaling vector which describes the necessary intensity of production processes, A is the database of process flows and production processes, and f is the final demand vector or the output desired from the system. The scaling vector calculated from the first equation is used to determine the intensity of emissions from unit processes (Equation 2).

$$\boldsymbol{g} = \boldsymbol{B}\,.\,\boldsymbol{s} \tag{2}$$

where g is the emission inventory vector describing the emissions caused by the whole system, and B is the unit emission matrix (a database of process values).

Equation 3 translates emissions into environmental impacts (e.g. CO2 emissions into climate warming potential).

$$\boldsymbol{h} = \boldsymbol{Q}\,.\,\boldsymbol{g} \tag{3}$$

where $\boldsymbol{h}$ is a vector representing the environmental impacts caused by the system and $\boldsymbol{Q}$ is a characterisation matrix (a database of impact intensity characterisation values).

The model follows the International Standard Organization's (ISO) 14040/14044 guidelines [39,40]. The characterisation factors and the impact categories used in this tool are those of the ReCiPe method at the midpoint level following a hierarchical perspective [55]. The following environmental impact categories were included in the tool: Global warming (GW), fossil resource scarcity (FS), stratospheric ozone depletion (OD), terrestrial acidification (TA), terrestrial ecotoxicity (TE), land use (LU), marine eutrophication (MEu), marine ecotoxicity (ME), human toxicity (HT), freshwater eutrophication (FEu), freshwater ecotoxicity (FE), water consumption (WC).

2.4 Interpretation

Having filled the inventory of relevant processes in the previous sections, the user can view the environmental results on the LCA results worksheet by clicking the "Next" button available in the top right corner of the tool. The charts built in this worksheet show the environmental impacts associated with each life cycle stage (raw materials, supplier, manufacturing, distribution, retail, wastes) for two scenarios in parallel: (1) the current environmental impact of the company and (2) the environmental impact after IoT technology implementation (REAMIT strategy). Results are shown for the 12 impact categories in terms of the relative contribution of each stage of the supply chain (Figure 3), while a table shows the absolute values of each impact category results per stage.

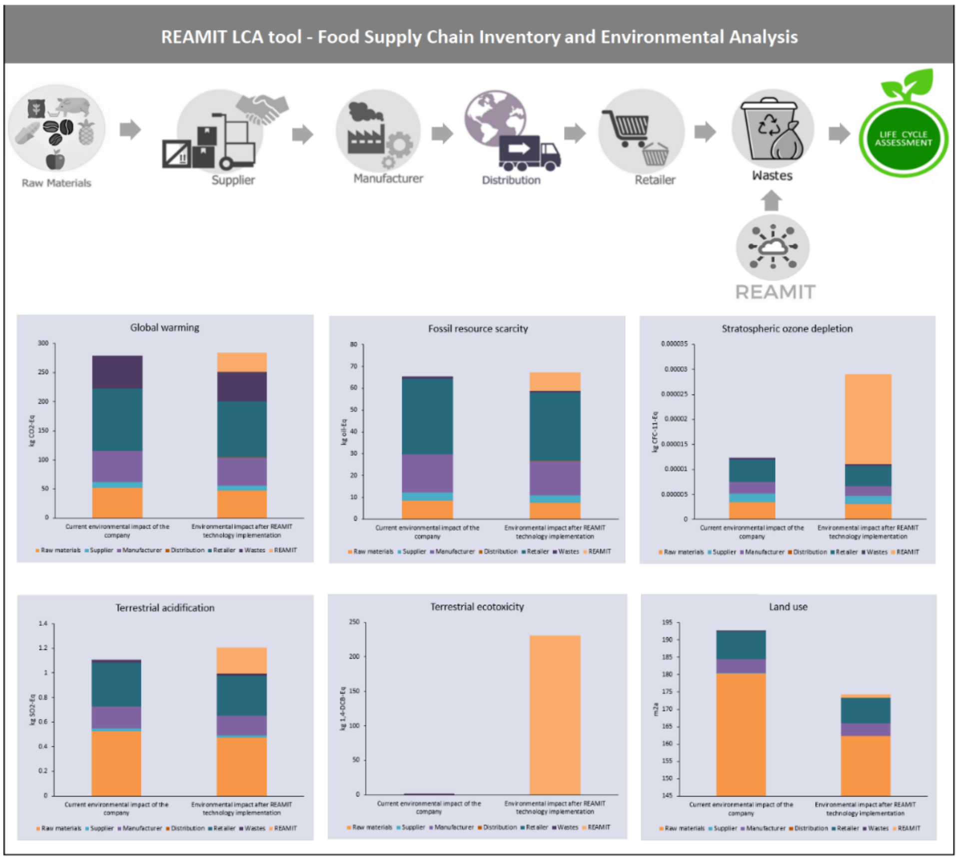

Figure 3. Example of results given by the REAMIT LCA tool.

These graphs can support the user in visualise the life cycle stages that substantially influence the overall environmental impact of the organisation under consideration. To better comprehend the causes behind the environmental impacts, the user can explore the details of the numerous process contained in those life cycle stages, which can then be used to identify viable solutions to reduce those impacts. The user can find further explanations about how to interpret LCA findings in Zampori et al. [56]. To select and copy an existing graph in the results, click the "Copy" button and then click the "Paste" button in another document. Save the file and exit the tool.

2.5 Tool assumptions and limitations

The use of results is designed to provide insight into the life cycle of a company's food products, as well as the contribution of company-specific production stages within the entire life cycle. It can also be used for assessing the environmental impacts of improvement options. However, caution should be taken when interpreting the LCA results. To use the REAMIT-LCA tool, knowledge about the manufacturing phases of food products and LCA interpretation is recommended. The user is responsible for the selection of the appropriate inputs and outputs. The tool does not check data quality. The user is responsible for reviewing the completeness, consistency, and accuracy of the data related to all items (type of food products, quantity, etc) used in the analysis.

In addition, the tool is built assuming that each alternative's functional unit is the same. The definitions of the functional units or the alternatives should be equivalent if the study's objective is to compare alternatives. When comparing different options, it is the user's responsibility to choose the proper functional unit. In addition, the tool does not check for improper comparisons or does not provide warning message notices. The tool will still present the results for any analyses the user sets up, but the results may be unreliable or inaccurate. Therefore, it is the user's onus to make sure that the proper comparisons are made.

The tool supports only specific measurement units, mainly from the International System of Units. If the units the user needs to include are different from what the tool can handle, the user must convert them to the ones compatible with the tool before entering the data. For example, pounds (lbs) are not supported by the tool. The user would need to convert that to other units of mass compatible with the tool (e.g., kilogram) before adding the data.

Avoided impacts due to food waste reduction were modelled in the tool through the system expansion by substitution [57]. Credit was given for avoiding additional food production and all related upstream activities, such as collection, transport and energy required to store the food. However, time frame mismatch was not considered, so avoided emissions estimates must be interpreted cautiously. In addition, the consumption phase is not included in the system boundaries nor the impacts due to infrastructure establishment.

3. Yumchop

3.1 Definition of goal and scope

The goal of the assessment is to assess the potential environmental impacts of a food manufacturing company located in the UK that prepares frozen food meals for customers via vending machines in which microwave ovens are integrated for heating the food. This innovative hot-cooked food business creates meals that combine multi-cultural traditions, responsibly sourced ingredients free from added preservatives, colouring or flavourings, and packaged in environmentally friendly recyclable and biodegradable packaging. The study focuses on one facility where the entire operations occur.

The functional unit was defined as the total production of frozen food meals during one year of operation, i.e. 9900 kg of frozen food boxes, between January and December of 2021 (reference period). Two scenarios were built to determine the potential environmental savings due to the implementation of a monitoring system based on IoT technologies. Scenario A represents the baseline and includes the processes associated with the food company. Scenario B follows the same processes as scenario A but includes the IoT technologies used to monitor the food quality conditions in the cold storage process during manufacturing.

The system boundaries are illustrated in Figure 4 and follow a cradle-to-grave approach. The processes include raw materials acquisition from the supplier and transportation to the factory, manufacturing (vegetable, meat, poultry and dry ingredients preparation, cooking, finish goods and storage), distribution, retail and solid wastes treatment. Scenario B also comprises digital sensors for measuring the specific parameters, the Big Data server and the food waste avoided. Both scenarios exclude food raw materials production and consumption.

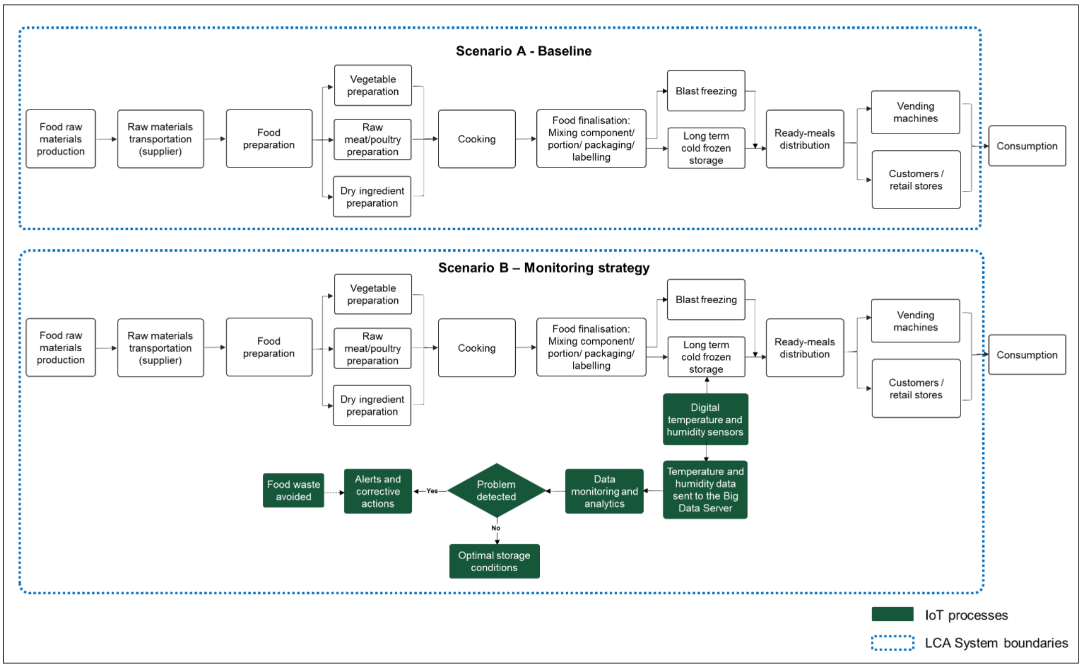

Figure 4. Schematic representation of the Yumchop's system boundaries. (A) refers to the baseline scenario, and (B) refers to the IoT monitoring strategy implementation.

3.2 Life cycle inventory

The direct activities data was collected through company interviews. The company uses locally sourced raw materials (vegetables and meat) to prepare their ready-meal products. Fresh vegetables (beans, pepper, etc.) are usually purchased from suppliers located within a radius of 100 km. The vegetables are manually washed, diced, and immediately frozen in blast freezers for 3 hours. After the blast-freezing stage, the vegetables are stored in a chest freezer. Rice and other dry foods are stored in the dry room.

Meat (chicken and sheep) is purchased from local suppliers located 30-50 km from the factory. It was considered the average distance (mean: 40 km) for calculation purposes. The meat is transported fresh in temperature-controlled vehicles and stored in fridge storage as soon as it arrives at the production site. The meat is left marinating with oil and spices for two days in the fridge before cooking. Once the food is cooked, it is transferred into a blast freezer to refrigerate the meals for approximately 3 hours. The food is weighed and manually packaged in paper boxes of 330g each. After this process, the boxes are transferred to long-term storage in a cold room with temperatures from -18 to -24 °C. Although cooking is a straightforward method, it involves some waste, nearly 8-10 %. For modelling purposes, it was assumed that the food waste would be sent to a municipal sanitary landfill for further management.

The food can be delivered directly to the consumer's home (online shopping) or sent to vending kiosks. The boxes are transported frozen over an average distance of 100 km in refrigerated lorries. Table 2 presents the transportation profile of the company under analysis.

Table 2. Yumchop transport profile.

Food Group	Inputs	Unit	Transport distance	Vehicle	Mode of transport	Gross lorry weight
Cereals, leguminous crops and oil seeds	Bean	km	100	Lorry	None	3.5 - 7.5 t
	Rice	km	100	Lorry	None	3.5 - 7.5 t
Vegetables, roots and tubers	Pepper	km	100	Lorry	None	3.5 - 7.5 t
Animal production	Chicken	km	40	Lorry	Freezing	3.5 - 7.5 t
	Sheep	km	40	Lorry	Freezing	3.5 - 7.5 t
Product	Food boxes	km	100	Lorry	Freezing	3.5 - 7.5 t

Currently, the company has 9 installed vending machines located at train stations, universities, and hospitals in London. Each vending machine can hold up to around 75 boxes of prepared food, and the stock is replenished when it goes below 25 packs (depending on the train station, it can take a few days). The retail kiosks are fitted with an integrated microwave, enabling the consumer to heat the food upon purchase. The product expiry date is 18 months from the production date when it is kept at a controlled temperature. However, the company is ensuring that no product spends more than 6 months in the freezer utilising the first in first out (FIFO) approach. The life cycle inventory of scenario A is shown in Table 3 and represents the total production of food boxes per year.

Table 3. Yumchop life cycle inventory per reporting flow.

Unit Process	Value	Unit
Inputs		
Vegetable preparation		
Beans	1200	kg
Pepper	4800	kg
Water	38.1	m^3
Plastic bag	8.4	kg
Electricity consumption blast-freezing	561.6	kWh
Electricity consumption short-term storage	232.8	kWh
Meat preparation		
Boneless chicken	6480	kg
Chicken wings	6480	kg
Sheep	3840	kg
Electricity consumption blast-freezing	561.6	kWh
Electricity consumption short-term storage	1555.2	kWh
Dry ingredient preparation		
Rice	18000	kg
Food finalisation		
Paper box	1000	kg
Electricity consumption long-term storage	1509.1	kWh
Retail		
Electricity consumption vending machines	77760	kWh
Outputs		
Products		
Food boxes	9900	kg
Solid Wastes		
Food losses	891	kg
Plastic bag	8.4	kg
Paper box	1000	kg
Liquid Wastes		
Wastewater	38.1	m^3

In scenario B, 8 sensors were installed to monitor the temperature and humidity to ensure that frozen food and raw materials for preparing the food are stored at the right temperature in the frozen food manufacturer's factory. Figure 5 presents the location of each sensor. The sensors considered in the REAMIT-LCA tool transmit data via a GSM-based communication network every 20 minutes.

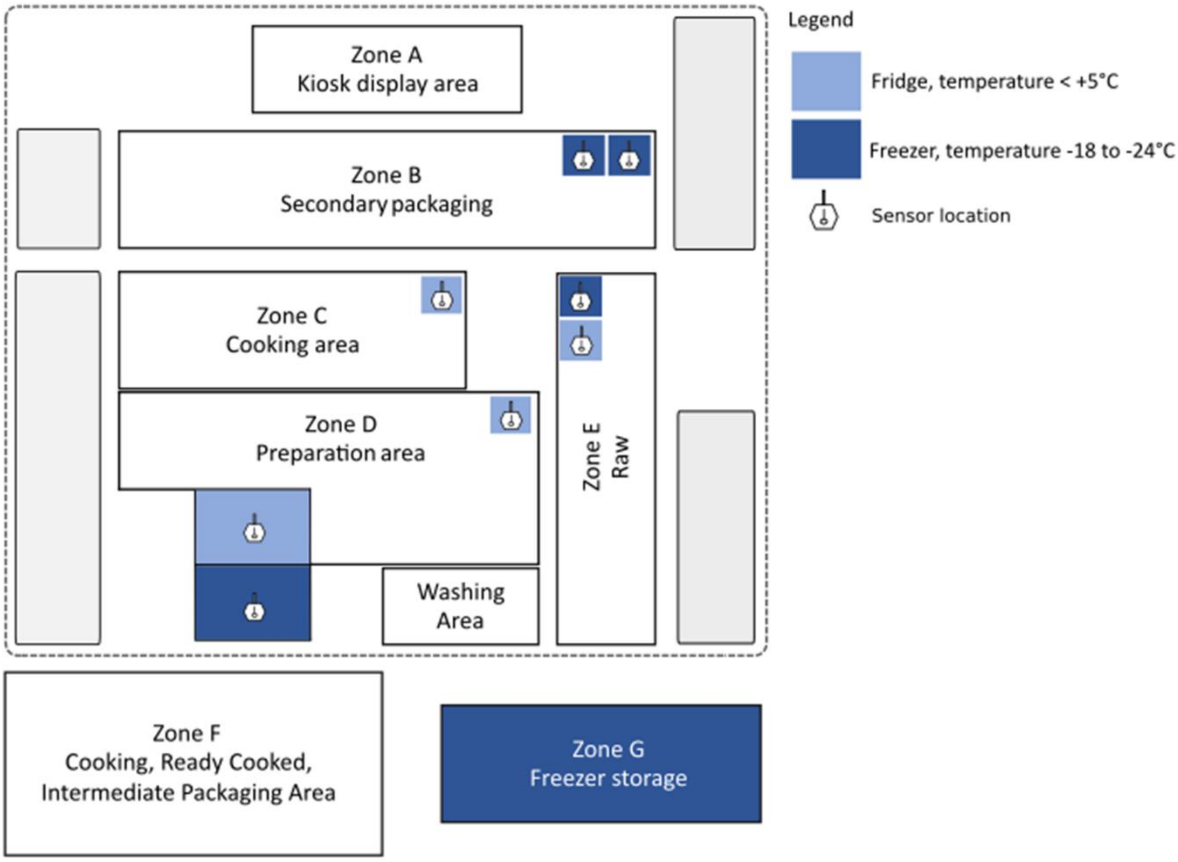

Figure 5. Layout showing the locations of REAMIT sensors in Yumchop's premises.

Although temperature monitoring and controlling are imperative measures of quality control, the fluctuations can be well within the acceptable range for ensuring the quality of food. Any measurement going beyond the suggested temperature range for a considerable time will result in food waste. Alerts are sent to Yumchop when two measurements in a row are over the temperature thresholds shown in Table 4.

Table 4. Temperature thresholds, food type and number of alerts for each equipment.

Equipment	Food type	Temperature thresholds	Number of alerts
Zone C – Fridge	Meat/Vegetables	+5 °C	50
Zone B – Freezer 1	Products	-18 °C	0
Zone B – Freezer 2	Products	-18 °C	0
Zone D – Cold room freezer	Products	-18 °C	10
Zone D – Cold room fridge	Products	- 18 °C	4
Zone D – Fridge	Meat/Vegetables	+5 °C	2
Zone E – Fridge	Meat	+5 °C	9
Zone E – Freezer	Vegetables	-18 °C	4

One year of data was analysed to determine the number of alerts, from 12th March 2022 to 12th March 2023. Temperature thresholds for food spoilage are those used for alerting at Yumchop defined on the Whysor platform.

The legal requirement in England, Wales and Northern Ireland, and recommended in Scotland for refrigerated foods state that it is recommended that fridges and chilled display equipment should be set at 5˚C or below. This is to make sure that chilled food is kept at 8˚C or below. If food has been kept at 8 ˚C or above for more than 4 hours, it should be thrown away [58]. Therefore, it was considered that threshold abuse for fridges needs recorded continuously for 4 hours before the load is considered waste. Once a load is considered waste, a 2-day period is applied to allow for stock to be replaced before checking for temperature abuse again (this is to avoid double counting food waste).

For frozen foods it is stated that a fully stocked freezer should stay at a safe temperature for roughly 48 hours if the door is kept closed. Without power, a half-full freezer should be safe for about 24 hours [59]. Therefore, it was considered that threshold abuse for freezers needs recorded continuously for 24 hours before the load is considered waste. Once a load is considered waste, a 2-day period is applied to allow for stock to be replaced before checking for temperature abuse again (this is to avoid double counting food waste).

3.3 Sensitivity analyses

Two sensitivity analyses were performed to understand the influence of some parameters on the environmental impact assessment results. A sensitivity analysis was made to assess the effect of the food waste avoided on the environmental impacts. Therefore, a scenario was considered in which the IoT technologies avoided wasting food products based on the alerts mentioned in the section above. In the tool, the environmental burdens avoided are modelled through the system expansion by substitution [57]. Credit is given to scenario B for avoiding additional food production to cover the losses in scenario A and all related upstream activities, such as transport and energy required to store and distribute the food.

The second analysis evaluated the influence of the number of vending machines on the environmental impacts. Currently, the company has 9 vending machines located at train stations, universities and hospitals in London. However, this number is expected to increase to 20 vending machines in the next 10 months. Therefore, this analysis evaluated the consequence of increasing electricity consumption due to the installation of new vending machines.

4. Human Milk Foundation (HMF)

4.1 Definition of goal and scope

The study focuses on one facility where the entire operations occur, the Hearts Milk Bank, located within the Rothamsted Institute in Hertfordshire. Hearts operates as part of the Human Milk Foundation (HMF), a charity dedicated to creating nationally equitable milk bank services. The mission of the charity is to support families facing feeding challenges in neonatal intensive care units through the provision of education and donor human milk (DHM), as well as where a bridge to a full milk supply is needed or lactation is not possible. Access to DHM is of particular importance for premature and very sick babies whose mothers temporarily or in the long term are not able to provide any or enough of their own milk. Hospital neonatal units are charged a fee to cover the milk bank's costs, but DHM and lactation support is provided free of charge to families who would not currently qualify on the National Health Service. The provision of the DHM is under the oversight of a healthcare professional.

HMBs play a vital role by recruiting donors, processing, storing, and supplying donor milk to neonatal units and similar settings in a safe and controlled manner [60]. However, if the milk doesn't pass the rigorous microbiology tests both before and after pasteurisation, it is discarded [61]. The main factor involved in human milk wastage is microbiological contamination, which represents around 10-12% of donated milk being discarded currently [62].

Therefore, a strategy implemented in this particular HMB to ensure that the milk has remained in optimal conditions from the point of expression until fed to a vulnerable infant is to monitor the temperature and humidity during milk transportation using IoT technologies. For every journey, a sensor was installed to monitor the milk in the right condition of temperature and humidity. The sensors transmit the temperature/humidity information to a Big Data Server and alerts are sent when the temperature exceeds the acceptable limit. Detailed information on the monitoring system will be presented in the following sections.

The goal of the assessment is to assess the potential environmental impacts of a single research-focused UK HMB and the potential environmental savings due to implementing a monitoring system based on IoT technologies. Table 5 summarises the main characteristics of the organisation analysed in this study. The reporting unit was defined as "human milk management during one year of HMB operation". The reporting flow is, therefore, 3936 L of human milk, which was the volume of human milk donated between January and December of 2021 (reference period).

Table 5. HMF organisational life cycle assessment characteristics.

Criteria	**Specific features**
Reporting organisation	Human milk bank in the UK
Organisation size	Small size (<50 employees and volunteers)
Intention of application	Environmental performance assessment and improvement, identification of environmental hotspots, strategic management and control
Targeted audience	Disclosed to the public, including HMB associations, policymakers, funding sources and costumers
Reporting period	January-December 2021
Reporting unit	Human milk management during one year of operation
Reporting flow	3936 L of human milk
Consolidation method	Operational control
Experience-based pathway	Existing environmental assessment gate-to-gate (Pathway 2)
System boundary	Cradle-to-grave (excludes the recruitment, selection, approval, consent and education of milk donors and the milk defrosting and consumption by the recipients).
Data collection method	Top-down: direct activities data was collected through company interviews. Indirect upstream and downstream activities data were taken from Ecoinvent database.

The consolidation method applied was the total control over operational terms, i.e., the reporting organisation has full operational control on how the human milk is distributed to final consumers, used, and disposed of. Under this approach, the organisation accounts for 100% of the impacts from units over which it has operational control. All activities and related life cycle processes of the reporting organisation were considered according to ISO/TS 14072. Four experience-based pathways are described in the UNEP/SETAC report [63] for conducting an O-LCA. The reporting organisation had initial environmental experience and information to perform a gate-to-gate analysis; therefore, it fits the "pathway 2".

Two scenarios were built to determine the effect of IoT technologies on monitoring/controlling the temperature and humidity during milk transportation on the environmental impacts of the HMB. Scenario A represents the baseline scenario and includes the processes associated with the HMB. Scenario B follows the same processes as scenario A but includes the IoT technologies used to monitor the transport conditions.

The system boundaries are illustrated in Figure 6 and follow a cradle-to-grave approach. The consolidation method applied allows to include in the system boundaries the processes over which the organisation has the full authority to introduce and implement its operating policies at the operation. In this study, the processes include milk collection, storage, first transportation from the donor's home/hospital to the HMB, processing (screening, pasteurisation, packaging and storage), second transportation from the HMB to the hospital/recipient home and final treatment provided to all solid waste generated (landfill, and recycling).

Scenario B also comprises digital sensors for measuring the specific parameters, the Big Data server and the human milk avoided. Both scenarios exclude the recruitment, selection, approval, consent and education of milk donors, the milk defrosting and consumption by the recipients, as well as the energy consumed by breast pumps and the freezers at donors' home/hospital. The use of containers to collect the milk was included in the boundaries, as they are provided by the HMB and are part of the bank's operational control.

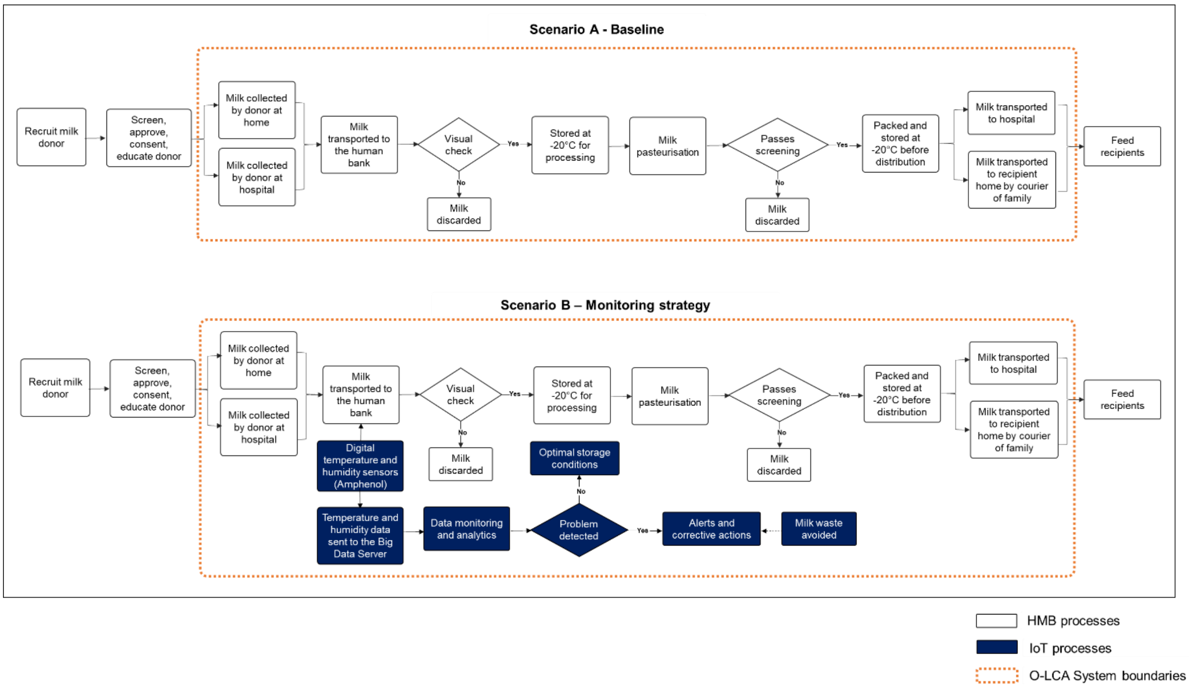

Figure 6. Schematic representation of the HMF's system boundaries. (A) refers to the baseline scenario, and (B) refers to the monitoring strategy implemented in the organisation.

4.2 Life cycle inventory

Data collection followed the recommendations for O-LCA provided by UNEP/SETAC [63]. According to its guidance, the system should include all inputs and outputs from direct and indirect activities. Direct activities represent the processes owned or controlled by the reporting organisation, while indirect activities are related to the consequences of the reporting organisation's actions that occur at sites controlled by other organisations of the value chain. Figure 7 shows the inputs, outputs, and direct and indirect activities under analysis.

In this study, the data collection method was defined as a top-down approach, that is, an inventory-oriented approach. It considers the reporting organisation as a whole and adds upstream models for all inputs of the organisation and downstream models for all outputs [63]. Therefore, specific data should be used for direct activities. There are two main methods to quantify the inventory for direct activities: direct measurement or calculation. In this study, direct quantification of all resources was systematically made by the reporting organisation, including a detailed list of all materials used and the energy consumed. Calculation procedures were used to quantify the indirect activities and required the use of activity data and consumption/emission factors.

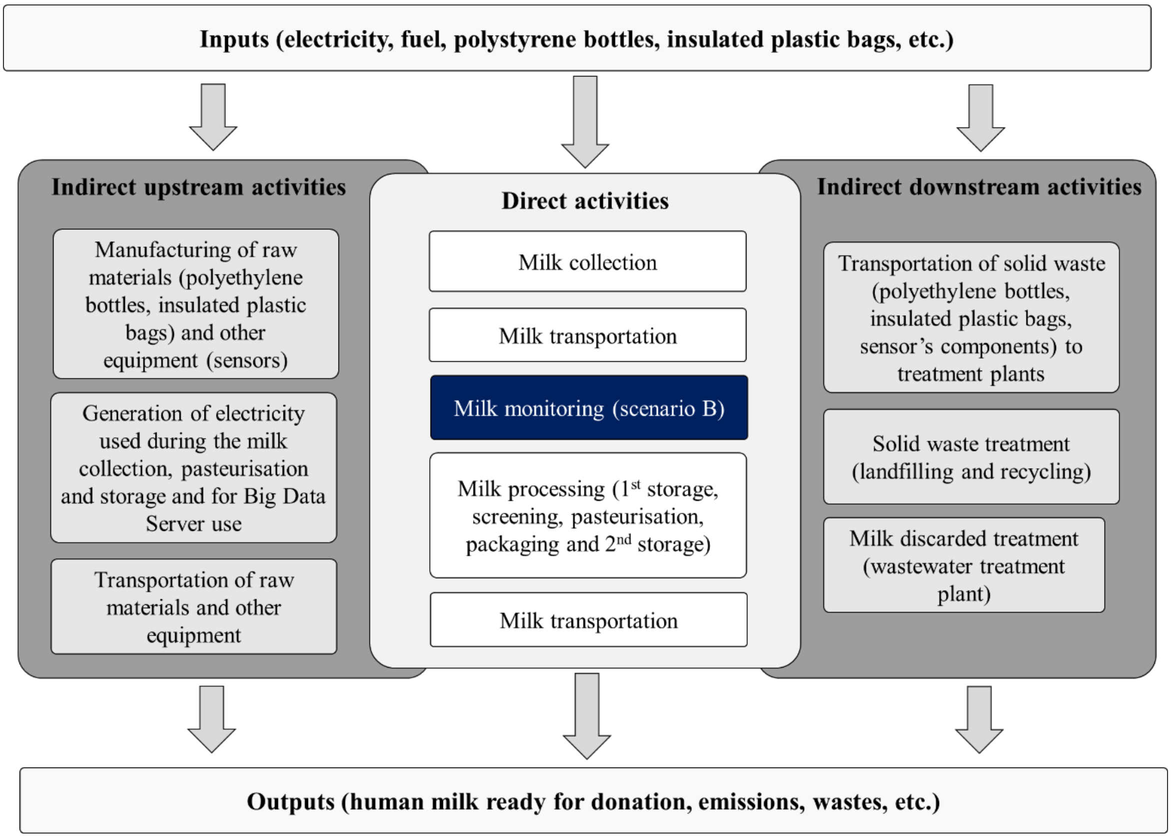

Figure 7. Inputs, outputs, and activities (direct and indirect) of the reporting organisation.

Direct activities include energy use, milk collection, processing (storage, screening, pasteurisation, and packaging) and transportation. Indirect upstream activities include extraction and manufacturing of raw materials (e.g., polyethylene bottles and insulated plastic bags), generation of electricity and transportation of the raw material to the HMB. Indirect downstream activities are related to the transportation of solid waste to the final destination, solid waste treatment (landfilling and recycling), and treatment of discarded DHM. The life cycle inventory of direct activities (scenario A) can be found in Table 6.

Milk collection

Breast milk is expressed manually or using electric or manual breast pumps. The milk is collected and stored in high-density polyethylene (HDPE) containers (free of bisphenol-A, bisphenol-S, DEHP and phthalates). The containers are single-use and are recycled after their end-of-life. The minimum volume required for donation is 2 litres per collection due to logistical limitations, maximising efficiency of milk bank processes, and operational costs of donor recruitment. The total time to collect the minimum volume of milk required ranges from 3 days to 3 months, depending on the mother's circumstances and her physiology.

Donors are responsible for freezing and controlling the temperature while the milk is under their responsibility. The HMB provides donors with a standard domestic freezer thermometer to check the freezer's temperature and requires them to record the temperature daily. The HMB under study typically recruits 40-50 donors per month and serves approximately 4000 infants annually.

Table 6. Life cycle inventory of an HMB in the UK per reporting flow.

Unit Process	Value	Unit
Inputs		
Milk collection		
Polyethylene bottles	388	kg
1st transportation		
Diesel	1006	L
Insulated plastic bags	2.83	kg
Dry ice	5.62	kg
Milk processing		
Electricity consumption - 1st storage	4795	kWh
Electricity consumption - pasteurisation	414	kWh
Electricity consumption - 2nd storage	33350	kWh
Polyethylene bottles	388	kg
2nd transportation		
Diesel	670	L
Insulated plastic bags	2.83	kg
Dry ice	5.62	kg
Outputs		
Products		
Human milk ready for donation	3361	L
Liquid wastes		
Human milk discarded	575	L
Solid wastes		
Polyethylene bottles	776	kg
Insulated plastic bags	5.67	kg
Air emissions (transportation)		
CO_2, fossil	3937	kg
CO, fossil	482	kg
CH_4, fossil	10.5	kg
NMVOCs	117	kg
N_2O	0.05	kg
NO_x	11.2	kg
SO_2	20.1	g
Particulates	1.59	kg

Milk transportation

Donated milk is normally transported by blood bike motorcycle volunteers. Normally, between one and six volunteers make the transportations per day, totalling about 20 volunteers working at the HMB. The milk is transported using insulated and weather-resistant bags of three different sizes, small (30x25 cm), medium (35x35 cm), and big (70x35 cm). The durability of the bags was assumed to be 10 years and was considered that they are recycled after their end-of-life. The average amount of human milk transported per bag is 7 litres. The insulated bags can keep the milk frozen for up to 4 h. If the transport time is longer, it is necessary to use dry ice. It was assumed that 1% of the trips require the use of 1 kg of ice, although this is likely an overestimate.

The average transport distance during the first transportation (from donor/hospital to HMB) is around 50 miles, but it can achieve up to 100 miles per route. For calculation purposes, it was considered the average distance (mean: 75 miles). The second transportation mode (from the HMB to the hospital neonatal units /recipient home in the community) is also made by motorcycle volunteers, but the average distance is 50 miles. The diesel-related emissions to air during combustion were taken from Ecoinvent [53].

Milk processing

The recently arrived frozen milk is unloaded, labelled for identification and transferred to freezers that maintain internal temperatures of at least -20°C. Four medical-grade freezers (262 L capacity) and seven upright food-grade freezers (365 L capacity) are used to store the incoming milk, while three fridges (400 L capacity) are used for defrosting the milk at the HMB. The milk can be kept frozen for some weeks before the first screening. The electricity consumed by each medical freezer is equal to 2.2 kWh per day, while the food freezers consume around 12 kWh per day and the fridges 4.4 kWh. The milk is then defrosted, and the contents of 10 to 20 containers are pooled by being poured into stainless steel jugs and gently stirred before decanting into 50-, 100- or 200-ml sterile containers. Samples from each batch are taken for microbiological analysis. Milk is not pooled between different donors.

After this process, the milk is pasteurised. The method involves heating the human milk at around 62.5°C for at least 30 min. The HMB has two pasteurisers, which process up to 19 L of milk and consume 2 kWh per cycle. A sample from each batch is screened after pasteurisation for microbial contamination, and milk is discarded if microbiological thresholds are exceeded in accordance with the NICE Clinical Guideline [64]. The processed milk is frozen and stored in freezers with a cooling capacity of -25°C. The milk is stored in polyethylene containers with different capacities (50-200 mL) depending on the final use (infants in hospital or recipients at home). The milk can be stored for up to 6 months after the date of the first expression until expiration, but it is typically used in less than 3 months.

Approximately 330 L of human milk were managed per month in the calendar year, but output from Hearts is increasing by approximately 40% year on year. The percentage of milk discarded monthly (considered unsuitable for consumption) ranged from 5.1% to 17.9% over the last year (mean: 11.7%; Sept 2021 - August 2022), with the highest failure rates during the summer months (June - August).

Milk monitoring (Scenario B - IoT technologies implementation)

A total of 12 sensors were installed to monitor the milk and ensure it remained in the right temperature and humidity condition. The Eagle datalogger (Digital Matter) was selected as the IoT platform, which formed the basis of the temperature and humidity monitoring system deployed in this human milk bank. The logger is an IP67-rated rugged cellular IoT device, supporting a range of inputs for various IoT applications. Each logger has four cell long-life power alkaline batteries, each with a capacity of 7800 mAh. Therefore, no other electricity or energy is required during the use phase.

Onboard, the logger contains a printed circuit board (PCB) with an array of sensor inputs, a GPS module and an accelerometer for geofencing and movement detection and is equipped with a cellular modem and sim card allowing the device to run on the IoT low-power LTE-M (CAT-M1) 4G network for data transmission. For sensing, the eagle was equipped with a T9602 temperature / relative humidity (T/RH; +- 2% RH, +-0.5°C, 0.01°C resolution) sensor probe (Amphenol, USA).

3.3 Sensitivity analyses

Four sensitivity analyses were performed to understand the influence of some parameters on the environmental impact assessment results. A sensitivity analysis was made to assess the influence of the monitoring IoT technologies at the transportation stage on the milk waste avoided and, consequently, on the environmental impacts. At this moment it is not possible to estimate the exact amount of human milk wasted during the transportation stage, and the value used in this sensitivity analysis considers two hypothetical scenarios, where: 1) the IoT technologies avoided discarding 1% of human milk and 2) 3% of human milk discarded due to transportation issues was prevented. The environmental burdens avoided were modelled through the system expansion by substitution [57]. Credit was given to scenario B for avoiding additional human milk production to cover the losses in scenario A and all related upstream activities, such as collection, transport and energy required to store and pasteurise the milk.

The second analysis evaluated the influence of transportation distances on the results. The assumed distances of the first transportation (from the donor's home/hospital to the HMB) used in the baseline scenario are related to the average distance. The distances were changed to make the assessment more representative of other regions. Therefore, the transport distances were adjusted to the extreme values of the baseline distances (i.e., 50 and 100 miles).

Another sensitivity analysis assesses the influence of substituting motorcycle volunteers with delivery drones. Drones have found applications in many civil sector areas during the last decade. A drone is an aircraft without a human pilot on board, whose flight is controlled either autonomously or under the remote control of a pilot on the ground or in another vehicle. Selecting this analysis was based on the Human Milk Foundation ambition to reduce reliance on fossil fuels for transportation purposes [65]. Ongoing projects aim to use drones to make 10% of the first and second transportation. In this scenario, the energy model used to determine the drone's electricity consumption is based on the specifications of the Wingcopter 198 drone with 8 lift rotors [66]. The delivery includes flying at 18 km/h and descending to the delivery site with a payload of 5 L. The return trip is similar but without the payload. The drone has two Li-ion batteries of 814 Wh each, which allows a range of 75 km considering ideal conditions (no wind, sea level altitude, 15 °C air temperature) and ideal operation (ideal cruise speed, 20% battery reserve, standard payload form factor).

The last sensitivity analysis evaluates the substitution of 10% motorcycles for electric vehicles. In this scenario, the impact of the carried payload of human milk was also examined. Two scenarios were considered: 1) the electric vehicle transports 10 L per journey, and 2) 50 L of milk is transported per journey. The average energy consumption, 200 Wh/Km, was taken from EV [67] and is based on real-world values corrected for multiple versions of vehicles.

5. Burns Farm Meats (BFM)

5.1 Definition of goal and scope

The goal of this assessment is to understand the trade-offs between optimising the refrigeration monitoring of an abattoir using IoT technologies to reduce food waste and its potential environmental impacts. The meat manufacturing company is located in Ireland and produces meat from three different animals' livestock, cattle, sheep and swine. The study focuses on one facility where all processes take place. The functional unit was defined as the total production of meat during one year of operation, i.e. the production of 134 tonnes of meat, between January and December of 2021 (reference period).

To assess the potential environmental consequences due to the adoption of a monitoring system based on IoT technologies, two scenarios were created. The activities related to the meat manufacturing company are included in the first scenario (A), which serves as the baseline. The second scenario (B) follows the same processes as A but includes the IoT technologies used to monitor the food quality conditions in the dry ageing chambers during the cold storage process.

Figure 8 presents the system boundaries of both scenarios, which follow a cradle-to-grave perspective. The processes common to both scenarios include livestock production, livestock reception, stunning and bleeding, removal of skin, head and hoof removal, splitting and evisceration, carcass chilling (dry ageing), and packaging. Blood treatment, transportation, retail and meat preparation/consumption were excluded from the system boundaries. Scenario B also comprises digital sensors for measuring the specific parameters, the Big Data server and the food waste avoided. Both scenarios exclude food raw materials production and consumption.

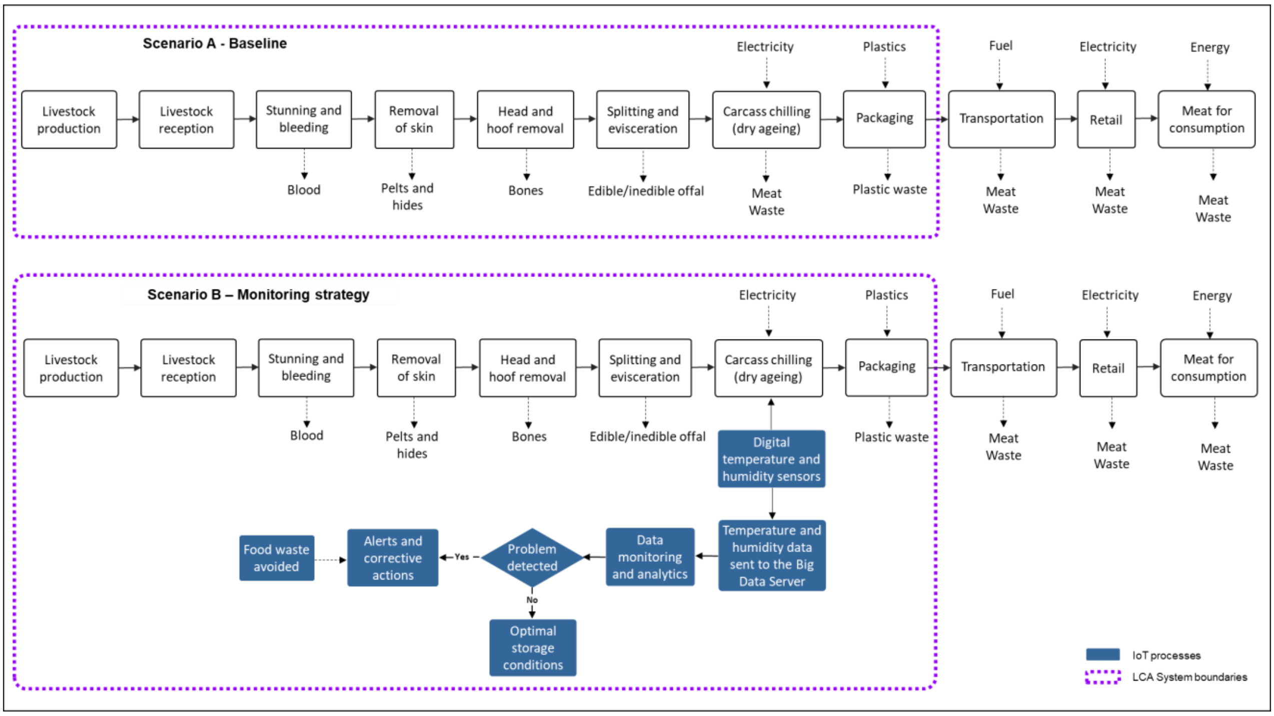

Figure 8. Schematic representation of the BFM's system boundaries (A), and the IoT implementation scenario (B) to monitor food quality.

5.2 Life cycle inventory

The direct activities data was collected through company interviews. The annual production comprises, on average, 250 cows, 900 sheep and 480 swine per year. Livestock production was taken from Ecoinvent [53] and can be divided following animal species: cattle, sheep, and swine. The cattle activity included in this study starts with the replanting of pasture. The system boundary includes operations for pasture maintenance and replanting. Pasture is not regularly fertilised but is replanted every 20 years. Mineral salt is served as supplement feed for all cattle in troughs on the field. Besides pasture and mineral salt, no protein supplement or other feed is served to cattle. This activity ends with the provision of fat steers, culled cows, and bulls at the farm gate, ready to be sent to the abattoir as live weight. In this study, it was considered that fat steers are sold for slaughter under 42 months. Fences are the only infrastructure included. Acquisition and use of grass seeds are not included (less than 3% of product mass). The production of young bulls for reproduction is not included for the same reason, but their emissions on the farm and their live weight as products are considered. Farm manure as an organic fertiliser is only accounted for in terms of direct field emissions. The study does not include the consumption of pharmaceuticals, although typical production systems use them.

The sheep production includes the processes and inputs of sheep husbandry on pastureland (20% intensive and 80% extensive pastureland). Inputs of fertilisers, feedstuffs, pesticides and irrigation are considered. Machine infrastructure and a shed for machine sheltering and shearing are also included, as well as the direct emissions on the field. The products of sheep husbandry are wool and sheep live weight, and the impacts were assigned by applying mass allocation.

The swine production represents the farrow-to-finish production of swine, which includes the consumption of feed and the operation of pig housing systems for the management of the herd and the production of finished pigs. Two sub-production stages are considered: the nursery stage, where sows are farrowing and piglets are grown until they enter the finishing stage, where they are intensively fed and become finished pigs. Culled sows are also sold for slaughtering. Thus, they are embedded in the reference product in addition to finished pigs and are not considered a by-product. The by-products considered are liquid manure and dead animals unsuitable for the food market. Liquid management of the manure (slurry) is the dominant mode of manure management. It was considered that the swine production stage uses slatted-floor barns without litter under the animals. The slurry collected from buildings is mostly stored at the farm in an open-pit system, as most pig farms have non-covered slurry storage systems. The system boundary also includes the emissions from animal housing and from manure storage. Litter consumption on the farm, boars and insemination are not included, as well as any drugs used on the pig farm, because of the lack of data available on quantities and content.

The company uses local animal livestock located within a radius of 10-50 km. The livestock reception is the place where animals are kept when they are brought to the abattoir. Here, the selection of the animal to be moved to the slaughterhouse bay is made. Animals are also given rest here to calm them from the transfer stress experienced throughout transportation. From the temporary reception area, the animal is taken to the stunning point. The stunning of animals is used to render the animal unconscious before bleeding. In this abattoir, stunning is carried out using mechanical stunning. The bleeding process involves letting out of the blood when the blood vessel at the neck is severed. To avoid contamination, complete or almost complete bleeding is recommended, as bacteria can grow as a result of residual blood in the cattle arteries. Blood waste from the abattoir's bleeding area needs to be properly handled since it quickly starts microbiological development. Blood treatment was not considered in this study.

The removal of skin is carried out after bleeding. The process is done to prepare the muscle tissues beneath for consumption and the use/tanning of the skin. Manual skinning is used in this abattoir. After the skinning operation, the head and hoof are removed. After this process, the carcasses are washed and positioned for evisceration and splitting. The contents and bones are removed in this operation using a knife and saw. The carcasses are now transferred to chilling chambers for the dry ageing process. In this process, carcasses are put into a controlled open-air environment for 21 days (at controlled temperature, relative humidity, and airflow) to undergo a flavour transformation. By exposing the meat to air, moisture is pulled out, and the natural enzymes in the beef break the muscles down slowly over time, making it more tender.

The company uses two chambers of different sizes (small and large) to store the meat. Electricity consumption during the dry ageing process was taken from Tachajapong et al.[68]. After chilling, the meat is transferred to tables for packaging and distribution to the market.

The life cycle inventory of the company is shown in Table 7 and represents the total meat production per year.

Table 7. BFM life cycle inventory per reporting flow.

Unit Process		Unit	Value
Inputs			
Live animal	Cattle	kg	143750
	Sheep	kg	29250
	Pig	kg	63600
Electricity	Large room	kWh	24864
	Small room	kWh	12432
Packaging	Plastic bag	kg	446.6
Transport	Diesel consumption	kg	440.5
Outputs			
Products			
Meat	Cattle	kg	74039
	Sheep	kg	12494
	Pig	kg	39981
Wastes			
Packaging	Plastic bag	kg	446.6
Air emissions			
Transport	Carbon dioxide, fossil	kg	1398.8
	Carbon monoxide, fossil	kg	1.092
	Methane, fossil	kg	0.0008
	NMVOC	kg	0.027
	Dinitrogen monoxide	kg	0.064
	Nitrogen oxides	kg	0.511
	Sulfur dioxide	kg	0.007
	Particulates	kg	0.005

Some food loss can be observed during this process. For modelling purposes, it was assumed that the inedible (bones, etc.) and edible wastes were sent to a municipal sanitary landfill for further management. Table 8 provides information on the trim weights of a 1 bone-in loin with fillet that has undergone a dry-aging process for a duration of 16 days. The trim weights represent the meat removed from the loin during the preparation process. This data is crucial in understanding the yield and efficiency of the dry-aging process, as it helps determine the actual usable portion of the fillet.

Table 8. Trim weights of a 1 bone-in loin with fillet (dry-aged for 16 days).

Part	Weight (kg)	Waste weight (g)	Approx. cost of waste (€)
The whole piece	12.79	-	-
Fillet	2.41	-	-
Waste (fillet)	-	640	21
Striploin	5.13	-	-
Waste (loin)	-	313	7.83

In the second scenario, sensors were installed to monitor the temperature and humidity of the dry ageing chambers to ensure the meat was stored in the right conditions. Four sensors were installed in the small chamber, and six were installed in the large chamber. The life span of the sensor is around 10 years, depending on the environmental conditions [51]. Each sensor has four batteries that will provide energy to support the temperature/humidity analysis and transmission via a 4G network. Therefore, no other electricity or energy is required during the use phase. According to the supplier, the batteries last about 4 years, considering one measurement every 20 minutes.

The sensors transmit the temperature/humidity information to a Big Data Server and alerts are sent when the temperature exceeds the acceptable limit (above 5 °C) via a specially designed interactive dashboard. This alert helps the company fix any malfunctioning of the fridge/freezer before the stored items go to waste due to temperature fluctuations. The Big Data Server comprises one unit of computer equipment, a redundant power supply, processors and storage drives. The estimated electricity consumption of the server is 1152 kWh per month. For the internet connection, the Ecoinvent database was used in the tool [53].

5.3 Sensitivity analysis

A sensitivity analysis was performed to understand the influence of food waste reduction due to IoT technologies implementation on the environmental impacts. Therefore, in this scenario it was considered that the IoT technologies helped reduce the trim losses. In the tool, the environmental burdens avoided are modelled through the system expansion by substitution [57]. Credit is given to Scenario B for avoiding additional production of food to cover the losses in Scenario A and all related upstream activities, such as transport and energy required to store and distribute the meat.

6. WD Meats

6.1 Definition of goal and scope

WD Meats is a renowned meat manufacturing company that has been delivering the highest quality meat products since its establishment in 1979. Founded by the managing director, Francis Dillon, WD Meats expanded into beef manufacturing and set up its custom-built premises in Coleraine, on Ireland's North Coast, in 1987. Situated in an area with a rich farming heritage, WD Meats continues to produce beef on its family farm.

Over the years, WD Meats has experienced consistent growth, which can be attributed to its commitment to continuous development and improvement, both in infrastructure and professional skills. The company's modern facility spans 100,000 square feet and is located on a 35-acre site, providing an integrated processing operation. From slaughtering to boning, packing, and dispatch, every aspect of the production process is handled in-house, ensuring quality control at every stage.

WD Meats processes approximately 400 cows per day, with each ageing chamber accommodating up to 22 animals. The functional unit was defined as the total meat dry aged during one year of operation, i.e. the 1738 tonnes of meat, between January and December of 2021 (reference period).

To assess the potential environmental consequences due to the adoption of a monitoring system based on IoT technologies, two scenarios were created. The activities related to the meat manufacturing company are included in the first scenario, which serves as the baseline. The second scenario follows the same processes as scenario 1 but includes the IoT technologies used to monitor the food quality conditions in the dry ageing chambers during the cold storage process. Figure 9 presents the system boundaries of both scenarios, which follow a gate-to-gate perspective focused on the dry ageing process. Scenario B comprises digital sensors for measuring the specific parameters, the Big Data server and the food waste avoided.

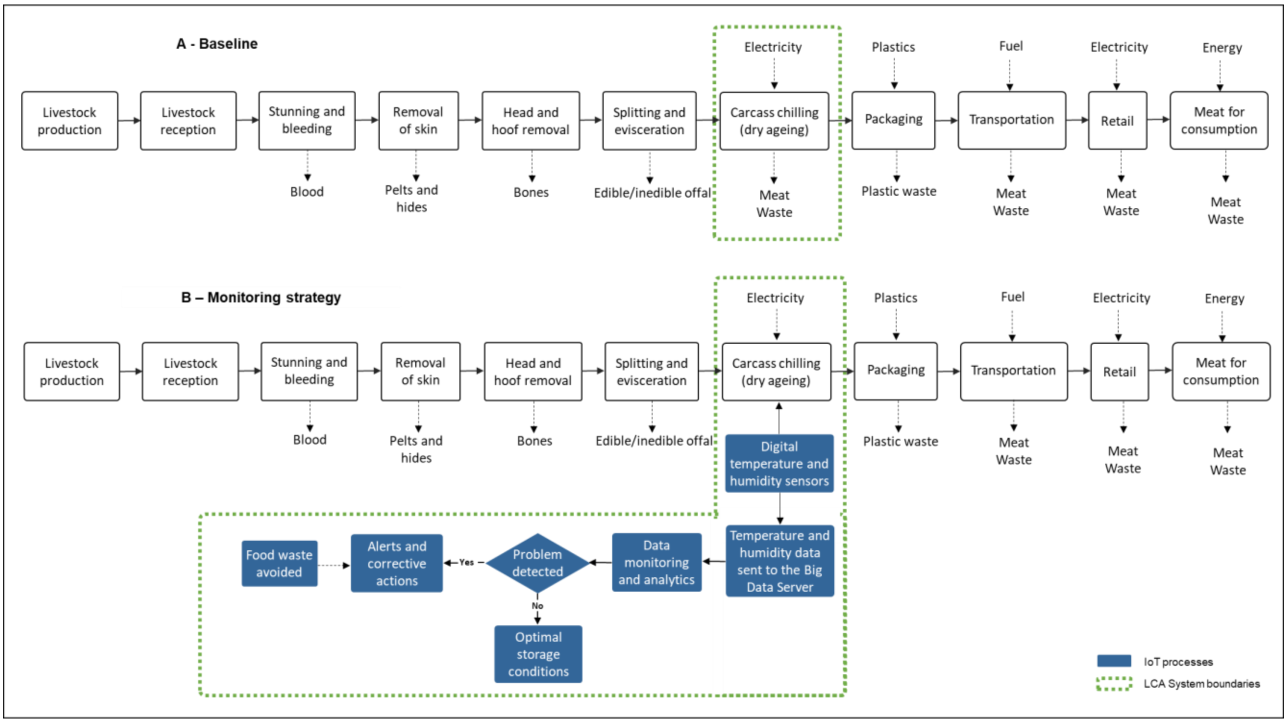

Figure 9. Schematic representation of the WD Meats's system boundaries (A), and the IoT implementation scenario (B) to monitor food quality.

6.2 Life cycle inventory

The direct activities data was collected through company interviews. The annual production comprises, on average, 400 cows per day. Livestock production was taken from Ecoinvent [53]. The cattle activity included was presentend in the section above.

The livestock reception is the place where animals are kept when they are brought to the abattoir. Here, the selection of the animal to be moved to the slaughterhouse bay is made. From the temporary reception area, the animal is taken to the stunning point. The stunning of animals is used to render the animal unconscious before bleeding. In this abattoir, stunning is carried out using mechanical stunning. The bleeding process involves letting out of the blood when the blood vessel at the neck is severed. To avoid contamination, complete or almost complete bleeding is recommended, as bacteria can grow as a result of residual blood in the cattle arteries. Blood treatment was not considered in this study.

The removal of skin is carried out after bleeding. The process is done to prepare the muscle tissues beneath for consumption and the use/tanning of the skin. After the skinning operation, the head and hoof are removed. The carcasses are now transferred to chilling chambers for the dry ageing process. In this process, carcasses are put into a controlled open-air environment for 21 days (at controlled temperature, relative humidity, and airflow) to undergo a flavour transformation. By exposing the meat to air, moisture is pulled out, and the natural enzymes in the beef break the muscles down slowly over time, making it more tender.

The company utilizes a total of fourteen chambers for meat storage. During the dry ageing process, each chamber consumes approximately 270 kWh of electricity per day. A loss of approximately 0.96% can be observed after this process. After chilling, the meat is transferred to tables for packaging and distribution to the market. For modelling purposes, it was assumed that the inedible (bones, etc.) and edible wastes were sent to a municipal sanitary landfill for further management. The life cycle inventory of the company is shown in Table 9 and represents the total meat processed in dry ageing chambers per year.

Table 9. WD Meats life cycle inventory per reporting flow.

Unit Process	Unit	Value
Inputs		
Meat	kg	1738081
Electricity	kWh	1379700
Outputs		
Products		
Meat	kg	
Wastes		1669145
Losses	kg	68936

In the second scenario, sensors were installed to monitor the temperature and humidity of the dry ageing chambers to ensure the meat was stored in the right conditions. Four sensors were installed in the dry ageing chambers. Each sensor has four batteries that will provide energy to support the temperature/humidity analysis and transmission via a 4G network. Therefore, no other electricity or energy is required during the use phase. According to the supplier, the batteries last about 4 years, considering one measurement every 20 minutes.

The sensors transmit the temperature/humidity information to a Big Data Server and alerts are sent when the temperature exceeds the acceptable limit (above 5 °C) via a specially designed interactive dashboard. This alert helps the company fix any malfunctioning of the fridge/freezer before the stored items go to waste due to temperature fluctuations.

6.3 Sensitivity analysis

A sensitivity analysis was performed to understand the influence of food waste reduction due to IoT technologies implementation on the environmental impacts. Therefore, a hypothetical scenario was considered in which the IoT technologies helped reduce edible meat waste generation to 1%. In the tool, the environmental burdens avoided are modelled through the system expansion by substitution [57]. Credit is given to Scenario B for avoiding additional production of food to cover the losses in Scenario A and all related upstream activities, such as transport and energy required to store and distribute the meat.

7. Musgrave

7.1 Definition of goal and scope

Musgrave Group Ltd. is an Irish food wholesaler, founded in Cork. It is currently Ireland's largest grocery distributor, with operations in Ireland and Spain. They operate from 10 warehouse locations in Ireland. Musgrave Northern Ireland, a subsidiary of Musgrave Group, has warehouses in Belfast, Lurgan, and Derry and is headquartered in Belfast, Northern Ireland.

On occasion, while performing deliveries to their business customers, the refrigeration units in the delivery vans operating in the greater Belfast area can break down, without any indication to either the driver or the logistics staff at the warehouse. The temperature in van carrying chill and frozen products would increase, surpassing the food storage temperature safety threshold, resulting in a van load of spoiled stock. It was estimated that out of their fleet of 5 delivery vans, at least one would suffer refrigeration problems over the course of a year. The vans have both a chill and a freeze zone, both of which should be monitored throughout a journey. Figure 10 presents the system boundaries of Musgrave processes, which follow a gate-to-gate perspective focused on the distribution process. Scenario B comprises digital sensors for measuring the specific parameters, the Big Data server and the food waste avoided.

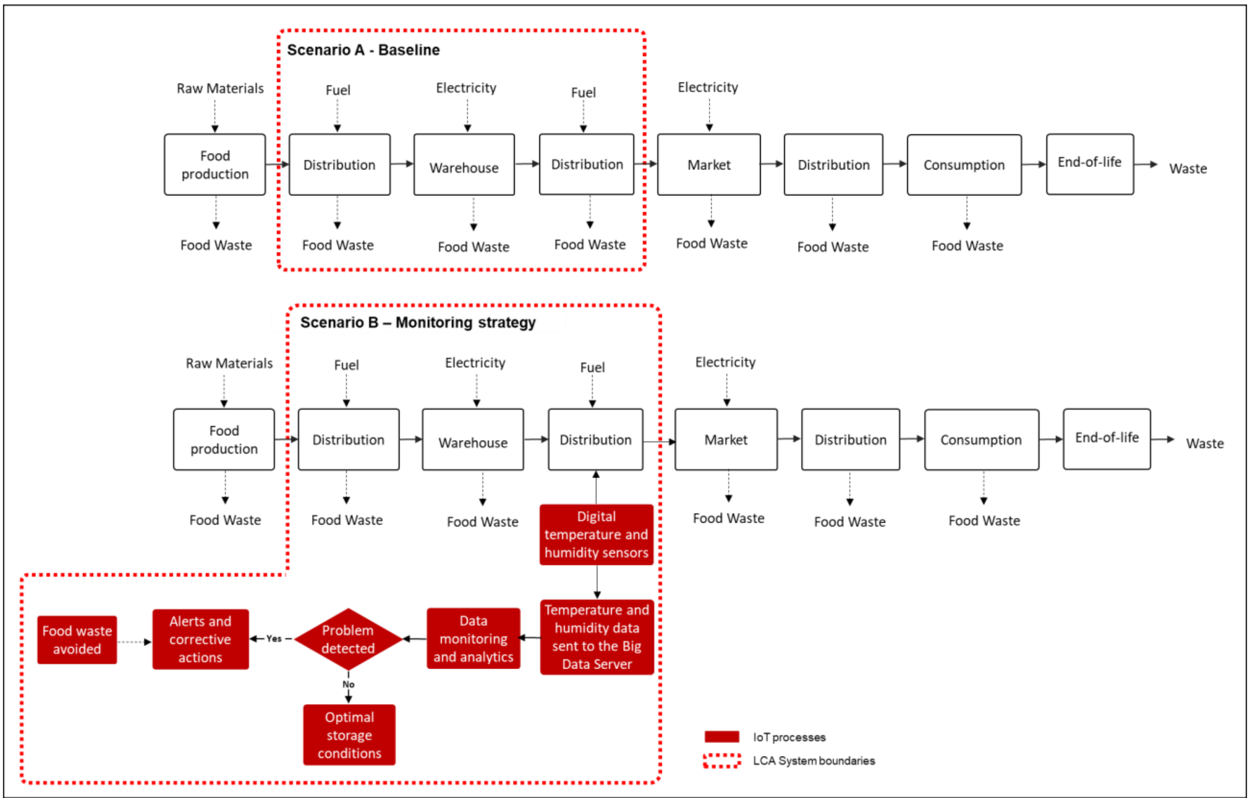

Figure 10. Schematic representation of the Musgrave's system boundaries (A), and the IoT implementation scenario (B) to monitor food quality.

7.2 Life cycle inventory

The average type and amount of products transported by markets like Musgrave per refrigerated truck can vary widely depending on several factors, such as the specific market, location, season, and customer demand. Musgrave is a wholesale supplier and distributor, operating in the grocery and foodservice sectors in Ireland and the UK, so the types of products transported could include fresh produce, dairy products, meat, seafood, frozen goods, and other perishable items. Based on general trends in food transportation and market size in Northern Ireland, it is reasonable to assume that a significant amount of food is transported by small, refrigerated vans to cater to various markets, including local markets, grocery stores, restaurants, and cafes.

Assumptions:

Frequency of Transport: The frequency of food transportation would depend on factors such as the van's capacity, the size of the markets, the type of food being transported, and the demand for perishable goods. Assuming the van operates daily, it could make around 3 to 4 trips per day. A total of 3 vans were analysed in this pilot.

Market Reach: Small refrigerated vans might serve both local markets and distribute food to more distant locations within Northern Ireland. Additionally, some vans may also cross the border to supply food to markets in the Republic of Ireland.

Vans capacity - The amount of products transported in refrigerated vans will depend on the capacity of the vans used by the markets. The average capacity of refrigerated vans can vary but based on typical data for food distribution and transportation, the average capacity is 1 ton (or 1 pallet) of refrigerated cargo and 2 tons (pallets) of frozen food per trip.

Average distance from the warehouse to the market: Assuming a mean distance of 20 km for each trip.

Type of Food: The type of food transported include perishable items like fruits, vegetables, dairy products, meat, fish, and other temperature-sensitive goods.

Amount of Food: Estimating the exact amount of food transported is challenging without specific data. However, given Northern Ireland's population size and consumption patterns, it's reasonable to assume that thousands of tons of food are transported each week to meet the demands of the market. The refrigerated amount of food transported can be found below. It has been determined that the quantity of frozen food is twice that of the refrigerated food.

- **Meat**: Given that meat is a staple in many diets, the van might carry a significant amount of meat. This could range from 200 to 300 kg of various meats (chicken, beef, pork, etc.) per trip.
- **Vegetables**: Vegetables are an essential part of a balanced diet. The van might transport around 150 to 250 kg of mixed vegetables per trip.
- **Fruits:** Fruits are also popular in Northern Ireland, and the van might carry around 100 to 200 kg of mixed fruits per trip.
- **Dairy products**: Dairy products, such as milk, cheese, and yogurt, are consumed regularly. The van might transport around 100 to 150 kg of dairy products per trip.

• **Seafood:** Seafood is also a part of many diets, though its consumption might be slightly lower compared to other food types. The van might transport around 50 to 100 kg of various seafood items (fish, prawns, etc.) per trip.

Seasonal Variations: The amount of food transported may fluctuate seasonally due to variations in agricultural production and consumer preferences. For example, during the summer, there might be higher demand for fresh fruits and vegetables, while the winter months could see increased demand for root vegetables and winter produce.

Carbon footprint: A rough estimation of the carbon footprint was made based on the general assumptions presented above, as specific data was not provided. The estimation for each group of products transported in the small refrigerated van involved considering various factors, such as transportation distance, mode of transportation, energy consumption, refrigeration, and other supply chain aspects.

Table 10. Estimated amount of refrigerated food transported and associated carbon emissions.

Product	**Amount (kg)**			**Carbon emission (CO_2-eq/kg)**			
	Min	**Average**	**Max**	**Min**	**Average**	**Max**	**Ref**
Meat	200	250	300	10	20	30	[69–71]
Vegetables	150	200	250	0.5	1	2	[72–74]
Fruit	100	150	200	0.5	1	2	[73,75,76]
Dairy products	100	125	150	3	4.5	6	[77–79]
Seafood	50	75	100	2	3.5	5	[80,81]

Observations:

The small van is powered by a standard diesel engine. Emissions factors for diesel fuel combustion and refrigeration are taken as averages for transport, freight, lorry with refrigeration machine, 3.5-7.5 ton, R134a refrigerant, cooling is equal to 0.65 kg CO_2 eq [53].

In the second scenario (B), sensors were installed to monitor the temperature and humidity of the vans to ensure the food was transported in the right conditions. Sensors were installed in their fleet of 3 vans serving the Belfast area, allowing staff to monitor the temperature of the vans every 5 minutes. Automatic text alerts would be sent to the logistics warehouse staff when the temperature rose above a defined threshold limit during a delivery.

7.3 Sensitivity analysis

A sensitivity analysis was performed to understand the influence of food waste reduction due to IoT technologies implementation on the environmental impacts. Therefore, a hypothetical scenario was considered in which the IoT technologies helped reduce edible food waste generation. In this scenario, the REAMIT system's timely alerts were credited with saving one trip per month. Credit is given to Scenario B for avoiding additional production of food to cover the losses in Scenario A and all related upstream activities, such as transport and energy required to store and distribute the food.

8. Results

8.1 Yumchop

8.1.1 Environmental impact assessment and hotspot analysis

Figure 11 presents the relative contribution of manufacturing, transportation and use for the total impact of the sensors used in this study. It was observed that batteries (manufacturing and use) are the main hotspot for the sensor life cycle, followed by the printed circuit board for all impact categories. The batteries represent 62-96% of the total impact, while PCB can achieve 3.5-36.6%. In this system, nitrogen oxide (NOx) is the main responsible for the impacts on stratospheric ozone depletion, while SO_2 is relevant for the impacts on terrestrial acidification. Copper (Cu) present during the batteries manufacturing is responsible for a great part of the impacts on ecotoxicity categories, including freshwater, marine and terrestrial, and Chromium VI is the most important contributor to the impact in the human toxicity category.

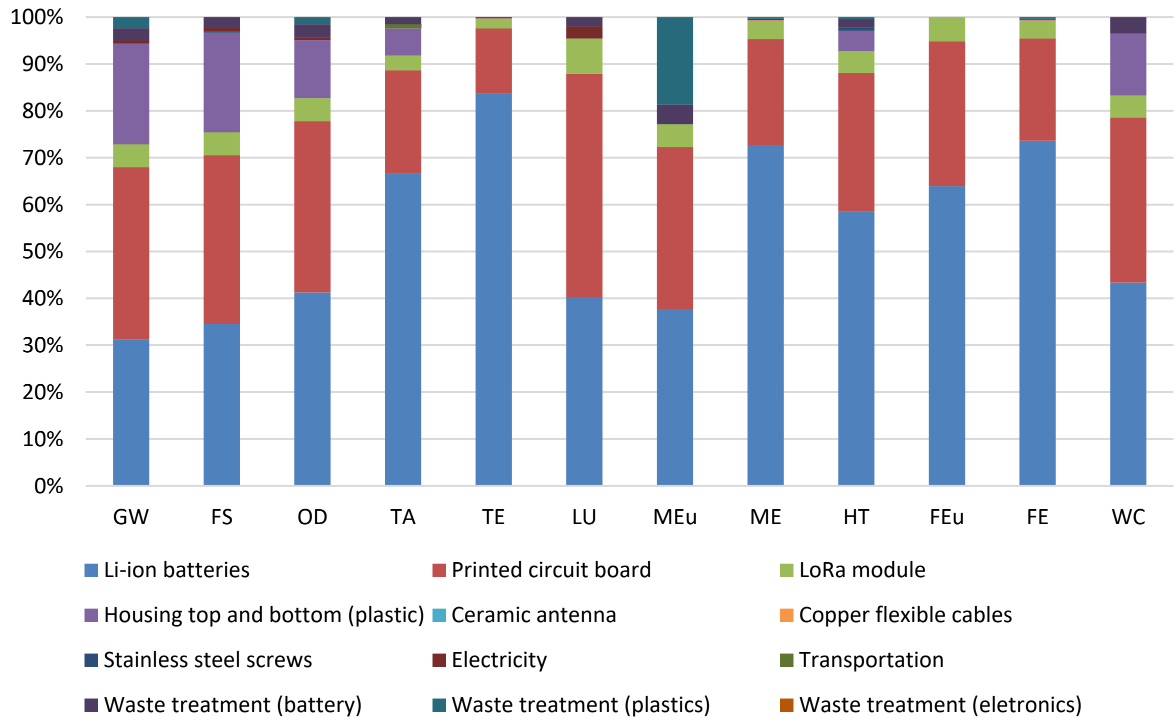

Figure 11. Relative contribution of each source to the total impact of sensors.

Figure 12 presents the relative contribution of each life cycle stage to the total impact obtained for the food company in the baseline scenario. Food raw materials production is the main hotspot of nine impact categories, global warming, terrestrial acidification, terrestrial ecotoxicity, land use, marine eutrophication, human toxicity, freshwater eutrophication, freshwater ecotoxicity and water consumption, contributing to 70 – 98.9 % of the total impact in those categories.

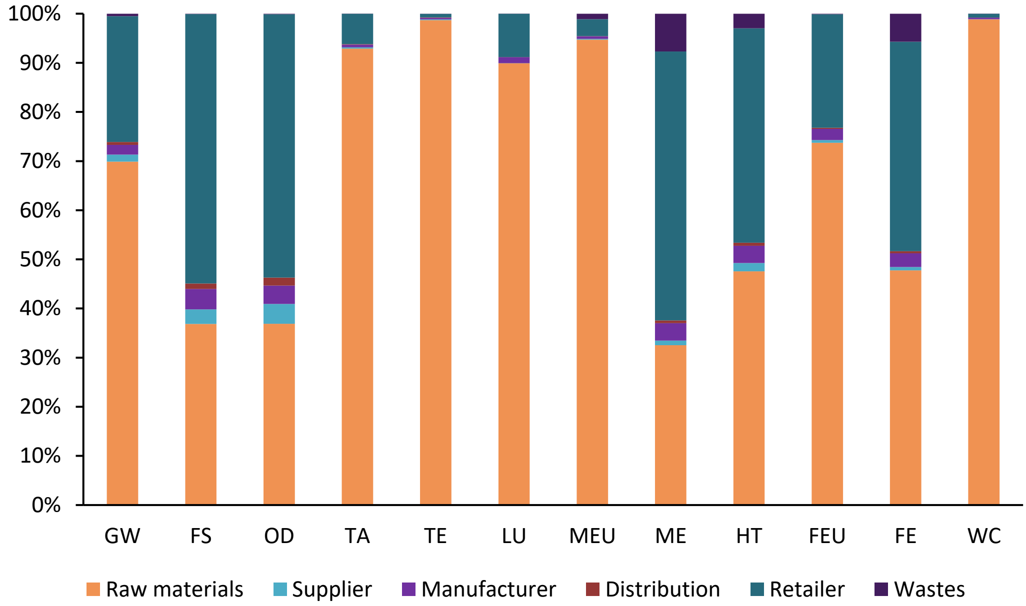

Figure 12. Relative contribution of each supply chain stage to Yumchop's environmental impact.

Sustainable food production, therefore, must be prioritised to mitigate climate change, reduce water stress and pollution and restore lands to grasslands. The production of livestock (animals raised for meat, dairy and seafood products) contributes to emissions in several ways, for example, by producing methane through their digestive processes (enteric fermentation) [82–84]. Manure and pasture management, land use change, production of crops for animal feed, and fuel consumption also fall into this category [82,85]. Crops and vegetable production are mainly responsible for direct emissions, including elements such as the release of nitrous oxide from fertilisers and manure application, methane emissions from rice production, and carbon dioxide from agricultural machinery [86–88].

Water consumption and freshwater eutrophication are also valuable indicators of food production's environmental impact, as 70 % of global freshwater withdrawals and 78 % of global pollution of waterways are caused by agriculture [89]. The pollution of water bodies and ecosystems with excess nutrients is a major environmental problem [90,91]. Agriculture can represent the runoff of excess nutrients into the surrounding environment and waterways, which affect and pollute ecosystems with nutrient imbalances, especially from nitrogen and phosphate [92,93].

Contrary to many other areas of energy production where there are prospects for expanding the use of low-carbon energy, it is less obvious how agriculture may be decarbonised [94]. In agriculture, it is necessary to use inputs such as fertilisers to meet the rising demand for food, and it is impossible to stop animals from producing methane. Some solutions to decrease those impacts can include diet changes, food waste reduction, improvements in agricultural efficiency, and technologies that make low-carbon food alternatives scalable and affordable [95–97]. For the impact categories fossil resource scarcity, stratospheric ozone depletion and marine ecotoxicity, the retail stage was the main hotspot, representing 53.6 – 54.8% of the total impact. The retail stage consumed a high amount of electricity due to the vending machines used to store and sell the food boxes of the company. The electricity consumed during the retail stage was also relevant for human toxicity and freshwater ecotoxicity impact categories, contributing to around 42.6-43.6% of the total impact.

In this company, the effect of transportation (supplier and distribution stages) was not significant for any of the impact categories under analysis. Many could assume that eating locally is key to a low-carbon diet [98]. However, eating locally would only have a significant impact if transport was responsible for a large share of food's final environmental impact, but this is not the case for most foods. The GHG emissions from transportation make up a tiny amount of the emissions from food and what is consumed is far more important than where the food travelled from [99–103]. Overall, animal-based foods tend to have a higher footprint than plant-based; whether they are grown locally or shipped from the other side of the world matters very little for total emissions [104,105]. Therefore, eating less meat or switching to lower-impact meats such as chicken or eggs is the most effective way to reduce the environmental footprint [106–108]. Figure 13 presents the relative contribution of the REAMIT IoT technologies to the company's total impact disregarding the potential food avoided.

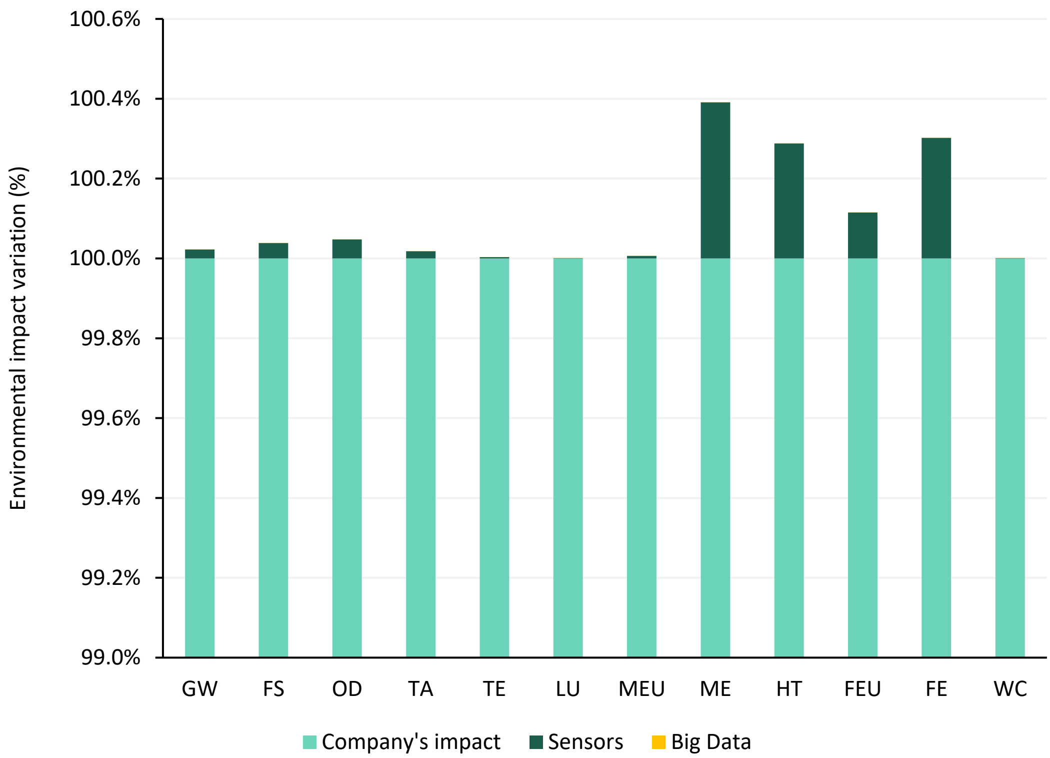

Figure 13. Relative contribution of the REAMIT IoT technologies implementation to the total impact of Yumchop (scenario B).

Although integrating IoT technologies to monitor temperature/humidity conditions can have many advantages, the environmental implications may also be analysed. In this study, it is possible to observe that this integration had little to no adverse effects on the company's overall impact. The contribution of the IoT technologies implemented in this study, including 8 sensors and a Big Data server to store and control the data, achieved a maximum impact contribution of 0.4% for the marine ecotoxicity category. Despite the impacts associated with implementing IoT technologies in this system, mainly due to components used to produce the sensors [109], there are still potential tangible benefits that should be considered. For example, a reduction in the environmental impact can be expected if part of the food waste is avoided due to implementing these technologies, which can equilibrate the additional impacts. The surplus food production to compensate for the waste may result in severe environmental and societal issues [110–112]. Therefore, to prevent food waste and the environmental impact related to this waste, it is advised to employ monitoring systems/technologies as the one suggested in this study. The potential avoided impacts resulting from the decreased amount of food waste due to implementing IoT technologies are shown in Section 7.1.2.

8.1.2 Sensitivity analysis

Figure 14 presents the total impact obtained for the first sensitivity analysis, i.e., the influence of the monitoring IoT technologies on the environmental impacts considering the reduction in food waste generation.

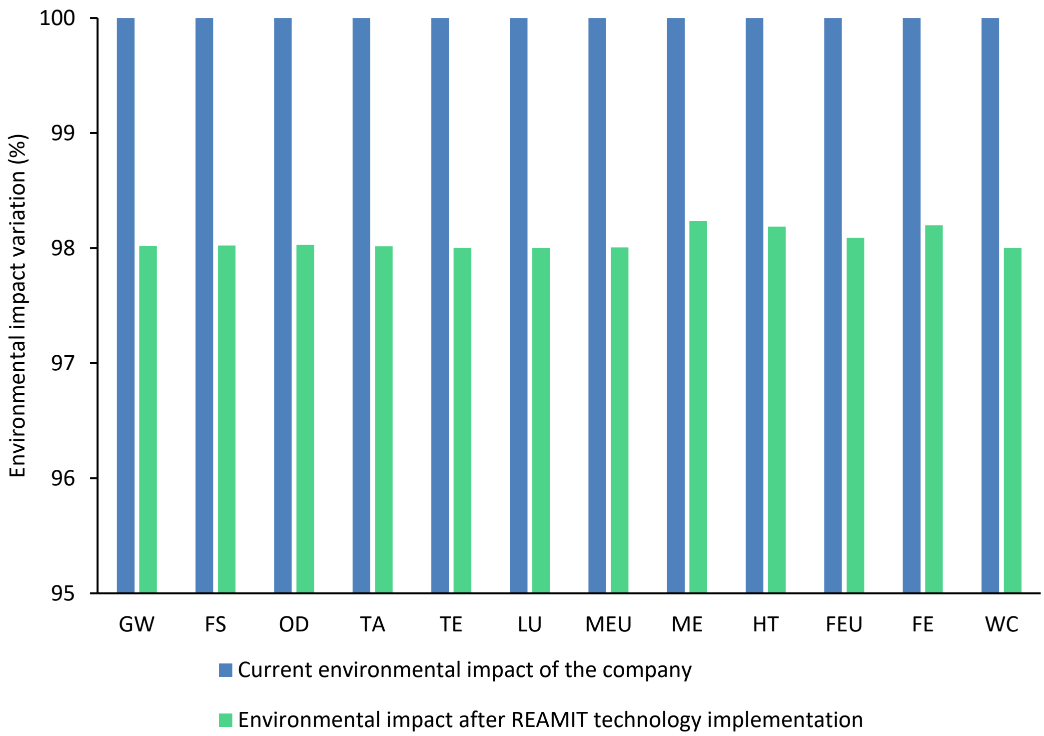

Figure 14. Results of the sensitivity analysis: effect of food waste reduction due to REAMIT technology implementation.

Food waste is linked to various adverse environmental effects [111,112]. When food is discarded, all the resources necessary to prepare, transport, process, and store it are also wasted. In addition, the environmental impact increases when food is discarded in the later stages of the supply chain because we also need to consider the energy and natural resources consumed in each stage [113]. In some cases, it is possible to decrease the environmental impacts from 1.7 to 2.1 %. In addition to the environmental impacts avoided, reducing and preventing food waste can enhance food security, improve productivity and economic efficiency and promote resource and energy conservation [114,115]. In this scenario, additional food production would not be necessary to compensate for these losses. Therefore, contributing to the reduction of all downstream impacts observed during the food supply stages under analysis. However, caution must be taken when affirming the positive effect of IoT technologies in reducing food systems' environmental impacts, as this can be a single case. Implementing IoT technologies in any system causes resource use, and if food waste reduction is not considered, the total impact of the organisation tends to increase. Furthermore, even considering the reduction, the overall balance of impacts depends on the amount of food avoided. Table 11 illustrates the environmental impacts that have been avoided as a result of the implementation of REAMIT technologies, leading to the reduction of food waste.

Table 11. Environmental impacts avoided through Reamit technology implementation.

Category	Unit	Zone C Fridge	Zone D Fridge	Zone E Fridge	Cold Room	Zone B Freezer 1	Zone B Freezer 2	Zone D Freezer	Zone E Freezer
GW	kg CO2 eq	93607	3744	16585	4070	0	0	10174	1116
FS	kg Cu eq	618	25	110	10	0	0	26	3.1
OD	kg CFC11 eq	0.8	0.0	0.1	0.0	0	0	0.0	0.0
TA	kg SO2 eq	977	39	175	27	0	0	67	5.8
TE	kg 1,4-DCB	106161	4246	17387	10959	0	0	27398	6714
LU	m2a eq	148255	5930	26535	2999	0	0	7497	819
MEu	kg N eq	98	3.9	17	3.6	0	0	9.0	1.6
ME	kg 1,4-DCB	1275	51	219	165	0	0	413	32
HT	kg 1,4-DCB	842	34	145	104	0	0	260	25
FEu	kg P eq	13	0.5	2.4	0.8	0	0	1.9	0.2
FE	kg 1,4-DCB	987	39	168	126	0	0	316	39
WC	m3	1600	64	263	619	0	0	1548	105

The second sensitivity analysis in Figure 15 shows the influence of increasing the number of vending machines in the retail stage.

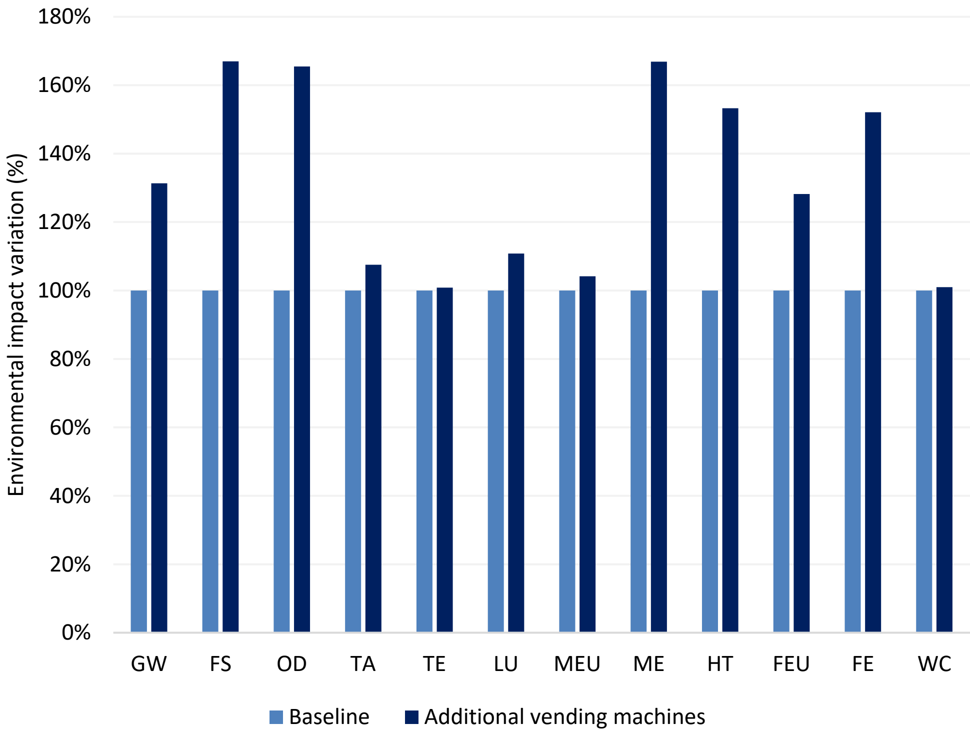

Figure 15. Results of the sensitivity analysis: effect of increasing the number of vending machines.

It was observed that the main categories negatively affected by this proposal were global warming, fossil resource scarcity, stratospheric ozone depletion, marine ecotoxicity, human toxicity, and freshwater eutrophication and ecotoxicity. For fossil resource scarcity, stratospheric ozone depletion and marine ecotoxicity, the environmental impact increased by more than 60%, suggesting an environmental risk from using additional vending machines due to the high electricity consumption.

The environmental impacts related to electricity consumption are intrinsically linked to the electricity mix supplied in the country. In 2020, the electricity supplied in the UK came from 41% fossil-fuelled power (almost all from natural gas), 30.6% from renewable energy (including wind, solar and hydroelectricity), 16.1% from nuclear power and a small percentage from imports [116]. To the extent that more renewable energy sources like wind and solar are used to generate electricity, the total environmental impacts associated with using electricity could be reduced. However, it might take several decades for that to happen [117].

8.2 HMF

8.2.1 Environmental impact assessment and hotspot analysis

Figure 16 presents the relative contribution of each unit process to the total impact obtained for the baseline scenario (A). Human milk transportation is the main hotspot of three impact categories, global warming, terrestrial ecotoxicity, and fossil resource scarcity. The contribution of first and second transportation combined represents 39.3 – 71.6% of the total impact in those categories. For global warming, carbon dioxide (CO_2) emitted from diesel combustion is the main contributor in this category. Other relevant emissions to consider during diesel combustion include non-methane volatile organic compounds (NMVOC) and copper (Cu) for terrestrial ecotoxicity.

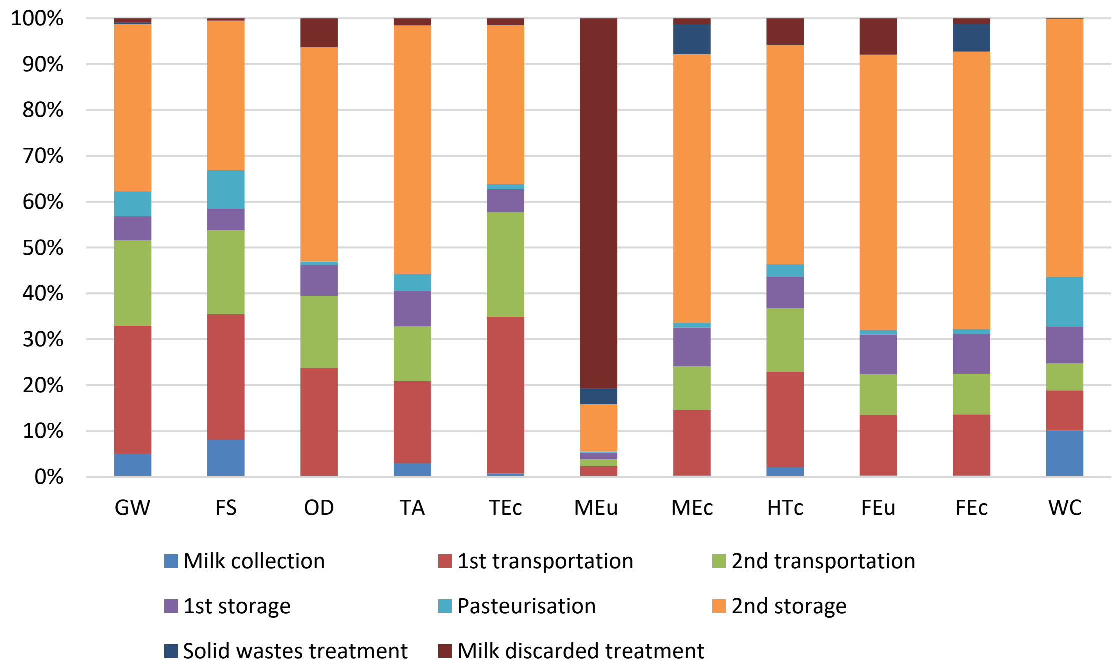

Figure 16. Relative contribution of each source to the total impact of the HMF - baseline scenario (A).

The electricity consumed during milk storage is relevant for stratospheric ozone depletion, freshwater eutrophication, freshwater ecotoxicity, marine ecotoxicity, human toxicity, terrestrial acidification and water consumption. Regarding marine eutrophication, the treatment of discarded milk represents 80.7% of the total impacts and was essentially due to the emissions of nitrate and ammonium to water.

Figure 17 presents the IoT technologies' relative contribution to the HMB's total impacts regarding the potential milk avoided. Although integrating IoT technologies to monitor temperature/humidity conditions can have many advantages, the environmental implications of using these technologies have been scarcely debated. On one hand, these technologies substitute physical processes and may help avoid impacts, which Weber et al. [118] described as "moving bits instead of atoms". On the other hand, they use electronics, an impact-intensive technology. In addition, the energy consumption of electronic products is far from insignificant. Consequently, the environmental impacts these technologies help to avoid must be balanced with the environmental impacts they generate themselves, keeping in mind that these impacts may not be of the same nature and therefore lead to dilemmas. In Figure 17, it is possible to observe that this integration did not adversely affect the organisation in a significant way. The contribution of the IoT technologies implemented in this study, including 12 sensors and a Big Data server to store and control the data, achieved a maximum impact contribution of 2.3% for the freshwater ecotoxicity category.

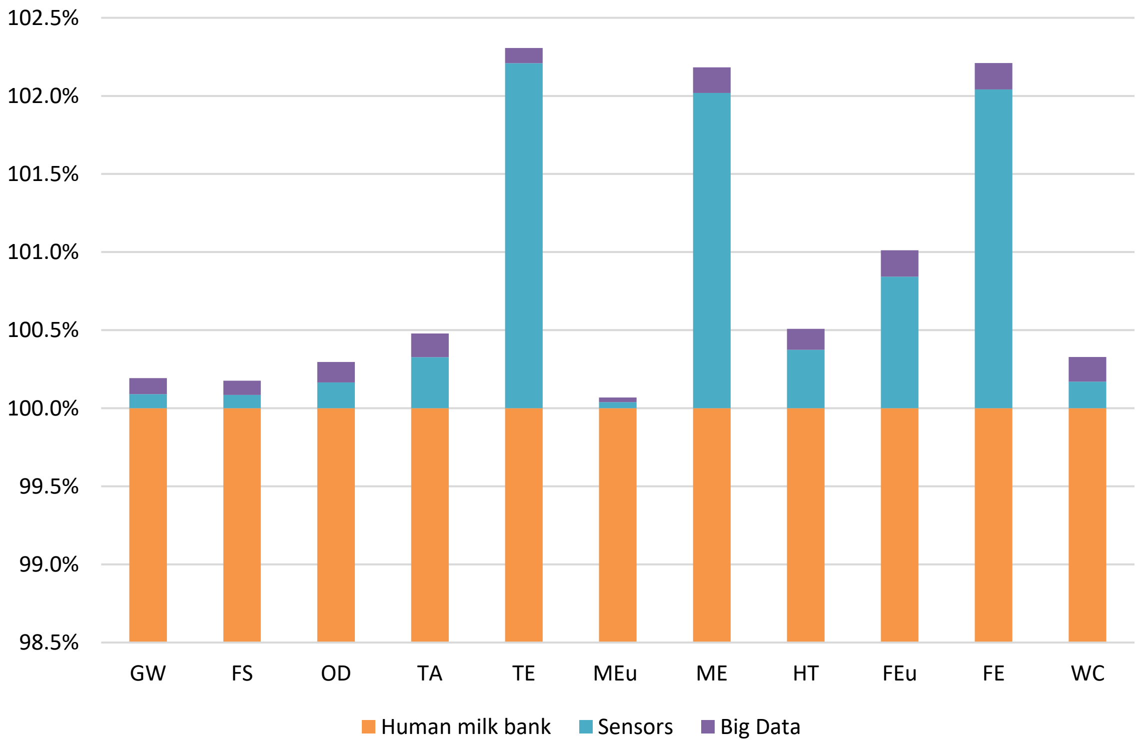

Figure 17. Relative contribution of each source to the total impact of the monitoring strategy scenario (B), disregarding the credits due to food waste avoided.

The main impact categories affected by the implementation of sensors are freshwater ecotoxicity, marine ecotoxicity, terrestrial ecotoxicity, and freshwater eutrophication, especially due to the use of batteries as a source of energy. The common environmental side effects of metals mining to produce the batteries are increased salinity of rivers, contaminated soil and toxic waste, ground destabilisation, water and biodiversity loss [109]. The substitution of these batteries for more environmentally friendly alternatives can be a strategy to mitigate their associated impacts [119,120]. For about a decade, scientists and engineers have been developing sodium batteries, which replace the metals used in current batteries [121]. Another alternative can be supercapacitors and ultracapacitors. These devices offer advantages over batteries in lifetime, power density and resilience to temperature changes [122]. They also benefit from high immunity to shock and vibration. However, they can be high initial costs and provide low energy density [123].

The electricity consumed to store and control the data by the Big Data server contributed to a slight increase (<1%) in the impacts mainly for the following categories: water consumption and freshwater eutrophication. However, a reduction in the environmental impact can be expected if human milk waste is avoided, which can equilibrate the additional impacts caused by the introduction of monitoring technologies. The surplus production of food to compensate in case of waste could cause a significant amount of environmental and social problems [110–112]. Therefore, it is recommended to use monitoring systems/technologies, such as the one proposed to avoid food waste and the environmental footprint associated with these wastes. The potential avoided impacts resulting from the decreased amount of milk waste discarded due to the implementation of IoT technologies are shown in following section.

8.2.2 Sensitivity analysis

Table 12 presents the total impact obtained for the first sensitivity analysis, i.e., the influence of the monitoring IoT technologies on the environmental impacts considering 1%-3% reduction in the total milk discarded. Figure 18 shows the percentage change based on the baseline scenario.

Table 12. Total results of the impact assessment associated with the baseline scenario (A) and the scenarios representing the implementation of monitoring technologies (B).

Impact category	**Unit**	**Scenario A**	**Scenario B (1% waste reduction)**	**Scenario B (3% waste reduction)**
GW	kg CO_2 eq	30749	30501	29886
FS	kg oil eq	9037	8962	8781
OD	kg CFC_{11} eq	0.0129	0.0128	0.0125
TA	kg SO_2 eq	126	125	122
TEc	kg 1,4-DCB	103960	105318	103239
MEu	kg N eq	4.22	4.19	4.10
MEc	kg 1,4-DCB	2972	3007	2947
HTc	kg 1,4-DCB	1112	1106	1084
FEu	kg P eq	7.77	7.77	7.62
FEc	kg 1,4-DCB	2320	2348	2302
WC	m^3	203	201	197

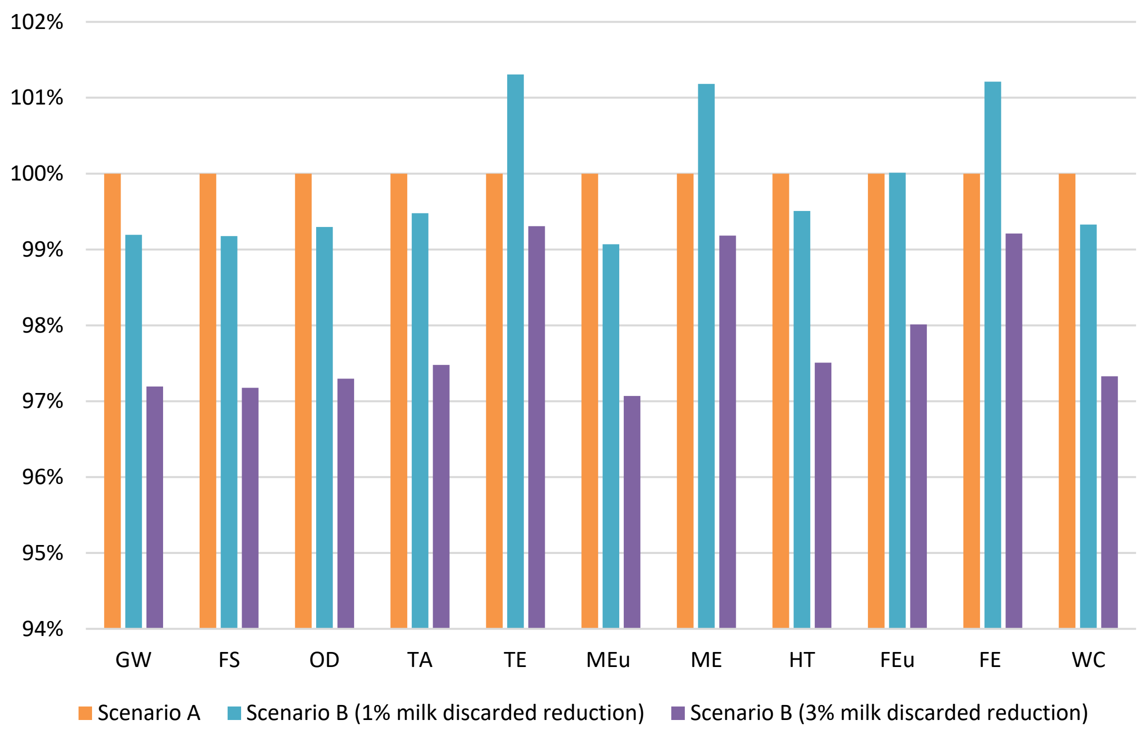

Figure 18. Results of the sensitivity analysis: effect of human milk discarded reduction.

A 1% reduction in discarded milk can decrease the environmental impacts from 0.5 to 0.9 % in some categories. Marine eutrophication fossil depletion and global warming were the impact categories more positively affected. However, this reduction is not sufficient to offset the impacts added to the system due to the implementation of IoT technologies in three categories, freshwater, marine and terrestrial ecotoxicity.

However, when milk discarded achieves a reduction of 3% in the second scenario, the impacts on the global warming category are reduced by 29.8 tons of CO2-eq per year in this organisation. In this scenario, the control of the milk conditions proved to be relevant to the reduction of impacts related to air emissions and resource consumption. In this particular case, the recommended amount of human milk avoided should be at least 90.8 L per year in order to compensate for the additional impacts due to IoT technologies implementation.

Food waste is associated with different adverse effects on the environment [111,112]. When human milk food is discarded, all inputs used in processing, transporting, preparing, and storing discarded milk are also wasted. The later the milk is wasted along the chain, the greater its environmental impact, because then we also need to take into consideration the energy and natural resources expended into each of those steps. In addition, the milk discarded that ends up in wastewater treatment plants produces a large amount of greenhouse gas emissions, which impact the environment [124,125]. Human milk management also involves steps that consume diesel, and fossil fuels. For instance, transporting the human milk from the donor's home/hospital to the HMB and then from the HMB to the hospital/recipient home needs diesel, and other fuels; storing the milk in the freezers and pasteurising it also uses a large amount of electricity. Wasting fuel, or electricity both in the back and front end by wasting human milk can have an impact on the environment and exacerbates the global warming crisis with its significant carbon dioxide emissions.

Reducing and preventing human milk waste can increase food security, foster productivity and economic efficiency, promote resource and energy conservation, and decrease global warming. In this scenario, the additional production of food to compensate for these losses would not be necessary. Therefore, contributing to the reduction of all downstream impacts observed during human milk handling, including transportation, storage, and pasteurisation. However, further assessment to quantify the precise amount of food waste avoided is recommended.

In the second analysis (Figure 19), the influence of transportation distances on the environmental impact results was evaluated. The transportation over larger distances results in higher consumption of diesel, increasing the emissions of CO, CO_2, SO_2, NOx, NMVOCs and others. These emissions are generated due to diesel combustion, which affects mainly the impact categories of global warming, terrestrial ecotoxicity and fossil resource scarcity. When the transport distance is changed by 25 miles, the net impact can vary by up to 14.3% in some impact categories. Therefore, the results show that human milk transportation depends highly on the transport distance, and the milk should be collected from donors located close to the HMB, and distribution should where possible be made to local hospitals in order to decrease the environmental impacts associated with transportation.

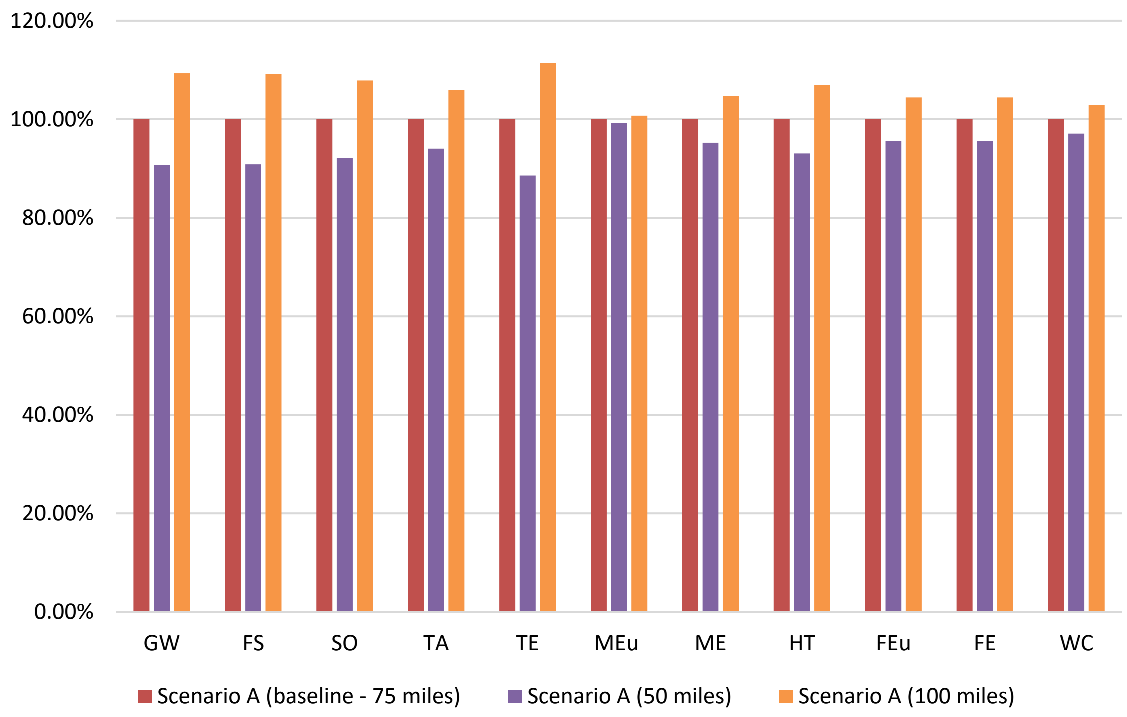

Figure 19. Results of the sensitivity analysis: effect of transportation distances.

An alternative is the introduction of more decentralised hubs, where local healthcare centres can be responsible for the collection and the human bank acts as the principal organising centre supervising different branches. The creation of hubs has been designed to mitigate the impacts of having fewer milk banks and ones that collect and provide DHM over a wide area. This alternative is already in practice in this HMB. However, this study did not take into account the additional impacts associated with the creation of the additional facilities that would need to be established to allow for local collections and distributions, i.e. all the additional equipment and facility impacts and the extra staffing and other resources.

8.2.3 Employing different transport modes in place of motorcycle volunteers

The Human Milk Foundation is developing the use of drones for milk collection and delivery. While drones can substitute motorcycle volunteers in some cases, drones are sometimes the only option, especially in sparsely populated areas. Hence, an analysis of the impact of employing delivery drones has been carried out. Figure 20 shows the influence of substituting 10 % of motorcycle volunteers with delivery drones to transport human milk.

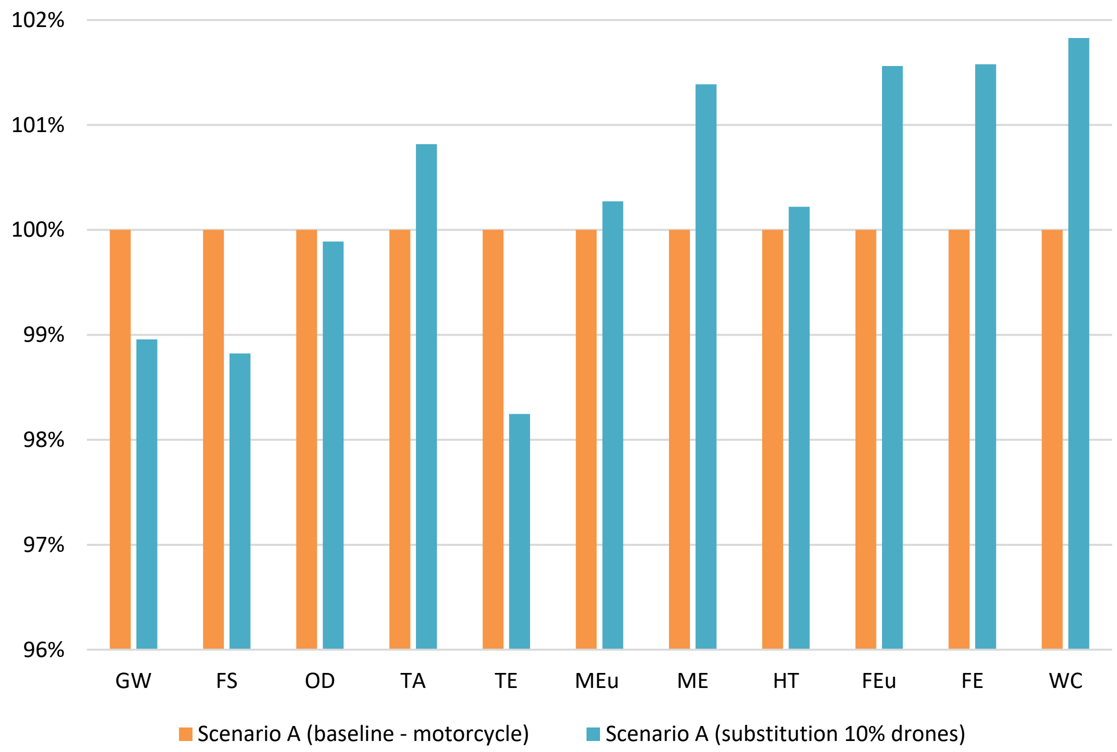

Figure 20. Results of the sensitivity analysis: effect of changing the transport mode to drones.

Effects on the environmental impacts were observed due to changes in the transportation mode. Effects on milk quality were not evaluated in this analysis. It was observed that the main categories positively affected by this substitution were global warming, terrestrial ecotoxicity, and fossil resource scarcity. The substitution of 10% of motorcycles by drones achieved a reduction of 1.8% in terrestrial ecotoxicity impact category. However, for other impact categories, such as freshwater eutrophication, freshwater ecotoxicity, marine ecotoxicity and water consumption, this change negatively affected the environmental performance of the organisation. For the water consumption impact category, the environmental impact increased by 1.8%, suggesting an environmental risk from using drones due to the high electricity consumption.

From an environmental perspective, there are pros and cons to using drones for delivery services. The main expected benefit for the environment is that, compared with many traditional methods of delivery using fossil fuel, drones could reduce CO_2 emissions locally as well as other air pollutants. However, although drones avoid environmental impacts from direct diesel combustion emissions, impacts relating to additional electricity production required by a drone-based logistics system may reduce or eliminate the benefits. The impacts depend on how local power is generated, e.g., using coal or natural gas, which emit carbon pollution, versus renewable resources like wind or solar, which do not. In 2020, the electricity supplied in the UK came from 41% fossil-fuelled power (almost all from natural gas), 46.7% zero-carbon power (including 16.1% nuclear power and 30.6% from wind, solar and hydroelectricity), and imports [116]. As environmental impacts related to electricity consumption are intrinsically linked to the electricity mix supplied in the country, successive UK governments have outlined numerous commitments to reduce fossil-fuelled power. To the extent that more renewable energy sources like wind and solar are used to generate electricity, the total greenhouse gases associated with the use of drones could be reduced. These results can serve as a precautionary note for policymakers planning to promote the use of delivery drones due to potential environmental impact reduction.

Among significant negative environmental effects, the threat to wildlife, especially birds, is another great concern. Beyond the apparent risk of collision, birds could be affected by the noise and stress caused by the frequent presence of drones in their habitat. To date, the consequences of excessive stress caused by drones on wildlife have not been studied systematically and are little understood. Other potential environmental risks include the wastes resulting from collisions and dropped cargo and the related responsibility for their disposal. Both factors might also result in resistance from society to the widespread use of delivery drones.

Figure 21 shows the influence of substituting 10% of motorcycles with electric vehicles to transport human milk. The results show that the environmental impacts of this substitution are highly dependent on the human milk payload transported. If the average amount of human milk transported per journey is around 50 L, it was observed a positive effect for all impact categories, except ionizing radiation and water consumption. The maximum reduction was achieved in terrestrial ecotoxicity, which could avoid 2.5% of the impacts.

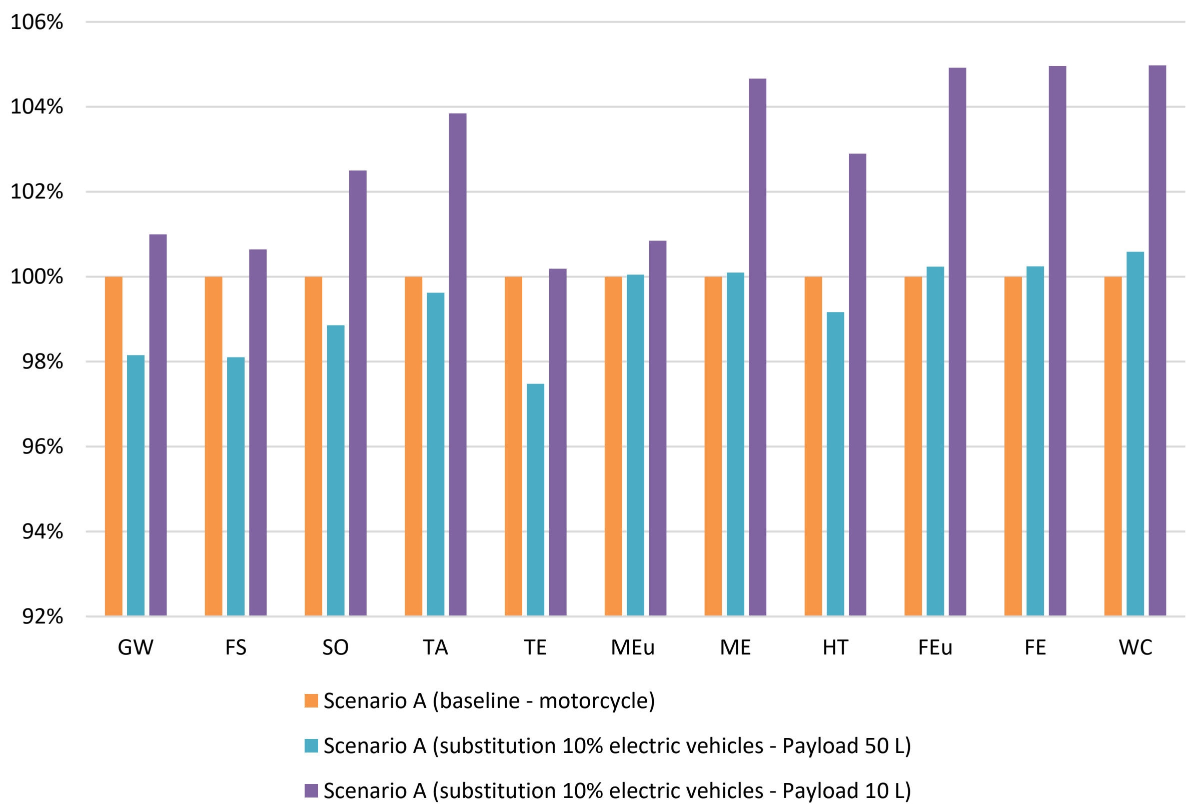

Figure 21. Results of the sensitivity analysis: effect of changing the transport mode to electric vehicles.

However, when less milk is transported per journey, and more trips are required, the environmental burden increase and a negative effect is observed for most of the impact categories. For example, the impact of freshwater eutrophication and freshwater ecotoxicity would increase by 5% in this scenario. Therefore, the distribution of human milk using electric vehicles should be made transporting quantities of milk above 40 L to reduce the environmental impacts in most of the categories.

As mentioned above, battery production is an energy-intensive process. Vehicle cars rely on rechargeable batteries to run, which requires the use of energy-intensive materials like cobalt and other metals. Producing electric vehicles leads to significantly more emissions than producing fossil fuel cars. Depending on the country of production, it can represent an additional 30 to 40% of production emissions [126].

In addition, the national electricity mix in most of the world is still powered by fossil fuels, such as coal or oil, and electric vehicles depend on that energy to get charged. The full benefits of electric vehicles will be achieved only after the electricity sources become renewable, and it might take several decades for that to happen [117]. Despite that, the local emissions per mile for electric vehicles are lower than vehicles with internal combustion engines [117], which highly affects the global warming category. However, other environmental categories should also be considered to make a more informed decision.

8.3 BFM

8.3.1 Environmental impact assessment and hotspot analysis

Figure 22 presents the relative contribution of each unit process to the total impact obtained for the meat manufacturing company in the baseline scenario. Cattle production is the main hotspot of five impact categories, contributing to 31 - 88 % of the total impact in those categories. Swine production was the main contributor to fossil resource scarcity, terrestrial ecotoxicity, human toxicity, and water consumption impact categories (8.2 - 62.4% of the total impact), while solid waste management was the main hotspot for marine ecotoxicity (41.5%).

The production of livestock (animals raised for meat) contributes to emissions in several ways, for example, by producing methane through their digestive processes (enteric fermentation) [82–84]. Manure and pasture management, land use change, production of crops for animal feed, and fuel consumption also fall into this category [82,85]. In addition, contrary to many other areas of food production where there are prospects for expanding the use of low-carbon materials, it is less obvious how meat manufacturing companies will be decarbonised [94]. For animal livestock production, is not possible to stop animals from producing methane, for example. However, some solutions to decrease those impacts can include food waste reduction and the use of IoT technologies to monitor the quality of the environmental conditions where the meat is being manufactured to prevent spoilage.

Electricity consumption during the dry ageing stage had a small contribution to the environmental impact. Packaging and animal transportation was not significant for the total impact of the company (<1% of the total impact). The greenhouse gas emissions from transportation make up a very small amount of the emissions from food. Therefore, eating locally would only have a significant impact if transport was responsible for a large share of food's final environmental impact, which is not the case in this scenario.

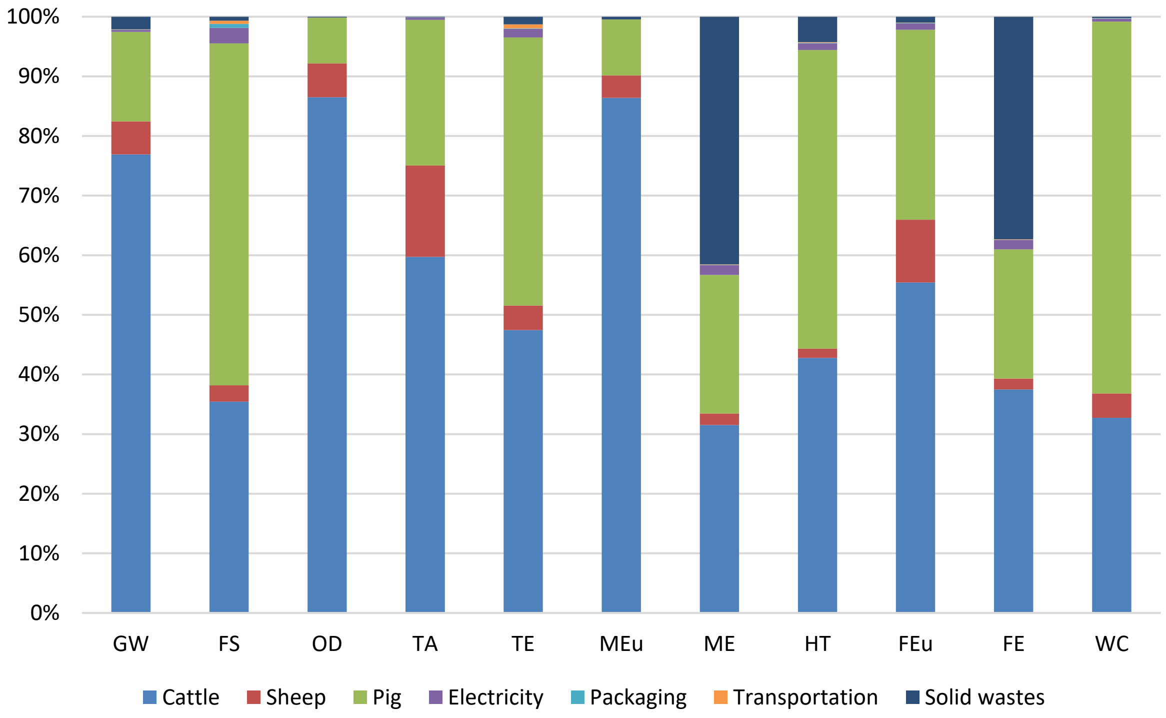

Figure 22. BFM hotspot analysis.

Figure 23 presents the relative contribution of the IoT technologies installed in the company and their influence on the total impact of the system, disregarding the potential food waste avoided.

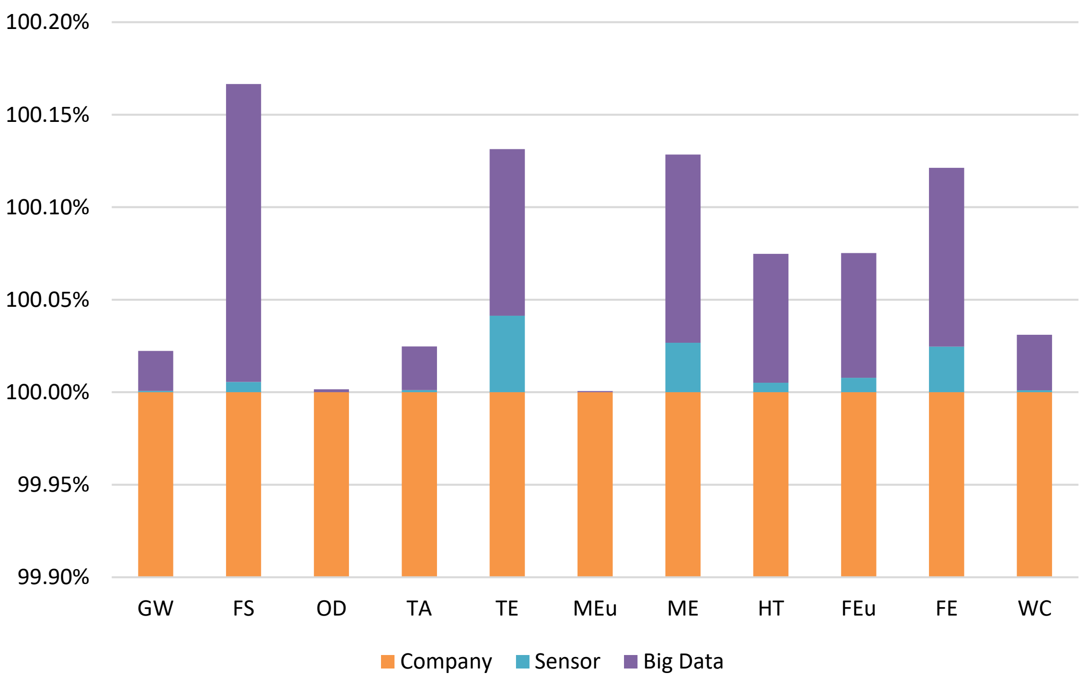

Figure 23. Relative contribution of the IoT technologies implementation to the total impact of the BFM company (B).

Although using IoT technology to track temperature and humidity conditions might have numerous benefits, the environmental consequences may also be evaluated. The contribution of the IoT technologies implemented in this study, including 10 sensors and a Big Data server to store and control the data, achieved a maximum impact contribution of 0.17% (fossil scarcity category). Therefore, it is possible to observe that the overall impact of the food manufacturing company was not negatively affected by this strategy in a significant way.

In addition, there are still potential tangible benefits that should be considered. For example, a reduction in the environmental impact can be expected if part of the edible meat waste is avoided due to the implementation of these technologies, which can equilibrate the additional impacts. The additional production of meat to offset these wastes is linked to a variety of negative environmental and social effects [111,112]. When food is discarded, all the resources necessary to prepare, transport, process, and store it are also wasted. In addition, the environmental impact increases when food is discarded in the later stages of the supply chain because then we also need to consider the energy and natural resources consumed in each of those stages [113].

Therefore, preventing meat waste and the associated environmental impact is essential, and the use of monitoring systems/technologies, such as the one suggested in this study, is highly recommended. The potential avoided impacts resulting from the decreased amount of food waste due to the implementation of IoT technologies are shown in the following section.

8.3.2 Sensitivity analysis

Table 13 presents the total impact obtained for the sensitivity analysis, i.e., the influence of the monitoring IoT technologies on the environmental impacts considering a reduction in the trim losses and its respective credits. Figure 24 shows the relative change based on the baseline scenario.

Table 13. Total results of the impact assessment associated with the baseline scenario (A) and the scenarios representing the implementation of monitoring technologies (B).

Impact category	Unit	Total impact	Impact avoided
GW	kg CO2 eq	3587219.9	267288.5
FS	kg oil eq	126100.1	9395.9
SOD	kg CFC11 eq	26.6	2.0
TA	kg SO2 eq	19887.2	1481.8
TEc	kg 1,4-DCB	2764169.7	205962.0
MEu	kg N eq	4993.1	372.0
MEc	kg 1,4-DCB	118125.2	8801.7
Hct	kg 1,4-DCB	52670.3	3924.5
FEu	kg P eq	477.3	35.6
FEc	kg 1,4-DCB	100218.0	7467.4
WC	m3	26238.2	1955.0

Considering that IoT technologies can prevent the generation of trim losses and the associated impacts, it is possible to achieve a decrease in the environmental impacts from 0.83 to 1 %. For most of the categories, the meat quality conditions control proved to be relevant to the reduction of impacts related to air emissions and resource consumption, contributing also to the reduction of downstream impacts observed during all supply stages. In the global warming category, this reduction would represent the avoidance of 267 tonnes of CO_2eq per year. In addition to the environmental impacts avoided, reducing and preventing food waste can enhance food security, improve productivity and economic efficiency and promote resource and energy conservation [114,115].

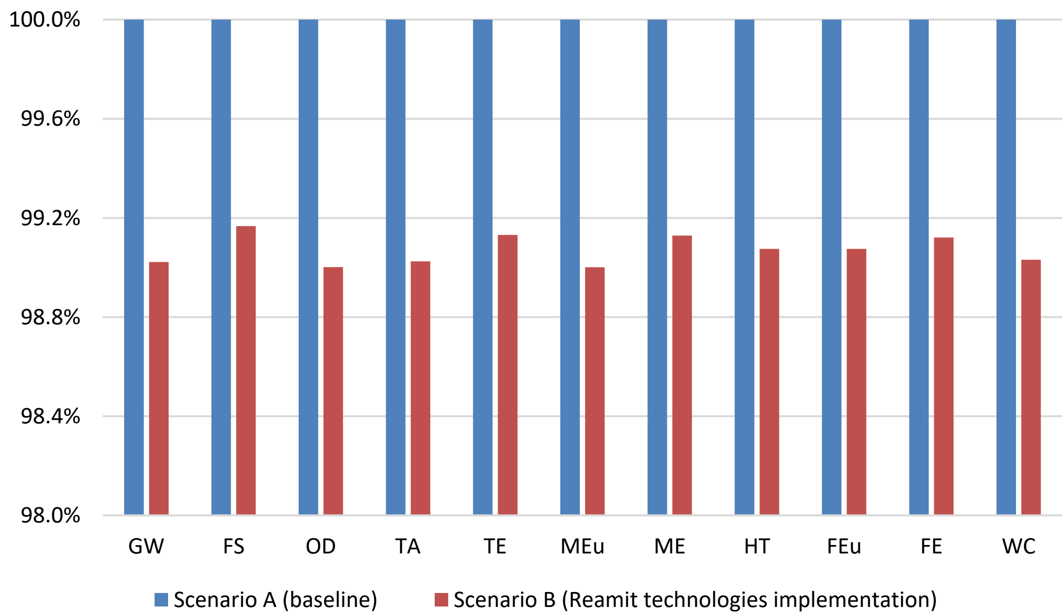

Figure 24. Results of the sensitivity analysis: effect of trim loss reduction due to IoT technology implementation.

8.4 WD Meats

8.4.1 Environmental impact assessment and hotspot analysis

A hotspot analysis was conducted on WD Meats to identify the areas of their operations that have the highest environmental impacts (Figure 25).

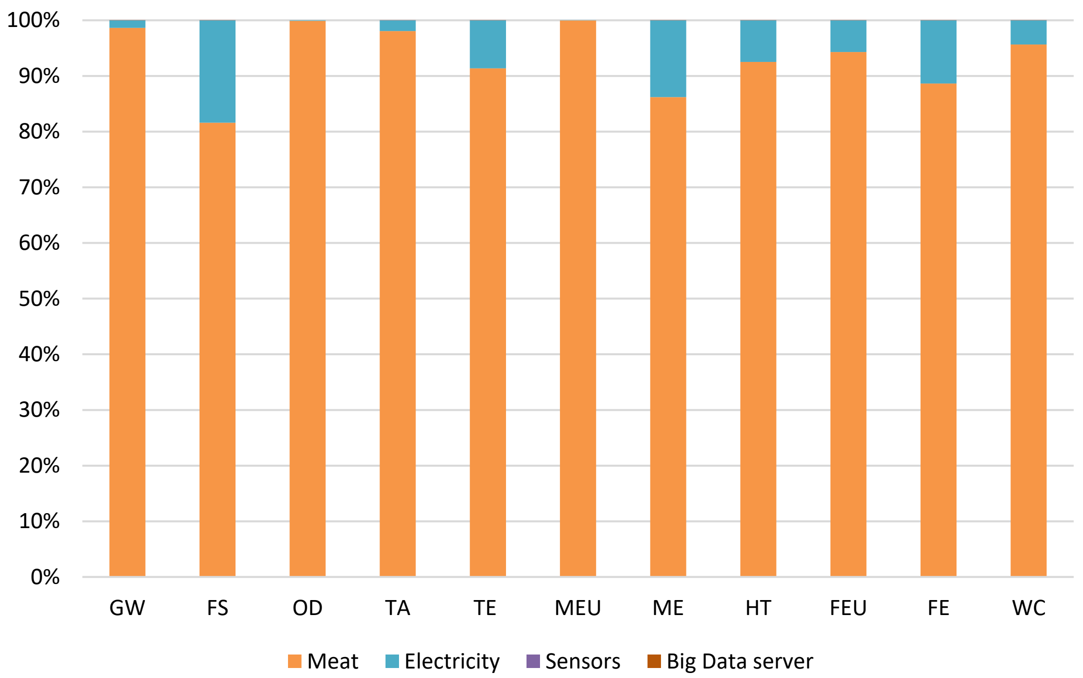

Figure 25. WD Meats hotspot analysis.

The results of the analysis showed that meat production emerged as the main hotspot across all impact categories. The hotspot analysis underscores the need for WD Meats to prioritize measures that directly address the environmental impacts associated with meat production. Strategies focusing on optimising production processes, improving resource efficiency, and minimising waste generation within this stage of their operations are likely to yield the greatest environmental benefits.

The LCA assessment indicated that the electricity consumption in the dry ageing chambers had relevance in three specific impact categories: fossil scarcity, marine ecotoxicity, and freshwater ecotoxicity. In these categories, the impact attributed to electricity consumption ranged from 12% to 18%, highlighting the importance of addressing energy efficiency and exploring renewable energy sources to mitigate these impacts.

8.4.2 Sensitivity analysis

Figure 26 also shows that the implementation of IoT technologies within the company did not have a significant effect on the overall environmental impact. Both the introduction of sensors and the utilisation of Big Data did not contribute substantially to the total impacts assessed in the LCA. It suggests that while these technologies may offer operational benefits and improved data insights, they did not present a major influence on the environmental performance of WD Meats.

Table 14 presents the environmental performance of the dry ageing chambers and the potential environmental impacts avoided due to the implantation of the REAMIT technologies to reduce food waste.

Table 14. WD Meats environmental impacts and REAMIT technology avoided impact.

Category	Impact/ chamber/ cyclo	Impact/ chamber/ year	Impact/ year for all chambers	Impact avoided per year (1 chamber)	Impact avoided (all chambers)
GW	138990	2415774	33820831	23200	324794
FS	2720	47282	661954	454	6357
OD	1.1	19.9	278.3	0.2	2.7
TA	602	10457	146397	100	1406
TE	71299	1239240	17349362	11901	166612
MEU	214	3727	52178	36	501
ME	2147	37311	522350	358	5016
HT	1210	21028	294398	202	2827
FEU	13.9	242.2	3391.2	2.3	32.6
FE	2105	36592	512295	351	4920
WC	446	7754	108552	74	1042

By leveraging IoT technologies, the company was able to optimise its operations and enhance resource efficiency, resulting in reduced environmental burdens. The IoT technologies likely facilitated real-time monitoring, data collection, and analysis, enabling the identification of areas for improvement and the implementation of targeted sustainability measures. These findings highlight the potential of IoT technologies to contribute to a more sustainable and environmentally friendly operation. While the reduction of 0.95% to 1.01% may appear modest at first glance, it should be noted that even small percentage reductions can accumulate into substantial absolute reductions when implemented across the entire company. Moreover, the reduction of 324 tonnes of CO_2-eq demonstrates the significant positive impact that can be achieved through the widespread implementation of IoT technologies. This reduction not only contributes to the company's sustainability goals but also helps to mitigate climate change and protect the environment.

The results of this environmental analysis provide valuable insights into the role of IoT technologies in driving environmental improvements. It emphasises the importance of adopting innovative solutions to enhance sustainability performance and encourages further exploration and implementation of IoT technologies in various industries. By embracing the potential of IoT technologies and leveraging their capabilities, companies can continue to reduce their environmental footprint, foster a more sustainable future, and contribute to global efforts in combating climate change.

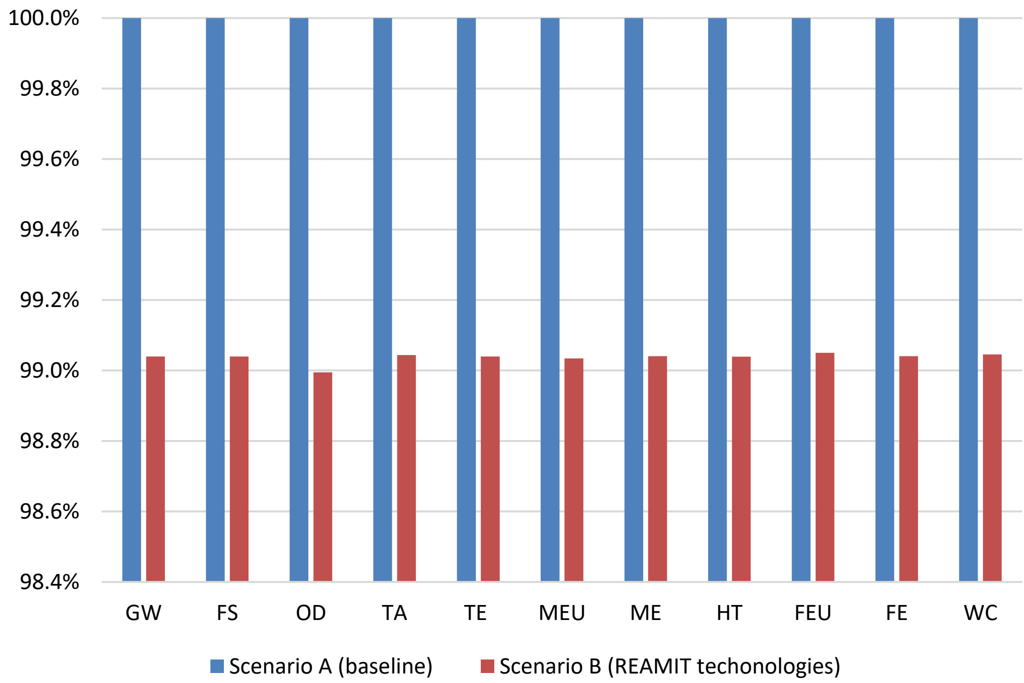

Figure 26. Effect of the implementation of IoT technologies in the total impact of the company.

8.5 Musgrave

8.5.1 Environmental impact assessment

Table 15 provides an overview of the carbon footprint (CF) associated with the production and transportation of various food products for both individual trips and monthly operations, taking into account three vans. The values are categorised into minimum, average, and maximum estimates. These estimates demonstrate the range of potential environmental impact depending on specific factors such as characterisation factors, and number of trips per month. Figure 27 shows the relative contribution of each product transported to the total impact.

Table 15. Estimated impact per trip and per month (Musgrave).

Product	CF per trip (CO_2-eq)			CF per month (CO_2-eq)		
	Min	Average	Max	Min	Average	Max
Meat	6008	15010	27012	378498	1103226	2268996
Vegetables	231	608	1510	14548	44681	126830
Fruit	154	456	1208	9699	33511	101464
Dairy products	904	1692	2706	56949	124394	227298
Seafood	302	790	1504	19024	58099	126332
TOTAL	**7599**	**18557**	**33940**	**478719**	**1363911**	**2850919**

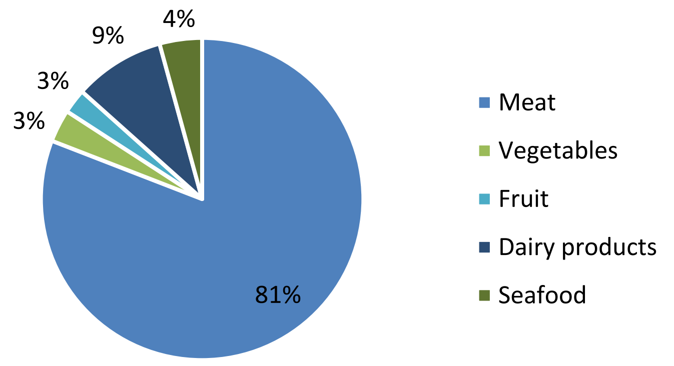

Figure 27. Relative contribution of each product group to the total impact.

The findings reveal the following distribution of impact percentages: 81% from meat, 9% from dairy products, 3% from fruits, 3% from vegetables, and 4% from seafood. This distribution can be attributed to both the quantity of food transported and the respective carbon footprint per kilogram of each food category. The prominence of meat in the overall impact is primarily due to its higher carbon footprint compared to the other food items considered in the analysis.

8.5.2 Sensitivity analysis

Table 16 presents the potential environmental impacts avoided due to the implantation of the REAMIT technologies to reduce food waste. Figure 28 shows the relative change based on the baseline scenario (average).

Table 16. Environmental impacts per year of food production and transportation and avoided impact due to REAMIT technology implementation.

Product	Baseline (CO_2-eq/year)			Impact avoided REMIT (CO_2-eq/year)		
	Min	**Average**	**Max**	**Min**	**Average**	**Max**
Meat	453600	661500	907200	432000	634500	874800
Vegetables	340200	529200	756000	324000	507600	729000
Fruit	226800	396900	604800	216000	380700	583200
Dairy products	226800	330750	453600	216000	317250	437400
Seafood	113400	198450	302400	108000	190350	291600
TOTAL	**1360800**	**2116800**	**3024000**	**1296000**	**2030400**	**2916000**

By leveraging IoT technologies, Musgrave successfully optimised its operations and significantly enhanced resource efficiency, leading to a reduction in environmental burdens. Although a 4% reduction may seem modest, it is crucial to observe that even small percentage reductions can accumulate into substantial absolute reductions when applied across the entire company. In this context, the average reduction of 668 tonnes of CO_2-eq serves as a remarkable example of the positive impact achieved through widespread IoT implementation. This reduction not only aligns with the company's sustainability goals but also plays a crucial role in protecting the environment. These findings encourage the adoption of IoT technologies beyond the scope of this particular company, showing that such initiatives can collectively drive a global positive impact on environmental preservation.

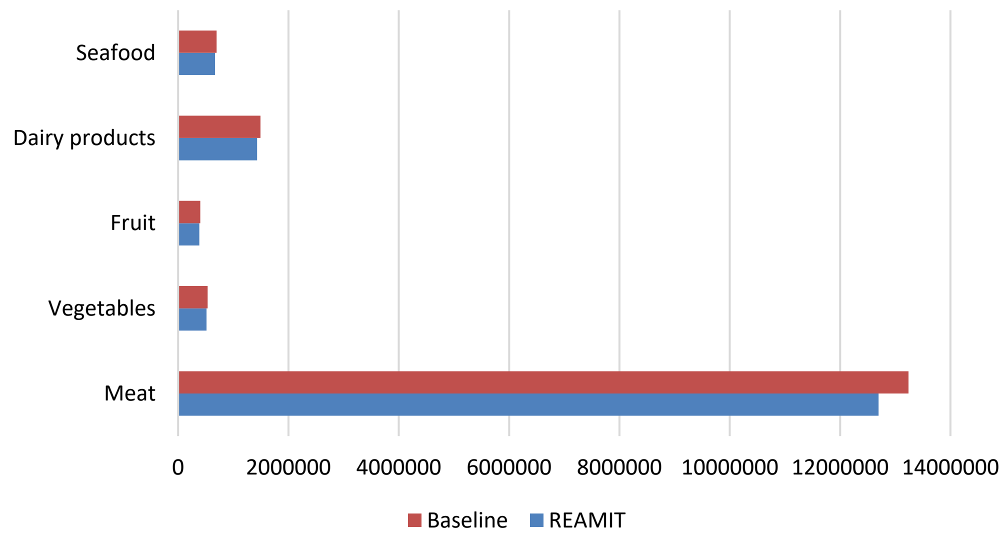

Figure 28. Effect of the implementation of IoT technologies in the total impact of the company.

9. Global Conclusions

The impact avoided due to REAMIT technologies implementation per year is presented in Table 17. The implementation of REAMIT technologies has demonstrated a significant environmental contribution through the reduction of environmental impacts. The analysis of the four pilots under consideration revealed that the implementation of REAMIT technologies resulted in the avoidance of approximately 1,419.1 tonnes of CO_2-eq per year. This substantial reduction underscores the effectiveness of the REAMIT project in achieving its goal of mitigating environmental impacts.

The considerable reduction in CO_2-eq emissions achieved through the implementation of REAMIT technologies demonstrates the potential of innovative solutions to drive environmental improvements. These technologies have enabled real-time monitoring, data analysis, and optimisation of processes, leading to enhanced resource efficiency and reduced environmental burdens. By embracing such technologies, industries and companies can make significant strides toward sustainability and contribute to global efforts to combat climate change.

The results of the REAMIT project serve as a compelling case for the broader adoption and implementation of IoT technologies in various sectors. The successful integration of these technologies not only drives environmental benefits but also enhances operational efficiency, reduces costs, and promotes overall sustainability. The REAMIT project serves as a model for future initiatives seeking to reduce environmental impacts through the deployment of IoT technologies and underscores the importance of collaborative efforts between academia and industry in driving sustainability.

Table 17. Impact avoided due to REAMIT technologies implementation per year.

Pilot	**Carbon emission avoided ($t\ CO_2\ eq/year$)**
Yumchop	129.3
HMF	29.9
Burns Farm Meats	267.2
WD Meats	324.7
Musgrave	668.0
Total	**1,419.1**

9.1 Yumchop

The hotspot analysis showed that food raw materials production is the main hotspot of nine impact categories. For the impact categories fossil resource scarcity, stratospheric ozone depletion and marine ecotoxicity, the retail stage was the main hotspot.

The contribution of the IoT technologies to the company's total impact, including installing ten sensors and using a Big Data server, increased the company's impact by around

0.4%. However, it is expected that employing these monitoring technologies would prevent food waste generation and the associated environmental impacts observed during the food supply stages under analysis. Considering the food waste reduction based on the alerts, it is possible to decrease the environmental impacts by up to 1.55 Mt of CO_2eq per year in the global warming category. Therefore, the results provide evidence of the benefits of using IoT technologies to explore the problem of food waste and the solutions to achieve more sustainable food systems.

9.2 HMF

According to the hotspot analysis, the transportation of human milk was found as the main hotspot of this organisation for most impact categories. The electricity consumed during the second storage was also relevant for some impact categories, while the treatment of discarded milk represented 80.7% of the impact for marine eutrophication. The strategy to integrate IoT technologies (sensors and Big Data server) to monitor temperature/humidity conditions did not adversely affect the organisation in a significant way. The batteries were responsible for a great part of the impacts of the sensors installed, followed by the printed circuit board. However, if the reduction in waste reaches 3%, then, the avoided environmental impacts resulting from this strategy could avoid 29.8 tons of CO2-eq per year in the global warming g category.

The sensitivity analysis regarding the influence of transport distance showed that the impacts of the HMB depend highly on the transport distance, the milk should be collected from donors located close to the HMB, and distribution should be made to local hospitals to decrease the environmental impacts associated with diesel combustion. The results of the sensitivity analysis also showed that changing part of the transportation mode from motorcycles to drones can positively affect some categories, such as global warming, terrestrial ecotoxicity and fossil resource scarcity. However, for other impact categories, this change could result in environmental risk due to the high electricity consumption. Therefore, human milk logistics must be studied in a multidisciplinary way, addressing organisational, safety, economic, environmental, and engineering aspects, before the transaction to a drone solution. Future studies could bring this approach to other sectors and companies. A similar analysis was performed considering the substitution by electric vehicles, and the results showed that the environmental impacts of this strategy are highly dependent on the amount of milk transported per journey. In order to reduce the environmental impacts, the amount of human milk that electric vehicles should transport in a single journey should be greater than 40 L.

While this is the first time the use of digital technologies for avoiding wasted human milk is evaluated using LCA, we are constrained by the availability of suitable data, which has limited our analysis and findings. For instance, the precise amount of food waste avoided due to IoT technologies implementation in this HMB is still under assessment, and further analysis is required. Despite these limitations, the results provide evidence of the sustainability benefits of modern digital technologies and bring out the value of investing in these technologies to support various needs of organisations.

9.3 BFM

The hotspot analysis revealed that meat production emerged as the primary contributor to the overall environmental impacts across all impact categories. Cattle production specifically accounted for a significant portion of the total impact in five categories, ranging from 31% to 88%. On the other hand, swine production had a considerable influence on fossil resource scarcity, terrestrial ecotoxicity, human toxicity, and water consumption categories, contributing between 8.2% and 62.4% of the total impact.

The implementation of IoT technologies within the company, encompassing the use of 10 sensors and a Big Data server for data storage and control, showed a maximum contribution of 0.17% to the total impact in the fossil scarcity category. Thus, it can be inferred that the adoption of IoT technologies did not significantly affect the overall impact of the food manufacturing company.

However, there are potential tangible benefits, such as the reduction in environmental impact through the avoidance of edible meat waste. The results showed that the implementation of IoT technologies could lead to a decrease in environmental impacts ranging from 0.83% to 1%. Notably, this reduction would translate into the avoidance of approximately 267 tonnes of CO_2eq per year in the global warming category. In addition to the avoided environmental impacts, reducing and preventing food waste can positively impact food security, productivity, economic efficiency, and resource and energy conservation.

9.4 WD Meats

The hotspot analysis have shed light on the areas of their operations with the highest environmental impacts. Meat production emerged as the primary hotspot across all impact categories, emphasising the need for targeted measures to address these impacts. Strategies focused on optimising production processes, improving resource efficiency, and minimising waste generation within the meat production stage are crucial for reducing the company's environmental footprint.

The implementation of IoT technologies within the company did not significantly impact the overall environmental performance. The introduction of sensors and the utilization of Big Data did not contribute substantially to the assessed impacts. On the other hand, the implementation of IoT technologies demonstrated a positive environmental impact. The analysis showed a reduction of 0.95% to 1.01% in the total environmental impacts, representing a significant absolute reduction of 324 tonnes of CO_2-eq if implemented across the entire company. This finding highlights the potential of IoT technologies in optimising operations, improving resource efficiency, and contributing to sustainability goals.

Overall, this environmental analysis emphasises the role of IoT technologies in driving environmental improvements and promoting sustainability. It underscores the importance of embracing innovative solutions and leveraging their capabilities to reduce environmental footprints and contribute to global efforts in combating climate change. By adopting IoT technologies and implementing targeted sustainability measures, companies like WD Meats can pave the way for a more sustainable future and contribute to a greener and more environmentally friendly industry.

9.5 Musgrave

The analysis of the carbon footprint associated with the transportation of various food products by Musgrave highlights the substantial contribution of meat to the overall environmental impact. This finding underscores the critical importance of developing and implementing solutions to reduce meat waste. To achieve meaningful progress, Musgrave can explore various strategies, such as optimising transportation routes, and promoting sustainable sourcing practices for meat products. Additionally, embracing technological advancements, such as IoT solutions, can enable real-time monitoring and data-driven decision-making to further enhance resource efficiency and reduce carbon emissions in their supply chain.

By taking proactive measures to address the environmental impact of meat transportation, Musgrave can not only align itself with sustainability goals but also set a positive example for the industry and contribute to a greener and more environmentally responsible future. The implementation of REAMIT technologies to reduce food waste showcases the potential environmental benefits that can be achieved through proactive measures and innovative solutions.

By harnessing IoT technologies, Musgrave effectively optimized its operations and resource efficiency, resulting in 4% reduction in environmental burdens. This reduction represents 668 tonnes of CO_2-eq and exemplifies the positive impact that can be attained through widespread IoT adoption, aligning with the company's sustainability goals and contributing significantly to environmental protection. In a broader context, these results serve as a model for other companies looking to enhance their environmental performance by adopting IoT technologies and fostering a more sustainable approach. Moving forward, it is essential for businesses and stakeholders to collaborate and continuously explore innovative strategies to minimise their carbon footprint and pave the way for a greener and more sustainable future.

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