A Survey on IoT as Enabler for Sustainable Supply Chains

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***Abstract*—text**

***Index Terms*—IoT, Internet of Things, supply chain, sustainability, emissions reduction, green supply chain management**

I. Introduction

Information technology has been used in companies since the 1970s [1]. The term Industry 4.0 refers to the fourth industrial revolution. It is the next stage in the organization and control of the industrial value chain. People, machines, and products are directly networked with each other. Along the supply chain, processes are digitally transformed and prepared for the digital age. An important component of data acquisition and control in supply chains is Internet of Things. Processes, machines, devices, and objects can digitally exchange data and process it in real-time via the Internet [2]. IoT serves as an enabler to digitally automate supply chains and become a key technology to make them sustainable. Companies are increasingly setting their own goals to make their supply chains more sustainable and to respond to the consequences of climate change.

According to the Paris Agreement art. 2, the global average temperature increase is to be limited to 1.5 degrees compared to the pre-industrial era [3]. The IPCC states that the remaining global carbon budget that may be emitted is about 400 billion tons to limit the temperature rise to 1.5 degrees [4]. This is intended to prevent serious and irreversible consequences of climate change [9]. Today, climatic changes in the global South, but also in the global North, are already having a strong impact on the ecosystem and on people. Many animal and plant species are threatened with extinction, heatwaves and droughts lead to crop failures and trigger large-scale fires, and people lose their homes due to heavy rainfall and floods. In particular, industrialized countries have a responsibility to reduce the pollution and exploitation of the environment. These countries have a particularly high per capita emission, as can be seen in [5]. Oceania had the highest carbon emission in 2020 with about 13 tCO_2/person, followed by North America with about 11 tCO_2/person. In Europe, emissions have been 6.6 tCO_2/person. Countries in the global South have particularly low emissions with South America (2.3 tCO_2/person), Central America (1.8 tCO_2/person), and Africa (1.0 tCO_2/person). A large share of carbon is generated in supply chains. Supply chains generate around 60% of global CO_2 emissions [6]. Thus, they take a major role in the fight against the climate crisis. However, according to [7], companies are struggling to decarbonize their supply chains and achieve net-zero emissions. Partly, action is needed at the industry level, which is difficult to implement because of many different interests. The supplier landscape is often fragmented and difficult to monitor, leaving sources of emissions unattended. In addition, collecting data to set concrete targets and implement standards is difficult.

The purpose of this paper is to address the issues described above. The aim of the paper is to identify and evaluate current solutions in research that use IoT to make supply chains more sustainable and environmentally friendly. From this, conclusions can be drawn for future research. In this way, areas that have not yet been sufficiently researched can be investigated in a targeted manner so that research gaps can be closed. This suggests the following research question: *What existing solutions are in research using the Internet of Things Technologie in supply chains to make them more sustainable and environmentally friendly?*

This paper is structured as follows. In Section II, the current state of research is presented. It provides a scientific classification of IoT and Green Supply Chain Management. The used methodology to conduct the survey is described in Section III. A systematic literature search was used. Section IV reviews scientific papers that use IoT to reduce emissions in supply chains and make them more sustainable. The papers are compared and examined in terms of various research aspects. Section V takes a different perspective on IoT and examines how sustainable IoT's own footprint is. In Section

VI, a specific solution is examined and studied in more detail. This solution deals with improving resource efficiency in food supply chains by the use of IoT. Interpretations of the paper results, open issues, recommendations for future research, and limitations of this study are discussed in Section VII. Finally, Section VIII concludes the survey.

II. Preliminaries

A. Internet of Things (IoT)

The term Internet of Things has been used since 1999 to describe the networking of objects and machines via the Internet. Devices are given a unique identity in the network. This enables them to communicate via the Internet and perform tasks in a fully automated manner. Production processes become more efficient and less expensive as a result. With these capabilities, IoT is an elementary component of Industry 4.0, as self-organization of industrial processes is enabled and production steps can be linked across the entire value chain [12]. In addition to Machine-2-Machine communication, they also provide an interface for users to operate and control devices from any location. Technology plays a particularly large influence in the development of intelligent smart systems in industry [10]. Especially in the field of Big Data, IoT plays a very important role, as a large amount of data can be generated by sensors [35]. Based on the multitude of possibilities for the use of IoT and the amount of data, new business models can emerge [11].

Microprocessor technology and the Internet form the technical basis of IoT. These processors are built into devices, giving them electronic intelligence. Another important component of IoT is RFID technology. This technology consists of two components. A small transponder is attached to an item with which the obejct can be scanned. An electromagnetic field is created by means of a reader, which allows data to be exchanged from the transponder to the reader. This makes it easier to identify and track items and goods. The data exchange is contactless.

In [13], a reference architecture for IoT based on the current state of research is described, as shown in Fig. 1. At the lowest level of the model are sensors and actuators. Sensors have the ability to measure various physical or chemical properties. The conversion of a physical parameter into an electronic signal takes place. Actuators work the other way around. They translate an electronic signal into a physical signal and thus can influence their environment. These two components are part of a hardware device. Drivers enable the control of all components on the device by means of software. Gateways are responsible for exchanging data between devices using protocols. They can translate data into other formats and send it over the Internet. IoT integration middleware takes care of receiving and processing data. Various functionalities can be implemented to analyze the data. Application is the top layer and, as software, provides the direct interface to users so that they can gain insights. The application accesses the middleware.

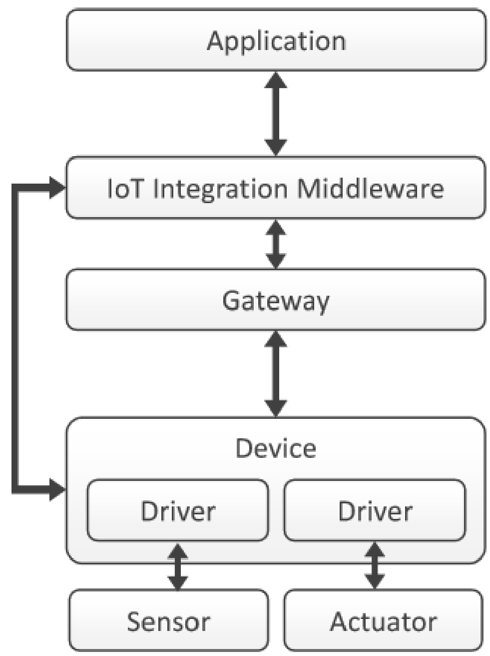

Fig. 1. IoT reference architecture based on [13]

B. Green Internet of Things (G-IoT)

According to [15], two different aspects are considered in Green Internet of Things. On the one hand, it is about using IoT technology to make existing software and hardware more sustainable. By using IoT, these can be made more efficient and effective. The entire supply chain can be integrated and monitored with complete coverage. This can reduce emissions and optimize logistics chains.

On the other hand, it is about IoT making itself more sustainable. Even if the energy consumption of IoT devices is low individually, however, a large amount of energy is consumed when entire IoT networks are considered. Therefore, these networks must be designed with respect to the lowest possible energy consumption. In general, throughout the lifecycle of

IoT devices, care should be taken to ensure that they have a low impact on the environment. For this, the aspects of design, production, utilization, disposal, and recycling are important [14].

C. Green Supply Chain Management (GSCM)

Supply chain, in general, refers to the establishment and management of logistics chains. The complete process, including the flow of materials, money, and information, is considered from the extraction of raw materials to the end consumer. Supply chain management then involves organizing the various players and steps along the value chain in such a way that products and services can be brought to market and to the customer economically.

Environmental practices and supply chain management are integrated, known as Green Supply Chain Management (GSCM), to support companies in improving their environmental performance throughout the supply chain. Several studies suggest that green supply chain management has a positive impact on the economic performance of companies [20]–[24]. In [17] it is defined that within the supply chain it is about using environmentally friendly inputs that are transformed into outputs and can be recovered and reused after their lifecycle. For a sustainable supply chain, the economic, social, and environmental aspects must be taken into account to the same extent [18]. Efforts are made to minimize emissions and waste, reduce the use of resources, and link supply chain steps more effectively so that all environmental standards are met [16]. Green supply chains can reduce pollution and production costs, drive economic growth, create competitive advantages in the form of increased customer experience, positive corporate reputation, and provide more opportunities for the export of their products to environmentally friendly countries [19].

Emissions are divided into three categories using the Greenhouse Gas Protocol. Scope 1 includes all direct emissions from own or controlled sources, such as company vehicles. Indirect emissions from the generation of electricity, steam, heating, and cooling used by a company are assigned to Scope 2. Scope 3 emissions, which include all upstream and downstream emissions in the supply chain, are particularly difficult for companies to measure.

III. Methodology

Based on [25], a systematic literature search was conducted to identify and extract relevant papers from previous research. The focus of the literature review is on the presented results of the papers considering the influence of the used IoT technology. In addition, the scientific methodology and the application area to which the paper refers will be considered. The aim of the literature review is to describe, explain and finally synthesize existing literature in the context of the domain. A neutral perspective is adopted so that the current state of research is presented in a value-free manner. The coverage of the literature review is representative-selective, so that a selection of papers is reproduced that reflects the most essential research aspects of the domain. Since this is a paper in the context of the Internet of Things & Security seminar, the target group can be defined as professionals with sufficient background knowledge.

Before searching the databases, a concept map was created to identify and infer relevant search terms, as shown in Fig. 2.

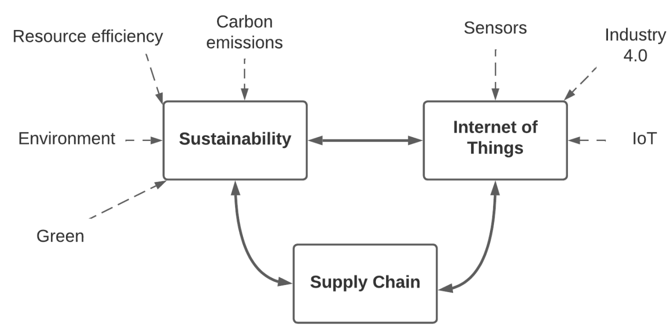

Fig. 2. Concept map for the systematic literature search.

Searches were conducted in the two databases Google Scholar and Primo FU Berlin. Title, abstract, subject, and keywords were queried. For the first run, the following search terms were used:

- supply chain AND sustainability AND internet of things
- supply chain AND carbon emissions AND internet of things
- supply chain AND green AND internet of ihings

Based on the concept map, further different search queries were carried out, in which relevant papers were selected for the survey. After the initial results of the search query, these were refined. Green and Sustainable Supply Chain Management were found particularly frequently in the papers, which is why the search term was thus expanded. Furthermore, a forward and backward search was performed on the most important papers in order to better classify the papers in the existing research and to identify additional relevant papers.

A bibliometric analysis was carried out using MAXQDA software, allowing computer-assisted qualitative data and text analysis. For this purpose, all surveyed papers, which are listed in Tab. I were imported. In order to identify relevant keywords and research directions, they were analyzed. The absolute frequency of words used, frequently occurring word combinations, and context words were evaluated. For the analysis, a stop word list was used to exclude non-relevant words, such as filler words or prepositions, to make the results more meaningful.

IV. Literature review on IoT as Enabler for Sustainable Supply Chains

In Tab. I the papers surveyed are compared with each other concerning various aspects. Concepts and solutions in the food sector are written about frequently. In particular, the focus is on preventing perishable food from going bad and thus avoiding waste. In general, most papers address industry-specific supply chains. This can also be seen in the research methods, as case studies are often conducted in cooperation with an industry partner. Data collected through exploratory and empirical surveys are further analyzed through simulation studies in which different scenarios are applied. Furthermore, the benefits of using a combination of different sensors, for example, measuring inventory levels, and RFID tags are described and incorporated into the concepts in almost every paper. In each solution, IoT technologies are used to make better use of available resources and to optimize supply chain operations. Based on the acquired data, every step in the supply chain can be monitored. In this way, ineffective processes and weak points can be made more visible and improved. The compared papers have different contributions to the research. Architectures and frameworks are presented that can be applied to supply chains to enable IoT to be utilized for greater sustainability. Research status and implications are also derived so that companies can get recommended actions for implementation in their own companies.

Most frequently used context words of *IoT* are shown in Fig. 3. The most commonly used context word is *adaption*. This observation suggests that there is particularly strong discussion in the research community about how IoT can be incorporated into the existing structures of companies and their supply chains so that the technological benefits can be realized. IoT adaptation seems to be strongly related to *infrastructure* (44), *systems* (33+21), and *applications* (32). In this context, the *integration* (38) of IoT is also important. The central role that IoT takes is the *enabling* (47) of supply chains to be more sustainable and green. The observation that *logistics* (20) is frequently mentioned puts the focus of the research, especially on the transportation, handling, and storage of goods. The context words can also be used to identify which IoT technologies are of importance. *blockchain* (26), *RFID*(26), and *sensors* (17) are frequently mentioned in the research in connection with IoT. Blockchain, in particular, is often used to make IoT systems more secure, traceable, and decentralized with cryptography. Another key component of the research is *data* (36), which is generated by a large number of sensors. The data can then be processed, analyzed, and visualized using various Big Data methods.

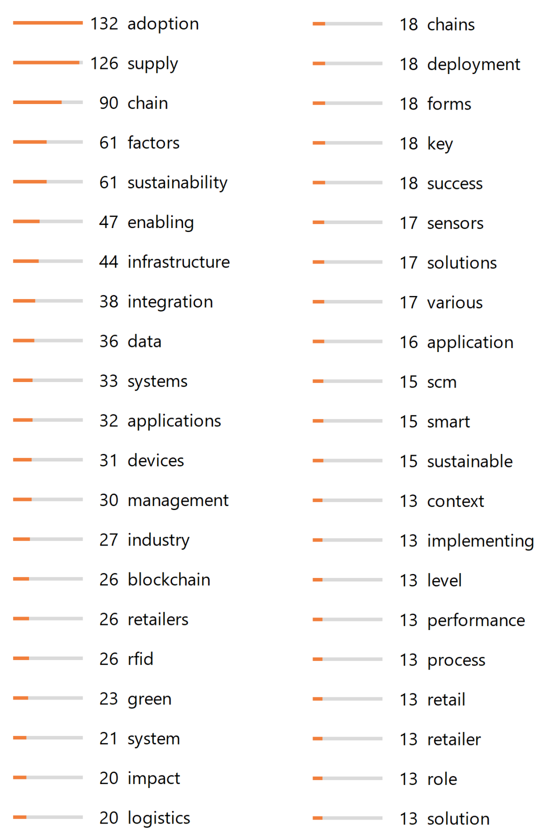

Fig. 3. Most frequent context words of the term IoT in surveyed papers.

In Fig. 4, the most frequent word combinations in which the word *sustainability* was used in the surveyed papers were examined. In accordance with the research framework, the most frequent combination is *chain sustainability* (44) and *supply chain sustainability* (43), reflecting the core aspect of

Reference	Application field	Research method	IoT technology	IoT impact	Outcomes
[27]	Food logistics	Simulation study	Wireless sensor network	Reduction of food losses and carbon emissions	Distribution network, Intelligent Containers by order exchange algorithm
[28]	Perishable goods	Case study with a major Swiss retailer	Temperature tracking sensors (TTI, data logger, RFID)	Profit increase and emission reduction	Supply Chain Simulation Model
[29]	Supply chain innovation	Literature review	EPC IoT architecture	Material flow, information flow, capital flow, and carbon footprint control	IoT based business model and research state
[30]	Order Management in food industry	Exploratory research based on simulation study	RFID, IoT infrastructure and blockchain	Reduction of order management times	Simulation scenarios highlighting the impact of new technologies on sustainability aspects
[31]	Manufacturing Systems	Empirical Analysis	IoT as part of Industry 4.0 technologies	Diminish the volume of resources misdirected and the emissions	Implications of technological change
[32]	Low carbon logistic	Conceptual analysis	RFID, GPS, and sensors	Improve circulating logistics, low carbon and reduction in logistics activity	Low carbon logistics model based on IoT
[33]	Manufacturing	Literature review, multiple criteria decision-making approach, expert interviews	Industrial Internet of Things	IoT adoption for sustainability in Supply Chain Management	Relative importance of enabling factors and interdependencies among them
[34]	Management of scrap metal	Case study from a scrap metal producer	IR fill level sensors	More efficiently and effectively management of resources	Framework for assessing SSCM for industry 4.0 and results of the proposed solution
[35]	Smart green businesses	Qualitative content analysis	Sensors, data warehouses, data processing platforms, and cloud	Big Data based on advanced IoT	Multilevel framework for implementing a green IoT-based supply chain
[36]	Retail sector	Exploratory semi-structured interviews and thematic analysis	Variety of IoT forms (RFID, sensors, telematic etc.)	Supply chain integration and performance	Findings on IoT forms providing additional capabilities in data auto-capture, visibility, intelligence, and information sharing for greater integration of retail supply chains
[37]	Agri-food supply chain	Interpretative structural modelling and Fuzzy-Decision-Making Trial and Evaluation Laboratory	RFID tags and readers, sensors, Blockchain, AI, BDA, robotics, cloud computing, and Zigbee	Multi-tier configuration type and IoT-based governance mechanisms	Sustainable based multi-tier system for agrif-food supply chain
[38]	Food logistics	Reference modeling	Sensors	Reduction of inefficiencies, costs, emissions, and social impact	Simulation tool to study the extant dynamics underling the Food supply chain
[39]	Retail sector	Empirical analysis	RFID, sensors	Information monitoring, flow, consolidation, and management	Significance of indicators for their perception of eco-quality

TABLE I
COMPARISON OF SURVEYED PAPER.

the survey. This is followed by different aspects of sustainability. With 34 combinations, *environmental sustainability* is used. The interaction and impact on the environment thus seem to have the greatest focus in the research of environmental aspects. This is followed by *economic sustainability* and *social sustainability* with 14 combinations each. From the perspective of the companies, it is important that sustainability is also ensured from an economic point of view because this directly influences the company's success. This will be particularly relevant if companies are also measured more strongly in terms of sustainability indicators in the future. The two essential sectors for supply chains in which there is a need for action are also reflected in the results of the analysis. With 4 combinations each, *retail sector sustainability* and *afsc sustainability* are used. Selling goods and services to customers seems to be given more focus in the research than the counterpart to wholesaling, which means selling goods to business customers or institutions. In addition, the supply chain with the largest carbon footprint is often referred to. Agriculture-food supply chain (afsc) includes all steps from growing food to delivery and has a strong impact on the environment.

Fig. 4. Most frequent word combinations of the term Sustainability in surveyed papers.

The most frequently used words in the surveyed papers are shown in Tab. 5. Again, the keywords of the literature search are represented with a high number: *IoT* (849), *supply chain* (810), and *sustainability* (349). The observation that *process* (379) is frequently mentioned suggests that especially the impact of the use of IoT on the processes and operations in companies is investigated. As discussed in Section II, supply chain *management* (417) is an important component of the research. This can be enriched with sustainability aspects so that IoT enables the organization and integration of individual steps in the supply chain across company boundaries.

Word	Frequency	%	Documents %
iot	849	1,47	83,33
chain	811	1,40	100,00
supply	810	1,40	100,00
management	417	0,72	100,00
process	379	0,66	100,00
system	365	0,63	100,00
sustainability	349	0,60	83,33
data	332	0,57	100,00
industry	318	0,55	91,67
food	285	0,49	83,33
order	277	0,48	91,67
information	256	0,44	91,67
retailer	256	0,44	75,00
logistic	238	0,41	91,67
product	232	0,40	100,00
sustainable	214	0,37	83,33
IT	207	0,36	100,00
time	200	0,35	100,00
performance	183	0,32	100,00
application	178	0,31	100,00

Fig. 5. Most frequent words in the surveyed papers.

V. IoTs own footprint

In [28], the authors conduct a case study examining a supply chain with perishable goods. The study examines the extent to which emissions generated by the sensors and emissions saved by the sensors offset each other. Furthermore, it is investigated how the profit changes. A cost-optimal solution is presented that both saves emissions and increases profit by using IoT. Four scenarios were simulated: (1) Switzerland, national (100km), (2) EU, short distance (500km), (3) EU, long distance (1,500km). The results of the simulation study are shown in Fig. 7. It can be seen that an increase in profit was achieved in all cases. In three of the four simulation scenarios, a reduction in emissions could also be achieved. Only in scenario 1 could no reduction in emissions be achieved over the short distance since the carbon footprint of the sensors is larger than the savings achieved.

VI. IoT in food manufacturing to optimize resource efficiency

For the detailed study of a specific solution, Ref. [26] was selected. This was published in 2021 and is therefore up

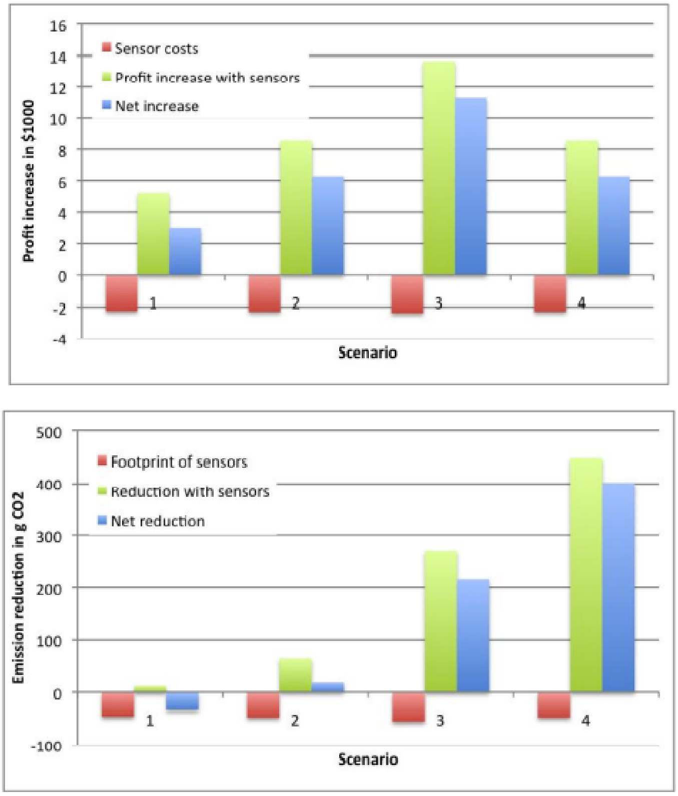

Fig. 6. Profit increase and emission reduction by IoT implementation based on [28].

to date and corresponds to the current state of research. In addition, the paper deals with the supply chain and the use of IoT in the food sector. According to [8], supply chains in the food sector have the largest footprint with about 25% of global supply chain emissions. Therefore, it is evident to take a solution from the food sector, which is also our base of life. Furthermore, good scientific work can be assumed because the paper was published in the journal *Computers in Industry* vol. 127. Thematically, this journal fits well, because, according to their own information, high quality, application-oriented research papers are published, which link new trends in information technology and industry topics.

The paper was written by the three authors Sandeep Jagtap, Guillermo Garcia-Garcia, and Shahin Rahimifard. All three have several years of experience in various projects on sustainable food supply chains and have completed their PhD in this field. Sandeep Jagtap focuses on Sustainable Manufacturing, Circular Economy and Industry 4.0 applications. While Shahin Rahimifard's research has a focus on Operational Planning of Manufacturing Systems, Guillermo Garcia-Garcia has a chemical background and specializes in Waste Management, Sustainable Engineering and Environmental Impact Analysis. The paper integrates with their current research projects and builds on their previous scientific contributions.

The paper addresses the negative impacts on the environment caused by emissions in food supply chains. The consequences are water, air, and soil pollution. In the individual steps of the supply chains, large quantities of raw materials are consumed that are not used effectively. Ineffective operations also generate large amounts of garbage and food waste. Furthermore, there is still low acceptance of technologies such as IoT in the food sector. Currently, processes are based on paper documentation and there is a lack of knowledge among employees to deal with the new technologies. Paper documentation is prone to errors, is not secure against forgery, and requires time and effort.

The goal of the paper is to improve the overall resource efficiency in the food manufacturing sector. To do this, IoT technologies will be used to collect data and better manage activities in the supply chain. In particular, this involves the generation of food waste, consumption of energy, and water (FEW). Currently, many sources of resource waste are not visible and therefore cannot be optimized. The use of IoT can help identify these and improve the consumption of FEW.

As a result of the authors' research, they present a framework to improve resource efficiency in food manufacturing using IoT-based tools to monitor food waste generation, energy consumption, and water use. It provides a more reliable and faster solution compared to paper-based documentation, as real-time data can now be provided using sensors. Furthermore, a decision support system was developed, which enables the stakeholders to make fact-based strategic and operational decisions.

In Fig. 7 the IoT-based FEW framework is shown. The framework is composed of three levels. At the first level, the information needs and data are determined. It is determined which FEW data is relevant for later evaluation. This involves looking at where the sources of the data are and where they can be extracted in the workflow. It is also determined how the data will be filtered and processed. At level 2, an IoT system is then designed to monitor the FEW data. Furthermore, the software and hardware requirements are defined, including sensors. The IoT system is divided into four layers and is based on the IoT reference architecture presented in Section II A: On the sensing layer, the FEW data is collected using sensors. The IoT specific protocols *Message queueing* *telemetry transport* (MQTT) and *Global System for Mobile Communications* (GSM) are used on the Networking Layer to exchange the data with local servers or the cloud. This FEW data is then aggregated and analyzed on the Service Layer from various sources. At the Application Layer, the data can then be prepared in a form that is readable and interpretable by the end-user in the form of a dashboard so that strategic decisions can be made to optimize FEW resources.

In the paper, the authors present an IoT system based on the framework. The FW monitoring is to be realized with the help of an intelligent scale and image processing. For this purpose, the data will be collected from the factory floor. Smart meters are used to measure the energy consumption in the factory. This can reduce irregularities, idle time, and non-value-added activities. Unnecessary water usage and leaks will be prevented by a water monitoring system. The water flow rate and quality is determined by sensors. These systems are then visualized collectively on a FEW dashboard. This provides a fact-based decision-making basis for taking measures to reduce resource consumption.

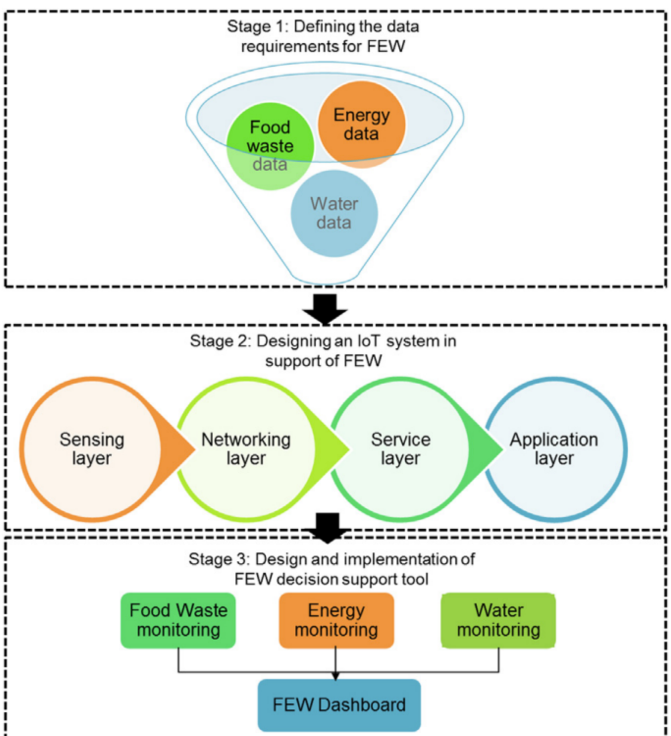

Fig. 7. IoT-based FEW framework for resource efficiency in food manufacturing.

VII. Discussion

The use of IoT to make supply chains more sustainable is still in its early stages and has a lot of untapped potential. The solutions developed reflect the need for action, especially in the food supply chain. Even though IoT offers great potential, the emissions generated by its use should also be considered. In many developed solutions, these are not sufficiently taken into account, so no meaningful overall picture can be generated. In future research, these aspects should also be given greater consideration.

IoT can improve the resource efficiency and carbon footprint of supply chains. Implementing IoT technologies involves many stakeholders who take ownership in the workflows. For IoT deployment to truly add value, it is important that stakeholders coordinate implementation in a meaningful way so that all process participants can benefit from Industry 4.0. Silo thinking would lead to the IoT system working well for individual players, but others possibly even showing a negative outcome. The influence and added value of the use of IoT, therefore, depends on how well all actors are integrated in the introduction of IoT. This aspect is still neglected in current research and should be addressed more in future research.

Some industries, e.g. the food sector, face the challenge of allowing disruption by IoT technology. In some cases, traditional ways of working are being held on to, making the diffusion of IoT more difficult. This is often a question of mentality, as the ”never change a running system” approach is referenced and it is argued that they have always done it this way. Companies thus have an obligation to actively promote digital transformation so that the use of IoT can succeed. The training of employees, the acquisition of specialist knowledge, and skilled workers occupy a key position in this respect.

VIII. Conclusion

For this survey, the relevant topics (Green) Internet of Things with Industry 4.0 and Green Supply Chain Management were taken. On this basis, a systematic literature search was then carried out with the help of which the currently existing research solutions could be found. These papers were then examined and compared using bibliometric analysis.

The survey reflects the current state of research on how existing solutions aim to make supply chains more sustainable with the help of IoT. This provides an answer to the research question. The sustainability question focuses not only on the environment, but also on other aspects, such as social and economic components. Overall, the supply chains of companies in every industry are facing major changes due to the digital transformation and Industry 4.0. The use of IoT provides opportunities but also challenges for companies. Therefore, the implementation should be carried out in a structured and organized way, as described in the existing solutions, through frameworks or simulation studies.

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