Internet of Things and Sustainability: A Comprehensive Framework

A thesis submitted for the

Master of Science in Information Management

by

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Declaration/ Erklärung

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Abstract (English)

The Internet of Things (IoT) is a fast-growing, technological concept, which aims to integrate various physical and virtual objects into a global network to enable interaction and communication between those objects (Atzori, Iera and Morabito, 2010). The application possibilities are manifold and may transform society and economy similarly to the usage of the internet (Chase, 2013). Furthermore, the Internet of Things occupies a central role for the realisation of visionary future concepts, for example, Smart City or Smart Healthcare. In addition, the utilisation of this technology promises opportunities for the enhancement of various sustainability aspects, and thus for the transformation to a smarter, more efficient and more conscious dealing with natural resources (Maksimovic, 2017). The action principle of sustainability increasingly gains attention in the societal and academical discourse. This is reasoned by the partly harmful consumption and production patterns of the last century (Mcwilliams et al., 2016). Relating to sustainability, the advancing application of IoT technology also poses risks. Following the precautionary principle, these risks should be considered early (Harremoës et al., 2001). Risks of IoT for sustainability include the massive amounts of energy and raw materials which are required for the manufacturing and operation of IoT objects and furthermore, the disposal of those objects (Birkel et al., 2019). The exact relations in the context of IoT and sustainability are insufficiently explored to this point and do not constitute a central element within the discussion of this technology (Behrendt, 2019). Therefore, this thesis aims to develop a comprehensive overview of the relations between IoT and sustainability.

To achieve this aim, this thesis utilises the methodology of *Grounded Theory* in combination with a comprehensive literature review. The analysed literature primarily consists of research contributions in the field of Information Technology (IT). Based on this literature, aspects, solution approaches, effects and challenges in the context of IoT and sustainability were elaborated. The analysis revealed two central perspectives in this context. *IoT for Sustainability (IoT4Sus)* describes the utilisation and usage of IoT-generated information to enhance sustainability aspects. In contrast, *Sustainability for IoT (Sus4IoT)* focuses on sustainability aspects of the applied technology and highlights methods to reduce negative impacts, which are associated with the manufacturing and operation of IoT. Elaborated aspects and relations were illustrated in the comprehensive *CCIS Framework*. This framework represents a tool for the capturing of relevant aspects and relations in this context and thus supports the awareness of the link between IoT and sustainability. Furthermore, the framework suggests an action principle to optimise the performance of IoT systems regarding sustainability.

The central contribution of this thesis is represented by the providence of the *CCIS Framework* and the contained information regarding the aspects and relations of IoT and sustainability.

Abstract (German)

Das Internet of Things (IoT) ist ein schnell wachsendes, technologisches Konzept, das darauf abzielt, verschiedenste physikalische und virtuelle Objekte in einem globalen Netzwerk zu vereinen um Interaktion und Kommunikation zwischen diesen Objekten zu ermöglichen (Atzori, Iera and Morabito, 2010). Die Einsatzmöglichkeiten dieser Technologie sind vielfältig und könnten Gesellschaft und Wirtschaft in ähnlicher Weise verändern wie die Nutzung des Internets (Chase, 2013). Darüber hinaus nimmt das Internet of Things eine zentrale Rolle in der Realisation von visionären Zukunftskonzepten ein, beispielsweise Smart City oder Smart Healthcare. Zudem verspricht die Anwendung dieser Technologie Möglichkeiten, verschiedene Aspekte der Nachhaltigkeit zu verbessern und zu einem bewussteren, effizienteren und schonenderen Umgang mit natürlichen Ressourcen beizutragen (Maksimovic, 2017). Das Handlungsprinzip der Nachhaltigkeit gewinnt im gesellschaftlichen und akademischen Diskurs zunehmend an Bedeutung und trägt den teils schädlichen Produktions- und Konsummustern des vergangenen Jahrhunderts Rechnung (Mcwilliams et al., 2016). Im Zusammenhang mit Nachhaltigkeit ist die fortschreitende Verbreitung von IoT Technologie allerdings auch mit Risiken verknüpft, die im Rahmen des Vorsorgeprinzips rechtzeitig bedacht werden müssen (Harremoës et al., 2001). Dazu zählen der massive Energie- und Rohstoffbedarf der Produktion und des Betriebs von IoT Objekten, sowie deren Entsorgung (Birkel et al., 2019). Die genauen Zusammenhänge und Auswirkungen von IoT im Bezug auf Nachhaltigkeit sind bisher nur unzureichend erforscht und nehmen keine zentrale Rolle in der Diskussion dieser Technologie ein (Behrendt, 2019). Diese Arbeit hat daher das Ziel, einen umfassenden Überblick der Zusammenhänge zwischen IoT Technologie und Nachhaltigkeitsaspekten zu erarbeiten.

Um dieses Ziel zu verwirklichen, verwendet diese Arbeit die *Grounded Theory* Methodik in Verbindung mit einer umfassenden Literaturanalyse. Die analysierte Literatur besteht dabei aus Forschungsbeiträgen, die besonders dem Gebiet der Informationstechnik (IT) entstammen. Auf Grundlage dieser Literaturanalyse wurden Aspekte, Lösungsansätze, Effekte und Barrieren im Kontext von IoT und Nachhaltigkeit erarbeitet. Im Laufe der Analyse kristallisierten sich zwei zentrale Sichtweisen auf IoT im Zusammenhang mit Nachhaltigkeit heraus. *IoT für Nachhaltigkeit (IoT4Sus)* beschreibt dabei den Einsatz und die Nutzung von IoT generierten Informationen, um eine Verbesserung im Hinblick auf verschiedene Nachhaltigkeitsaspekte zu erzielen. *Nachhaltigkeit für IoT (Sus4IoT)* hingegen fokussiert Nachhaltigkeitsaspekte der eingesetzten Technologie und zeigt Lösungen auf um, mit der Produktion und dem Betrieb verknüpfte, negative Auswirkungen auf Nachhaltigkeit zu verringern. Die erarbeiteten Aspekte und Beziehungen wurden in einem umfangreichen Rahmenwerk, dem *CCIS Framework*, festgehalten und dargestellt. Dieses Rahmenwerk stellt ein Werkzeug zur Erfassung relevanter Aspekte und Beziehungen in diesem Bereich dar und trägt damit zur Bewusstseinsbildung in diesem Kontext bei. Darüber hinaus empfiehlt das Rahmenwerk ein Handlungsprinzip um die Performance von IoT Systemen im Rahmen der Nachhaltigkeit zu optimieren.

Der zentrale Beitrag dieser Arbeit besteht in der Bereitstellung des *CCIS Framework*, sowie der darin enthaltenen Informationen hinsichtlich der Aspekte und Beziehungen von IoT und Nachhaltigkeit.

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List of Abbreviations

CE	Circular Economy
DIY	Do it yourself
EI	Environmental Informatics
GHG	Greenhouse gas
GPS	Global positioning system
ICT	Information and Communications Technology
IIoT	Industrial Internet of Things
IoT	Internet of Things
IoT4Sus	Internet of Things for sustainability
IP	Internet Protocol
IT	Information Technoloy
LCA	Life-Cycle Assessment
LoRa	Long Range
M2M	Machine to Machine
NFC	Near-Field Communication
NGO	Non-governmenal organisation
RFID	Radio Frequency Identification
SDG	Sustainable Development Goal
Sus4IoT	Sustainability for Internet of Things
TBL	Triple Bottom Line
WSN	Wireless Sensor Network
WBAN	Wireless Body Area Network

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1 Introduction

The first chapter provides a short introduction to this thesis. This chapter contains the problem statement, which emphasises the motivation and execution of the presented research. Following the problem statement, the research aim, objectives and particular research questions are introduced. The outline of this thesis completes the chapter and provides a summary of the composition of the executed research.

1.1 Problem Statement

The Internet of Things (IoT) is one of the fastest-growing technological innovations of the last decade and will be one of the most dominant Information Technology (IT) paradigms of the next years (Atzori, Iera and Morabito, 2010). The basic idea of Internet of Things is to enable the interaction between objects, such as radio-frequency identification (RFID) tags, sensors, mobile phones and actuators through the internet (Atzori, Iera and Morabito, 2010). By 2025, it is envisioned that internet nodes will reside in everyday objects like food packages, furniture or paper documents. This pervasive technology will contain 25 billion over the internet connected objects by that time (Zhu et al., 2015). The impact of IoT on society and economy is expected to be as revolutionary as the impact of the internet itself (Chase, 2013). As IoT is going to be a pervasive technology, it is essential to consider its effects on the environmental, economic and societal development (Routray and Sharmila, 2017).

Society, public sector and non-governmental organisations (NGOs) are increasingly demanding for production and consumption in an economically, environmentally and socially sustainable manner (Mcwilliams et al., 2016). The reason for this increased awareness of sustainability issues lies in the unsustainable consumption and production patterns of the last century. These patterns resulted in several pressing issues, which are threatening nature and human life on planet earth. Among those threats are the pollution of air, water and soil, global warming, depletion of resources and rising amounts of long-lasting waste (Aguilera et al., 2007).

Among other technologies and aspects of modern society, Information Technology contributed to these problems. The lack of environmental skills, knowledge and consciousness has resulted in many forms of waste, unused resources, energy inefficiency and pollution from IT operations (Watson, Boudreau and Chen, 2010; Shuja et al., 2017; Maksimovic, 2017). It is estimated that IT operations are accountable for 2.4 – 3% of the global energy consumption with a predicted increase of 20% annually of the total consumption (Wang et al., 2012). Likewise, IT could produce as much as 6 – 8% of the global carbon footprint by 2020 (Shaikh et al., 2015). In contrast to this intensifying function of IT regarding sustainability issues, IoT is expected to provide broad possibilities of being a solution, not just a problem.

The possibility of connecting anyone, anything, anywhere, anytime enabled by billions of sensors and smart objects will revolutionise various sectors such as transport, education, healthcare, agriculture, waste management, production, education and more. This revolution will lead to a smarter, greener, fairer and more efficient world (Maksimovic, 2017). Although the Internet of Things paradigm promises several benefits regarding sustainability issues, the long-term impacts on sustainable development are still unclear (Bonilla et al., 2018; Smit et al., 2016). Potentially adverse effects of IoT in the context of sustainability arise from concerns regarding the high raw material consumption during production, the energy consumption during operation and the difficult disposal of electronic components (Birkel et al., 2019). These possible negative effects, linked to large-scale IoT deployments, pose a severe threat to human health and environment. Following the concept of the precautionary principle, it is crucial to consider and reduce potential hazards before those threats are proven in reality (Harremoës et al., 2001). A potent example of this necessity is represented by the technology of nuclear energy. Though the harmful impacts of nuclear materials on human health were observed and discussed in researches, the promise of a cheap, almost infinitely available energy source pushed the development and deployment of numerous nuclear power plants. Policies for the security of those plants, the protection of the surrounding environment and the secure disposal of long-lasting, toxic and radiant materials were neglected. This reckless development and deployment of a once-promising technology eventually resulted in a substantial environmental and economic burden for today’s society (Harremoës et al., 2001; Rashad and Hammad, 2000). Against this background, it is necessary to build comprehensive knowledge about the impacts of IoT on sustainability. However, the awareness of the link between IoT and sustainability is still limited, and there is little discussion around this relationship within politics, research and organisations (Behrendt, 2019; WEF, 2018).

Sustainability is the dominant challenge of the 21st century and organisations, researchers and politics alike have to react to this new challenge (Watson, Lind and Haraldson, 2012). Some even state that there are no more important and socially relevant studies that IT researchers can encounter and need to pursue. Furthermore, the Information Technology community largely disregarded sustainability issues in the past and now has to catch up with many other academic and practitioner communities to provide their share regarding a multidisciplinary approach to overcome these problems (Sarkis, Koo and Watson, 2013). Research within the field of sustainability is gaining attention among various disciplines. Nevertheless, it often focuses solely on the environmental dimension of sustainability and neglects the societal and economic aspects (Dao, Langella and Carbo, 2011).

Furthermore, research mostly centres the description of single aspects and therefore, often lacks a comprehensive and holistic overview of all dimensions of sustainability (Müller and Voigt, 2018). The description of aspects and effects of IoT on sustainability must provide a detailed and reflected assessment. The segmentation of IT aspects being either good or bad in terms of sustainability is too simplistic to examine such a complex and interrelated system. It is believed to be rather harmful as it lacks a comprehensive description of positive potentials alongside reasoned advice regarding the prevention of adverse effects (Hilty, 2008). Moreover, a systematic approach to address IoT in terms of sustainability requires a conceptual framework which focuses on potential aspects and impacts which are relevant for sustainability (Hilty and Aebischer, 2015).

The previously mentioned pervasion of IoT technology combined with the rising importance of a transformation towards a more sustainable future constitutes the foundation of the overall research aim of this thesis. The thesis aims to extend the knowledge and awareness of sustainability aspects in the context of Internet of Things technologies. This is realised by systematically examining aspects and impacts and proposing a conceptual framework, which reveals essential aspects, impacts, possibilities, threats and solutions in this context.

The conceptual framework aims to contribute to the aforementioned research gap: the lack of awareness between the link of IoT and sustainability and a comprehensive assessment of this complex interconnection with a holistic view on sustainability. This contribution will further clarify the interconnection of IoT and sustainability by synthesising different threats, effects, aspects, opportunities, solutions and recommendations discussed in this context. Therefore, it will be a useful instrument for both practitioners and researchers to address the sustainability of IoT.

1.2 Research Aim, Objectives and Questions

The development of an extensive conceptual framework requires the systematic inclusion and examination of a wide variety of IoT aspects, functions and solutions and their classification in terms of sustainability. In order to achieve the aim of this research, several research objectives and respective research questions have to be answered.

The purpose of this thesis demands a fundamental understanding of IoT and sustainability to elaborate the link, threats and possibilities further. The first objective (RO1) of this thesis is to acquire an understanding of the link between IoT and sustainability in order to obtain foundational knowledge about the context.

RO1 Identification of a suitable definition and capturing of relevant aspects and characteristics of sustainability in the context of IoT.

As previously described, sustainability is a complex construct which relates to several aspects and dimensions of today's society (Tomičić and Schatten, 2016). For this reason, a large variety of different definitions and views of sustainability exist (Dao, Langella and Carbo, 2011). RO1 requires the elaboration of sustainability definitions which are used in academic literature to assess the impact of IoT. Based on the evaluation of different definitions and views, a definition of sustainability in the context of IoT is determined, which will create the basis of this thesis.

Subsequently, this definition will be used to identify characteristics as well as aspects of IoT, which may affect dimensions and components of sustainability. Those characteristics and aspects are consisting of functions, IoT-enabled solutions, technology characteristics and deployment-related effects. They will capture a holistic and comprehensive overview of IoT features, which must be considered in the context of sustainability. To meet RO1, the following questions need to be answered:

RQ1.1	How is sustainability defined in the context of IoT?
RQ1.2	Which aspects and characteristics need to be considered in the context of IoT and sustainability?

RO1 builds the foundation of this thesis and gives the first general overview of the topic. Based on the findings on RO1, the following objective aims to further elaborate the deployment, possibilities, threats, consequences and relations of IoT in connection with sustainability. Challenges and drivers of IoT concerning sustainability are identified to create a broad in-depth knowledge regarding the circumstances and features to consider when addressing sustainability problems with IoT technology. The second research objective focuses on the link between IoT and sustainability by systematically examining the relations between IoT features from a sustainability standpoint.

RO2	Examination of the link between IoT concepts and sustainability.

To achieve the second objective (RO2), several research questions need to be answered. At first, it is crucial to identify and classify different types of IoT characteristics and solutions which are relevant in this context. This classification will provide the foundational categories to examine their impact and effects on different sustainability-related variables further. To identify and detail the effects on sustainability, adequate indicators and measurement methods need to be defined. The findings of RQ2.1 and RQ2.2 are subsequently used to examine the effects of IoT on sustainability. This question will provide a detailed insight into the focused link. The final question aims to elaborate under which circumstances these effects can be deployed. Therefore, RQ2.4 focuses on drivers and challenges which are related to the deployment of IoT technology in the context of sustainability. The answer to this question supports RO2 in terms of transferring theoretical effects into real benefits. To meet RO2, the following questions need to be answered:

RQ2.1	How can IoT characteristics and solutions be classified in terms of sustainability?
RQ2.2	What are suitable indicators and measurement methods to assess the effects of IoT on sustainability?

RQ2.3 What are the effects of certain IoT features and solutions on sustainability characteristics?

RQ2.4 What are key drivers and challenges for the deployment of IoT in the context of sustainability?

The findings of RO1 and RO2 establish the foundational knowledge of this thesis and are requirements for the last research objective of this work. In order to satisfy the overall aim of this thesis, the findings are synthesised into a conceptual framework. The final research objective, therefore, focuses on the development and proposal of a conceptual framework which summarises the findings and illustrates them in a meaningful form. For this reason, the framework needs to meet two basic requirements. First, as previously described, it must provide a comprehensive, holistic and detailed view of IoT in the context of sustainability. Second, it must provide this view in a manner which is comprehensible and usable for both practitioners and researchers.

RO3 Development of a conceptual framework, which can be used to address sustainability in the context of IoT.

RO3 is achieved by the handling of a set of referring questions. To address the linkage of sustainability and IoT in a manner which is applicable for a broad group of researchers and practitioners, general rules and aspects in this context must be identified. The framework will support decision-making and knowledge in an extensive scope rather than for a specific solution or area. To ensure this broad applicability, the presented relations and conclusions must be generally valid in the context of IoT. This research question (RQ3.1) might be faintly reminiscent of RQ1.2. In contrast to RQ1.2, which derives insights about aspects from the gathered literature, RQ3.1 aims to apply this knowledge, alongside with other findings, in an inductive way into the conceptual framework. Furthermore, the framework aims not just to raise the knowledge about IoT concerning sustainability but also to point out implications on how to design IoT deployments sustainably. Thus, the question of how to enhance the sustainability of IoT projects needs to be answered. The objective RO3 is completed with the elaboration of a suitable method to display and present the results. To meet RO3, the following questions must be answered:

RQ3.1 What are general rules and aspects to consider when addressing sustainability in the context of IoT?

RQ3.2 How can the sustainability of IoT deployments and projects be enhanced?

RQ3.3 How can the findings be presented in a suitable manner?

With the fulfilment of research objectives RO1, RO2 and RO3, alongside with the reply of the particular research questions, the overall aim of this thesis, to increase the knowledge and awareness of sustainability aspects in the context of Internet of Things technology, is met. A summarisation of the objectives and respective questions is depicted in Figure 1.1.

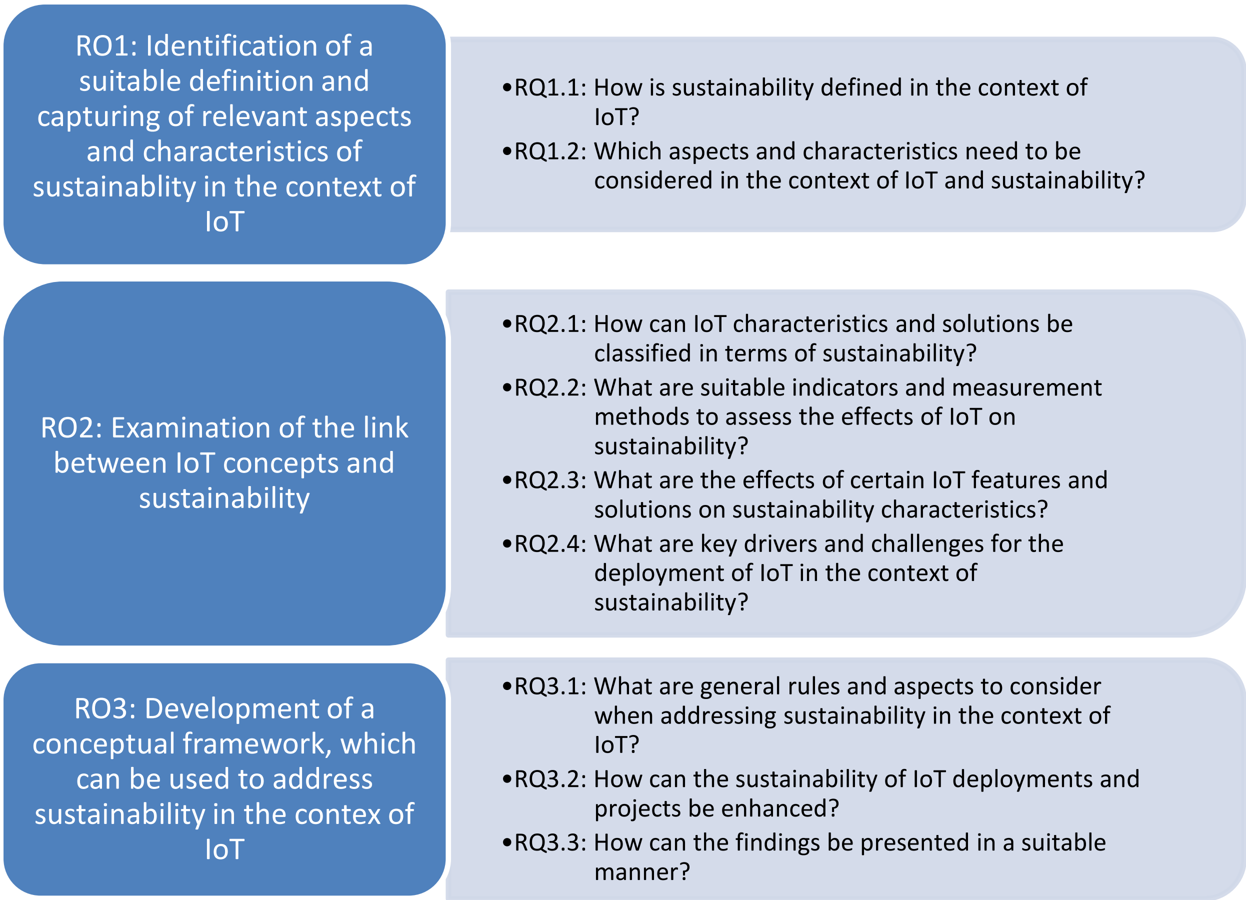

Figure 1.1: Research objectives with respective research questions (own illustration)

1.3 Outline of the Thesis

This paragraph provides a summary of the structure and course of this thesis. The thesis is divided into six chapters, which are concisely delineated in the following.

The first chapter provides the introduction to this thesis. It consists of the problem statement (section 1.1), the research aim, objectives and questions (section 1.2), which build the foundation for the course of this thesis. The chapter closes with the outline of this work (section 1.3).

Chapter two presents the research design. It describes the methodology of *Grounded Theory*, which is used in this thesis (section 2.1). Following the methodology, corresponding research methods are presented and their application throughout this thesis is described (section 2.2). In order to set the scope and underlying theory of this thesis, section 2.3 discusses the extent of the executed research. Section 2.4 describes the process of data collection and the respective methods and sources. The chapter concludes with a brief description and overview of the research steps (section 2.5).

Chapter three provides an overview of the theoretical frame for this thesis. Firstly, it describes the ideas, perspectives and definitions of the Internet of Things (section 3.1). Secondly, this chapter illustrates the vision of sustainability in general and relating to Information and Communications Technology (ICT) (section 3.2).

Chapter four examines the link between IoT and sustainability. The definition of sustainability in the context of IoT is provided in section 4.1. Subsequently, aspects of IoT and sustainability are presented and described further (section 4.2). Based on the emerged aspects, section 4.3 provides and examines solutions, concepts and paradigms in this context. Ultimately, project examples are described and classified in section 4.4.

Chapter five summarises the findings into a conceptual framework. Therefore, the requirements and objectives of the framework are described (section 5.1). Section 5.2 derives components, relations and the design of the framework regarding the identified requirements. The developed framework is shown in section 5.3.

Chapter six concludes this thesis. Therefore, a summarisation of the findings regarding the research questions is given in section 6.1. Section 6.2 emphasises the contribution to research of this work. Subsequently, the limitations of this thesis and respective findings are described (section 6.3). Identified implications for future researches are provided in section 6.4.

2 Research Design

This chapter illustrates the research design, which is used to execute the study and accomplish the previously described research aim and objectives. Therefore, chapter two describes the research methodology (section 2.1), the research methods (section 2.2), scope and basic theory (section 2.3) and the data sources and collection methods (section 2.4). Deduced from this, an overview of the specific research steps carried out in this thesis is given in section 2.5.

2.1 Methodology

The thesis aims to increase the knowledge and awareness of sustainability aspects regarding IoT technology by providing a comprehensive conceptual framework. This aim requires the generation and analysis of knowledge and insights about the relationship between IoT technology and sustainability. Qualitative data are suitable to explore the consequences of events and relationships between paradigms (Miles, Huberman and Saldaña, 2014). Hence, qualitative data build an appropriate foundation to assess the consequences of the deployment of IoT technology for sustainability. Consequently, relevant literature in this context needs to be analysed. The analysation of literature, thus textual data, requires a qualitative approach of data analysis. In addition, the development of a conceptual framework can be achieved through an inductive, theory-building and synthesising research approach (Miles, Huberman and Saldaña, 2014).

These requirements are met by the research methodology of *Grounded Theory*. *Grounded Theory* is defined as a set of inductive strategies for analysing qualitative data (Charmaz, 1996). Although originating from the field of social sciences, *Grounded Theory* is among others applicable for organisation and management research, including information systems and organisational change (Rose, Spinks and Canhoto, 2015). It is suitable for the development of theories about topics which are relatively unknown to researchers. Furthermore, *Grounded Theory* is applicable to reveal patterns, relations and effects between entities and processes (Charmaz, 1996). These characteristics of *Grounded Theory* match the requirements of the research aim of this thesis as the knowledge about the link between IoT and sustainability is limited, and to be further investigated. To explore this link, the methodology of *Grounded Theory* recommends the neglection of prior theories in advance of an inductive, explorative approach. This approach is meant to provide a considerable degree of openness and flexibility. Thus, it generates a result which is firmly rooted in the data and not biased by adapted theories (Rose, Spinks and Canhoto, 2015). *Grounded Theory* starts with individual cases and progressively develops conceptual categories with a higher level of abstraction. This enables the researcher to synthesise, to explain and to understand large sets of data and furthermore, to identify patterned relationships within the data (Charmaz, 1996). The methodology of *Grounded Theory* does not provide a rigorous or predefined way of conducting researches (Charmaz, 1996). In order to support the flexibility of the methodology, researchers can choose from a set of strategies to accomplish their research aim. The characterising element of

Grounded Theory is its iterative shape. Data is continuously revised and complemented with additional data to support, test and strengthen emerging theories (Rose, Spinks and Canhoto, 2015).

This thesis adopts an approach of *Grounded Theory* suggested by Rose, Spinks and Canhoto in 2015. The process starts with the definition of research questions, which were already described in section 1.2 of this thesis. Subsequently, an iterative process of theoretical sampling, data collection, data analysis and the examination for theoretical saturation follows. Theoretical sampling is a sampling approach, that aims to support theory development. Is suggests to adjust sampling in response to emerging theories and to neglect a prefixed procedure of sampling. Therefore, this method of sampling is open to concepts and theories which occur during the process of data analysing and theory building. Theoretical sampling enables researchers to respond to rising theories and issues by collecting data that clarifies and refines their ideas further (Charmaz, 1996; Rose, Spinks and Canhoto, 2015). Following the process of theoretical sampling, i.e. planning which data to look for, the data is collected. *Grounded Theory* can involve a variety of data collection methods and types, including interviews, memos, documents and more. Although the methodology of *Grounded Theory* is mostly used in qualitative research, quantitative data can also be included (Glaser and Strauss, 1967). The specific method of data collection used in this thesis is described in detail in section 2.4. Collected data is subsequently analysed. *Grounded Theory* suggests analysing the data by utilising the research method of *Qualitative Coding*. *Qualitative Coding* enables researchers to search for patterns in textual, unstructured data (Miles, Huberman and Saldaña, 2014). This research method is seen as the pivotal link between the collected data and the development of a theory to explain the data, and thus, a central element of *Grounded Theory* (Charmaz, 1996). *Qualitative Coding* is the process of attaching keywords or conceptual labels to segments of text. The used codes are continuously refined and categorised in order to reveal patterns in the analysed data (Miles, Huberman and Saldaña, 2014). Section 2.2 provides a detailed description of *Qualitative Coding* and its specific utilisation in this thesis. The circulatory approach concludes with the examination of theoretical saturation. The state of theoretical saturation is achieved if the analysis revealed no significantly new explanations, insights or categories of data (Miles, Huberman and Saldaña, 2014; Rose, Spinks and Canhoto, 2015). *Grounded Theory* demands a constant iteration between data analysis and the emerging theory. This process of iteration is called constant comparison. It involves the perpetual confrontation of coded data with other similarly coded data. For this reason, it supports the refinement and specification of emerging concepts (Charmaz, 1996). The final stage of this methodology is the capturing and definition of the concepts, which emerged during the previously described process steps. The defined theory represents the result of this methodological approach. Referring to this thesis, the defined theory will constitute the central element in order to achieve RO2 and RO3. A summarisation of the methodological approach of *Grounded Theory* applied in this thesis can be found in Figure 2.1.

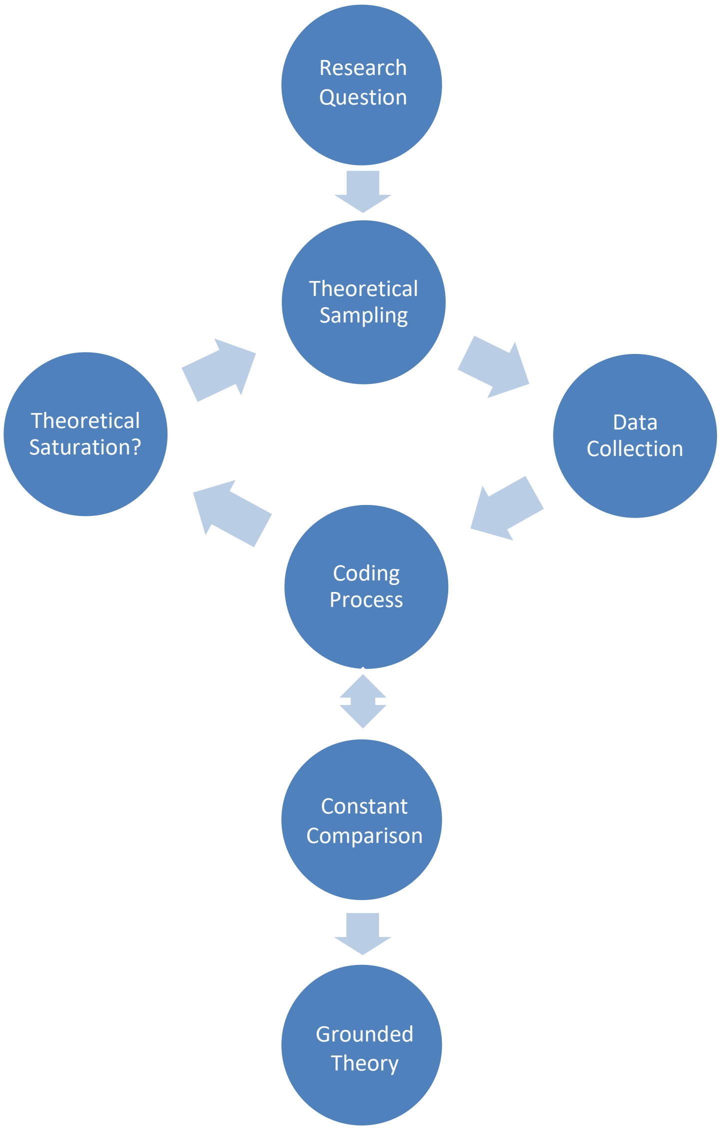

Figure 2.1: Steps in grounded theory research design (adapted from Rose, Spinks and Canhato 2015)

2.2 Research Methods

The previously presented research methodology of *Grounded Theory* requires the selection of adequate methods to be applied. Steps which demand appropriate methods are particularly the data collection and the coding process with the related step of constant comparison. The process of data collection is explicitly described in section 2.3 of this thesis. Therefore, this section focuses on the methods used in the coding process, the comparison and theory building. As briefly explained in the previous section and already implied by the name, the method used in the stage of the coding process is *Qualitative Coding*. *Qualitative Coding* is a central element within the methodology of *Grounded Theory* (Charmaz, 1996). According to Saldaña (2013, p.3), a code is "*most often a word or short phrase that symbolically assigns a summative, salient, essence-capturing, and/or evocative attribute for a portion of language-based or visual data*". Data, to which these labels are assigned, can consist of numerous types, such as interview transcripts, field notes, journals, documents, pictures, videos, literature and others. The magnitude of the portion of data which is coded can range from single words to entire pages of text (Saldaña, 2013). The systematic allocation of codes allows researchers to retrieve and categorise portions of data with similar meaning. Furthermore, it enables the researcher to find, gather and cluster data relating to a particular research question or hypothesis (Miles, Huberman and Saldaña, 2014). These clusters of codes are a first step to structure the data and provide the researcher with the first impression of central topics, events and relationships within the data. The process of coding can be divided into two major steps, *First Cycle Coding* and *Second Cycle Coding* (Saldaña, 2013). *First Cycle Coding* is the first step to gain insights into data by using the method of *Qualitative Coding*. This first phase represents the process of initial coding, thus the assignment of meaningful codes to portions of data. *Second Cycle Coding* is the process of working with codes and patterns that emerged during *First Cycle Coding*. Its objective is to condense and structure the data further through categorisation, classifying, abstracting, synthesising, conceptualising and theory building (Miles, Huberman and Saldaña, 2014).

The specific usage and naming of codes during *First Cycle Coding* is not bound to a predefined set of rules and strongly depends on the researcher's objectives as well as the nature and content of the data. This freedom of choice is highly beneficial and suitable for the methodology of *Grounded Theory* as it enables the researcher to focus on concepts which emerge from the data instead of attempting to fit the data into predefined categories and theories (Charmaz, 1996). However, Saldaña (2013) suggests 22 different coding methods, which may be used during *First Cycle Coding*. Those methods are not separated strictly and overlap with others. The 22 coding methods are divided into six groups: Grammatical Methods, Elemental Methods, Affective Methods, Literary and Language Methods and Exploratory Methods. For a detailed description of *First Cycle Coding* Methods see Saldaña's (2013) *The Coding Manual for Qualitative Researchers*. Moreover, the method of *First Cycle Coding* does not require the commitment to just one of these suggested methods. Aligned to the specific data, methods can be mixed and adjusted (Miles, Huberman and Saldaña, 2014). For this thesis, the coding methods of *Descriptive Coding, Process Coding* and *Evaluative Coding* were applied for RO2. *Descriptive Coding* summarises the primary topic of a portion of qualitative data and is an adequate instrument to identify main topics and concepts of the coded part (Saldaña, 2013). Referring to RO2, it is used to answer the question of which IoT-related solution or feature is affecting what kind of sustainability aspect. *Process Coding* is deployed to identify activities, answering the question of how these effects occur. Evaluation Coding assigns judgements to the coded data to determine outcomes in terms of quality. It thereby summarises and allocates qualitative perceptions within a context (Saldaña, 2013). *Evaluation Coding* is used in this thesis to capture the outcomes and impacts of IoT-related concepts or features on sustainability aspects, answering the question of the type and quality of the effect.

Second Cycle Coding is the process of further synthetisation and abstraction of the data and insights that emerged from *First Cycle Coding*. The foundational results of *First Cycle Coding* are gathered and assigned to appropriate categories. The goal of this process is to generate insights about categories, themes, concepts and theories from results of *First Cycle Coding*. Saldaña (2013) suggests six methods of *Second Cycle Coding*: Pattern Coding, Focused Coding, Axial Coding, Theoretical Coding, Elaborative Coding and Longitudinal Coding. This thesis primarily adapts the method of *Pattern Coding*. Pattern codes are defined as "*explanatory or inferential codes, ones that identify an emergent theme, configuration or explanation. They pull together a lot of material from First Cycle Coding into more meaningful and parsimonious units of analysis. They are a sort of meta code.*" (Miles, Huberman and Saldaña, 2014, p.67). According to Miles, Huberman and Saldaña (2014), *Pattern Coding* provides four essential functions: The condensation of large amounts of data into a smaller number of analytic units, the integration of analysis during data collection, the elaboration of a cognitive map and the surfacing of common themes and directional processes. The specific application suggests categorising *First Cycle Coding* into pattern codes of the classes: Categories or themes, Causes/explanations, Relationships and Theoretical constructs. In order to refine the *Pattern Coding* further, subcodes can be created (Miles, Huberman and Saldaña, 2014). As previously mentioned in section 2.1, it is crucial to execute the process of coding in a circular, iterative and not in a linear way in order to gain meaningful results and allow concepts and theories to emerge from the data.

To analyse and draw conclusions from the coding process, Miles, Huberman and Saldaña (2014) provide a comprehensive set of analytic methods. Among those methods are such to display the data and such to draw conclusions. For this thesis, the primarily used method is a combination of the analytical method of *Counting* and the display method of *Matrix Display*. According to Miles, Huberman and Saldaña (2014), *Counting* is a suitable method to reveal relevant themes in the examined context. Moreover, counting provides rapid insights into large sets of coded data, helps to verify or discard emerging conclusions and relations and keeps the researcher *"analytically honest"* (Miles, Huberman and Saldaña, 2014, p.225). *Matrix Displays* as a visual way to assess data analysation consist of rows and columns which are filled with different variables, depending on the context and purpose of the examination. *Matrix Displays* can be used to analyse, explore, describe, explain, order and display data in a pithy way (Miles, Huberman and Saldaña, 2014). *Counting* is combined with the display method of *Matrix Display* and formed to a so-called *Co-Occurrence Matrix*, which is meant to verify and assess the significance of emerging concepts and relations between IoT and sustainability. Therefore, the utilisation of *Co-Occurrence Matrices* is suitable to achieve RO2 and RO3. However, throughout the analysation of data in this thesis other methods for qualitative data analysation are used in order to generate insights about the data and answer the research questions stated in section 1.2 of this thesis. These methods include analytical memos, the notion of patterns and relations, making contrasts/comparisons and subsuming particulars into general. For a detailed description of these methods see Miles, Huberman and Saldaña's (2014) *Qualitative data analysis: a methods sourcebook*.

The coding and analysis process of this thesis is carried out with the Computer-Assisted Qualitative Data Analysis (CAQDAS) software ATLAS.ti 8. The use of CAQDAS software is appropriate for qualitative research and the method of *Qualitative Coding* as it allows to organise, store and access large sets of data efficiently. Furthermore, CAQDAS software provides a useful set of analytical tools to develop a deeper understanding of regarded data (Miles, Huberman and Saldaña, 2014).

2.3 Scope and Basic Theory

To achieve the overall research aim of this thesis, a comprehensive literature review is to be conducted, a catalogue of application examples is to be compiled, and subsequently, a conceptual framework which presents the link between IoT and sustainability is to be developed. The literature review creates the basis for the project catalogue. Insights gained from the literature review combined with the project catalogue will be transferred into the conceptual framework. To carry out the data collection process, which is explicitly described in the following section 2.4, a scope is to be defined.

Sustainability is a complex, versatile and multidisciplinary concept. The paradigm of sustainability will be further described and defined in section 3.2. However, to set an appropriate scope for this thesis, it is crucial to acknowledge that sustainability is no state which is defined through the values of predefined variables and depends on the context and numerous influential factors. Internet of Things, as an emerging technology, can affect sustainability in various ways. Some of these effects can be directly linked to the deployment of IoT technology, while others might affect sustainability through indirect, unobvious effects (Bonilla et al., 2018). To develop a comprehensive conceptual framework, it is essential to consider an extensive view of IoT in the context of sustainability. In order to achieve this aim, detailed examinations and evaluations of specific aspects are rather neglected in benefit of the holistic picture. Furthermore, aspects which might have an effect in this context but are located within other research fields than Information Technology are neglected and not included in the initial collection of data. Such aspects are, for example, the precise chemical composition of specific electronic components which might affect the environment. However, if the collected data provides and describes such effects, they are considered and included in the course of the investigation. The literature review, i.e. the foundation for further examination, focuses on research which is directly related to IoT and sustainability. Thereby the initial data collection involves only literature which addresses both topics and draws a link between IoT and sustainability. Specific inclusion and exclusion criteria regarding the initial data collection is provided in the ensuing section 2.4. Nevertheless, it is essential to acknowledge that the selected methodology of *Grounded Theory* suggests iterating over the process of data collection and analysis in order to investigate emerging concepts further (see Figure 2.1).

The upfront adaption of fundamental theories for this thesis is neglected for two reasons. As described in section 2.1, the methodology of *Grounded Theory* suggests an unbiased approach and the neglection of predefined theories in benefit of emerging theories and concepts, which are grounded in the data. Furthermore, as mentioned in the introductory section of this thesis, the knowledge of the link between IoT and sustainability is limited and often relates to specific dimensions of sustainability (Müller and Voigt, 2018; WEF, 2018). In order to avoid a biased interpretation of the data, no theory is adapted in advance of the analysis. However, applicable theories may emerge and be utilised during this thesis. Such theories will be explained and described in the respective part of the investigation.

2.4 Data Sources and Collection Methods

The data collection of this thesis is initially built with a literature collection. As described in the preceding sections, the literature collection and review are foundational for the further course of this work. The process of data collection, in this case, literature, is crucial for the selected methodology of *Grounded Theory* (Charmaz, 1996). According to vom Brocke et al. (2009, p.1), a literature review "*seeks to uncover the sources relevant to a topic under study and, thus, makes a vital contribution to the relevance and rigour of research"*. The process of reviewing is represented by the method of *Qualitative Coding*, which is described in section 2.2. This step of coding ensues the process of data collection, thus, literature collection. The search for literature comprises the querying of scholarly databases applying keywords. It is completed by the backward and forward search based on relevant articles (Webster and Watson, 2002). Backward search is the process of gaining new literature based on the references of a reviewed document while forward search focuses on sources which cited the reviewed document. In order to construct the process of literature collection transparent and comprehensible, this section provides a taxonomy of the literature review and subsequently describes the process of literature search.

Literature reviews can serve a large variety of different purposes, e.g. gaining new and synthesising existing research outcomes or identify research methodologies (vom Brocke et al., 2009). Cooper (1988) suggest a taxonomy to describe the purpose of a literature collection and search to keep the process and the researcher's motivation comprehensible. The application of the taxonomy for this thesis is shown in Table 2.1. Selected concepts are highlighted in blue.

Table 2.1: Taxonomy of the literature review (adapted from Cooper 1988)

<table>
<tr><td>Focus</td><td colspan="3">Research Outcomes</td><td colspan="3">Research Methods</td><td colspan="3">Theories</td><td colspan="3">Applications</td></tr>
<tr><td>Goal</td><td colspan="4">Integrate</td><td colspan="4">Criticise</td><td colspan="4">Identify central issues</td></tr>
<tr><td>Perspective</td><td colspan="6">Neutral Representation</td><td colspan="6">Espousal of Position</td></tr>
<tr><td>Coverage</td><td colspan="3">Exhaustive</td><td colspan="3">Exhaustive (selective)</td><td colspan="3">Representative</td><td colspan="3">Central/Pivotal</td></tr>
<tr><td>Organization</td><td colspan="4">Historical</td><td colspan="4">Conceptual</td><td colspan="4">Methodological</td></tr>
<tr><td>Audience</td><td colspan="3">Specialised Scholars</td><td colspan="3">General Scholars</td><td colspan="3">Practitioners</td><td colspan="3">General Public</td></tr>
</table>

The literature review executed in this thesis focuses on research outcomes, theories and applications regarding documents that discuss IoT in the context of sustainability. The goal is to integrate and synthesise findings and identify central issues in this context. As suggested by the research method of *Grounded Theory*, the neutral perspective does not adapt a predefined theory. In terms of coverage, this thesis claims to conduct a *Representative Literature Review*. A *Representative Literature Review* aims to cover a sample of literature that typifies larger groups of material (Cooper, 1988). Although this thesis intends to gain an extensive view of IoT concerning sustainability, time and extent limitations impede the compilation of an exhaustive review, as exhaustive reviews claim to review all relevant documents in this context. The organisation is conceptual according to the application of *Qualitative Coding*, introduced in section 2.2. Relevant documents are grouped and presented by their central ideas and outcomes. This thesis aims to turn to general scholars and practitioners alike, as it provides a rather broad than a detailed picture of IoT in the context of sustainability. However, specialised scholars might draw implications for their further research from the conceptual framework. For a detailed description of the taxonomy and the particular characteristics see Cooper's (1988) *Organizing Knowledge Syntheses: A Taxonomy of Literature Reviews.*

Concerning the ensuing chapter, which addresses the theoretical background of Internet of Things and sustainability, the execution of respective literature reviews in order to gain knowledge about those topics emerged. This was rejected for two reasons. Firstly, the previously described research methodology of *Grounded Theory* suggests neglecting the adaption of predefined theories about the research topic. Secondly, the process of backward search was adjudged to be suitable to gain knowledge about the theoretical background as articles in the context of IoT and sustainability mostly provide a reasonable overview of both concepts.

The initial search for literature was conducted with the scholarly database Web of Science[1]. This database was chosen due to its comprehensive functionality, the scope of included literature and the supply of metadata. As already stated, the data collection requires a broad picture of documents regarding IoT in the context of sustainability. The used query consists of two groups. The first group contains the keywords "Internet of Thing*" and its commonly used abbreviation "IoT". The second group consists of the keyword "sustainab*" and "green", which is frequently utilised in the context of sustainability. The "*" acts as a placeholder in order to include all modes of the keywords, e.g. "sustainability" and "sustainable". Keywords within the groups are connected with an "OR" operator while the groups itself are connected with an "AND" operator to find all documents which contain at least one keyword of each group. Consequently, the specific query is "("IoT" OR "Internet of Thing*") AND ("sustainab*" OR "green"). The search function of the used database allows no search functionality focusing on the abstract. Thus, each document matching the query's conditions anywhere in its title, abstract, keywords or body was found. The initial search compiled a result of 858 articles (as of 13/03/2019). As the analysis of this amount of literature is not manageable for a single researcher regarding the scope of this thesis, the number of articles was further narrowed by applying different filters and criteria for inclusion and exclusion. The results were filtered by selecting the categories of "Computer Science, Information Systems" and "Green & Sustainable Science & Technology" as these two categories are highly relevant for the aim of this thesis and match the research scope. Based on the 858 results from the initial search, 315 results matched this filter. In regard of the previously described absence of a functionality to search for the keywords within the abstract of articles, results were further narrowed by filtering for articles which contain the keywords "Internet of Thing*" or "IoT" in their abstract. This filter was adjudged to be suitable as it ensures that the concept of IoT occupies a central role in matching documents. The

[1] http://www.webofknowledge.com/

remaining set of 156 articles was then checked for a set of including and excluding criteria which are described in the following.

Articles were included, which:

- Directly refer to sustainability aspects of IoT (e.g. energy usage, disposal and resource consumption).
- Suggest the deployment of IoT for sustainability issues (e.g. Smart Healthcare, Waste Management and Circular Economy).
- Refer to sustainability in the context of massively IoT supported concepts like Smart City.

Articles were excluded, which:

- Use a definition of sustainability that differs from the aim and area of this thesis (e.g. sustainable Customer Relationship Management).
- Are loosely connected to IoT but are not focusing on it any further (e.g. the examination of 5G waveform candidates in terms of energy efficiency).
- Focus on a particular aspect or potentially useful method in the context of IoT and sustainability but do not match the research scope of this thesis (e.g. the mining of travel patterns from incomplete data with use cases).

The application of these criteria resulted in a total of 80 relevant articles. The first collection of data was contemplated by the iterative data collection process described in section 2.1, backward search, forward search and relevant articles from the scholarly databases Google Scholar[2], ACM Digital Library[3] and Science Direct[4]. The entire data collection process resulted in a compilation of 92 articles which were found to be relevant and build the foundation of this thesis.

2.5 Research Steps

The research steps taken to reach the aim of this thesis are briefly described in Figure 2.2. The steps are ajar to the methodology of *Grounded Theory*, which is described in section 2.1. The research questions, described in section 1.2, affect the iterative process of theoretical sampling, data collection, coding and the check for theoretical saturation. A central element of this thesis is the literature collection, which is depicted as a result of the data collection and the input for the coding process. The literature collection is used as a basis to achieve RO1 and respective research questions (RQ1.1 and RQ1.2). Furthermore, a catalogue of projects is derived from the literature collection. This collection of projects is used to test emerging concepts for their applicability in reality. This process takes place in the step of constant comparison, where emerging concepts and codes are confronted with other emerging theories. The process

[2] http://scholar.google.com/

[3] http://dl.acm.org/

[4] http://www.sciencedirect.com/

of coding and constant comparison ultimately results in the grounded theory, which aims to achieve RO2 and particular research questions (RQ2.1, RQ2.2, RQ2.3 and RQ2.4). The attainment of a grounded theory is the basis for the final step of this thesis, the development of a conceptual framework for sustainability in the context of IoT. This framework will synthesise the findings of the grounded theory and therefore meet RO3 and corresponding research questions (RQ3.1, RQ3.2 and RQ3.3).

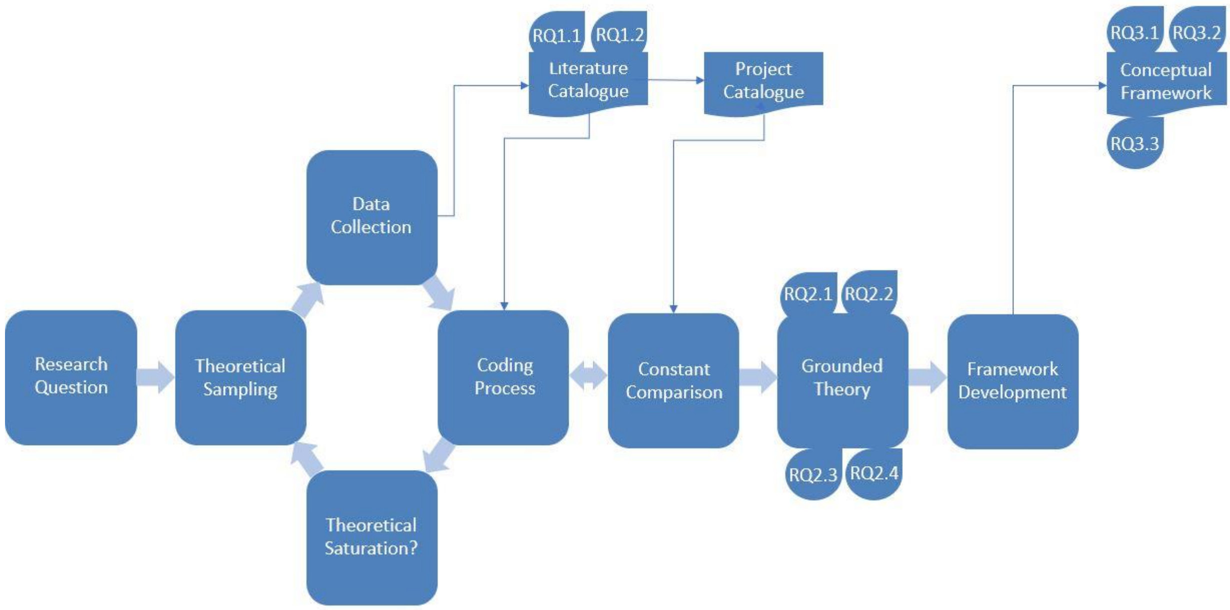

Figure 2.2: Research steps (own illustration)

3 Theoretical Foundations

The third chapter provides an overview of the two focal concepts and thus, creates the basis for this thesis. Section 3.1 presents a definition of the Internet of Things. Section 3.2 explains the concept and definition approaches to sustainability.

3.1 Internet of Things

The Internet of Things can briefly be described as a vision of connecting physical objects to a virtual world. According to Atzori, Iera and Morabito (2010, p.1), it is defined as "*novel paradigm that is rapidly gaining ground in the scenario of modern wireless telecommunications. The basic idea of this concept is the pervasive presence around us of a variety of things or objects – such as Radio-Frequency IDentification (RFID), tags, sensors, actuators, mobile phones etc. – which, through unique addressing schemes, are able to interact with each other and cooperate with their neighbors to reach common goals".* The aim of this paradigm leads to the transformation of physical everyday objects into smart objects by enabling them to seamlessly integrate into the resulting global cyberphysical infrastructure (Miorandi et al., 2012). This transformation is facilitated by the exploitation of underlying technologies such as ubiquitous and pervasive computing, embedded devices, communication technologies, sensor networks and internet protocols (Al-Fuqaha et al., 2015). The resulting Internet of Things has an enormous impact on everyday life and the behaviour of potential users (Atzori, Iera and Morabito, 2010). The importance of IoT is emphasised by the role which the National Intelligence Council (NIC) ascribes to this technology. The NIC includes IoT in its list of six disruptive civil technologies with potential impacts on the United States interests out to 2025 alongside Biogerontechnology, Energy Storage Materials, Biofuels and Bio-based Chemicals, Clean Coal Technologies and Service Robotics (National Intelligence Council, 2008). Estimations about the extent of connected objects vary from 24 billion as soon as 2020 (Garrity, 2015) to 25 billion in 2025 (Zhu et al., 2015).

The first appliance of a via internet connected object occurred in the early 1980s. A Coke machine at Carnegie Mellon University was equipped with a server program which checked the time that past since a storage column in the machine had been unfilled. This system enabled people to check remotely if there were cold drinks available (Madakam, Ramaswamy and Tripathi, 2015). An advancement of this system is the Smart Fridge, presented by LG in 2000, which is commonly used as an example for customer IoT (Rothensee, 2008). Since, IoT technology is utilised for a variety of purposes and visions, e.g. Industrial Automation, Smart Home, Smart Buildings, Smart City, Smart Healthcare, Big Data, Smart Grid, Smart Vehicles, Environmental Monitoring and the improvement of sustainability issues, which is the focal area of this thesis (Al-Fuqaha et al., 2015; Gubbi et al., 2013; Atzori, Iera and Morabito, 2010; Garrity, 2015).

The first definition of IoT occurred in the context of a worldwide network of academic research laboratories, studying networked RFID and emerging sensing technologies. The goal of this approach by the so-called Auto-ID Labs was the implementation of RFID and internet-enabled communication technologies into trading networks to improve the visibility of certain objects, thus their current location and status (Atzori, Iera and Morabito, 2010). However, the definitions and views of IoT within the research community differ, and to this day, there is no common sense about what IoT exactly means and which basic ideas this concept entails. Atzori, Iera and Morabito (2010) distinguish between three different perspectives of IoT that feature specific aspects. These are the *Thing-Oriented Perspective, the Internet-Oriented Perspective and the Semantic-Oriented Perspective*. These perspectives should not be seen as standalone. Instead, they are combining to build the IoT paradigm.

- *Thing-Oriented Perspective:* This perspective centres the objects which are connected via internet-enabled communication. These objects, e.g. wireless sensors, actuators and smart items, are equipped with respective communication technology in order to improve the object visibility. Everyday objects equipped with wireless technologies, such as Near-Field Communication (NFC) or RFID, are called spimes. A spime is defined as an object which can be tracked through space and time throughout its lifetime and furthermore is uniquely identifiable. Those objects can be distinguished into three categories (Kortuem et al., 2010):
  - *Activity-Aware Objects:* These objects detect their activity, use and handling. There is no interaction with other objects. The primary purpose is the recording and communicating of their activities.
  - *Policy-Aware Objects:* In addition to *Activity-Aware Objects,* those objects compute their recorded information to a certain degree. They can interpret events and activities concerning predefined rules.
  - *Process-Aware Objects:* These objects understand and interpret processes within a context-driven model. Therefore, they can provide context-aware information and detailed recommendations.
- *Internet-Oriented Perspective:* Network features of IoT are the defining object of the *Internet-Oriented Perspective*. The aim is to enable objects to communicate with anything, anytime and anywhere. Discussions and researches within this perspective deal with the further development of communication protocols and addressing schemes, such as Internet Protocol (IP), to ensure interoperability between a large variety of objects within the Internet of Things. The goal is to standardise and simplify communication to a certain degree. This will allow a large variety of objects, that may be limited in their computing power, data storage and power consumption, to participate in the IoT (Atzori, Iera and Morabito, 2010).
- *Semantic-Oriented Perspective:* Due to the large number and variety of devices connected to the Internet of Things, the *Semantic-Oriented Perspective* assumes that processing, storage and representation of information via interfaces will become increasingly challenging. Discussions and researches ascribed to this perspective focus on the advancement of interoperability, storage, representation, search and organisation of IoT resources by utilising semantic technologies. Therefore,

this perspective centres the meaningful utilisation of IoT-generated information for services and applications (Atzori, Iera and Morabito, 2010).

Another approach to conceptualising the Internet of Things is provided by Al-Fuqaha et al. (2015). An IoT system is divided into five different basic layers which build an IoT architecture. Namely *Objects Layer, Object Abstraction Layer, Service Management Layer, Application Layer* and *Business Layer:*

- *Objects Layer:* This layer, also referred to as the *Perception Layer*, represents the physical objects within an IoT network. It includes connected objects such as sensors and actuators, which perform basic functionalities like sensing. Hence, the *Objects Layer* is responsible for the creation of data.
- *Object Abstraction Layer:* This pillar is responsible for the transfer of data, generated by smart objects. It contains technologies like RFID, Wi-Fi, Bluetooth or ZigBee, which are used to transfer data in a specific form to the Service Management Layer. Functions like cloud computing and data management processes are also ascribed to this layer.
- *Service Management Layer:* The *Service Management Layer*, also referred to as *Middleware*, pairs a particular service with its requester. It processes the received data, makes decisions and delivers the treated information in a specific form to the respective requester. Furthermore, this layer enables the usage of heterogeneous objects without consideration of a specific hardware platform.
- *Application Layer:* This layer includes the functionalities which are required to provide services to the customer. It processes the previously generated and transmitted data in a way which is useful and interpretable for the customer. Therefore, the *Application Layer* provides high-quality smart services for customers.
- *Business Layer:* The *Business* or *Management Layer* is responsible for the management of the overall IoT system activities and services. It provides a higher and more sophisticated level of abstraction than the *Application Layer* and is able to build graphs, flowcharts, predictions and advanced analysis from received data in the context of previously received or in a different way acquired data.

In addition to these architectural layers, Al-Fuqaha et al. (2015) identify six IoT key elements which are required to provide the functionality of IoT:

- *Identification:* This element is needed to address a specific IoT object within the network and match services with their demand. The identification distinguishes between the object ID and the network address. Technologies which are used in terms of *Identification* are Electronic Product Code (EPC), Ubiquitous Codes (uCode), IPv6, IPv4 and 6LoWPAN.
- *Sensing: Sensing* describes the gathering of relevant data from respective objects. These objects can be smart sensors, actuators, wearables or anything which can capture a relevant variable.
- *Communication:* This element is required to connect heterogeneous objects and exchange data in order to deliver specific smart services. Technologies commonly used for IoT communication are Wi-Fi, Bluetooth, IEEE 802.15.4, Z-wave, ZigBee, LTE, 3G, RFID, NFC and Ultra-Wide Bandwidth (UWB). The choice for an appropriate communication protocol strongly depends on the requirements of the communication in terms of data rate, transmitting distance and available power of the node.

- *Computation:* The processing units, e.g. microcontrollers like Arduino, alongside respective software applications, represent the computational ability of the IoT. These units run the IoT applications and sometimes are also used to provide specific IoT functionalities. Another computational part of IoT is built by cloud platforms. They extend the computational power of the IoT devices for data collection, data storage and analysis if required.
- *Services: Services* are the essential purposes of IoT systems. The can be divided into four different categories: *Identity-Related Services, Information Aggregation Services, Collaborative-Aware Services* and *Ubiquitous Services. Identity-Related Services* are the most basic services and used to identify real-world objects in the virtual network. *Information Aggregation Services* collect and summarise sensor data collected by real-world objects. *Collaborative-Aware Services* use the collected and summarised data for decision-making and reaction. *Ubiquitous Services* provide this information to anyone, anywhere, anytime.
- *Semantics:* This element refers to the ability to extract insights from different devices to provide the required services. It contains the discovery, extraction and modelling of information. To achieve this goal, it is necessary that decisions are automatically made in terms of sending demands to the right resource at the right time.

The described perspectives, layers and key elements of IoT provided by Atzori, Iera and Morabito (2010) and Al-Fuqaha et al. (2015) are synthesised and mapped in Figure 3.1. The three big circles depict the perspectives described by Atzori, Iera and Morabito (2010). Rectangles represent the layers and ovals illustrate key elements stated by Al Fuqaha et al. (2015).

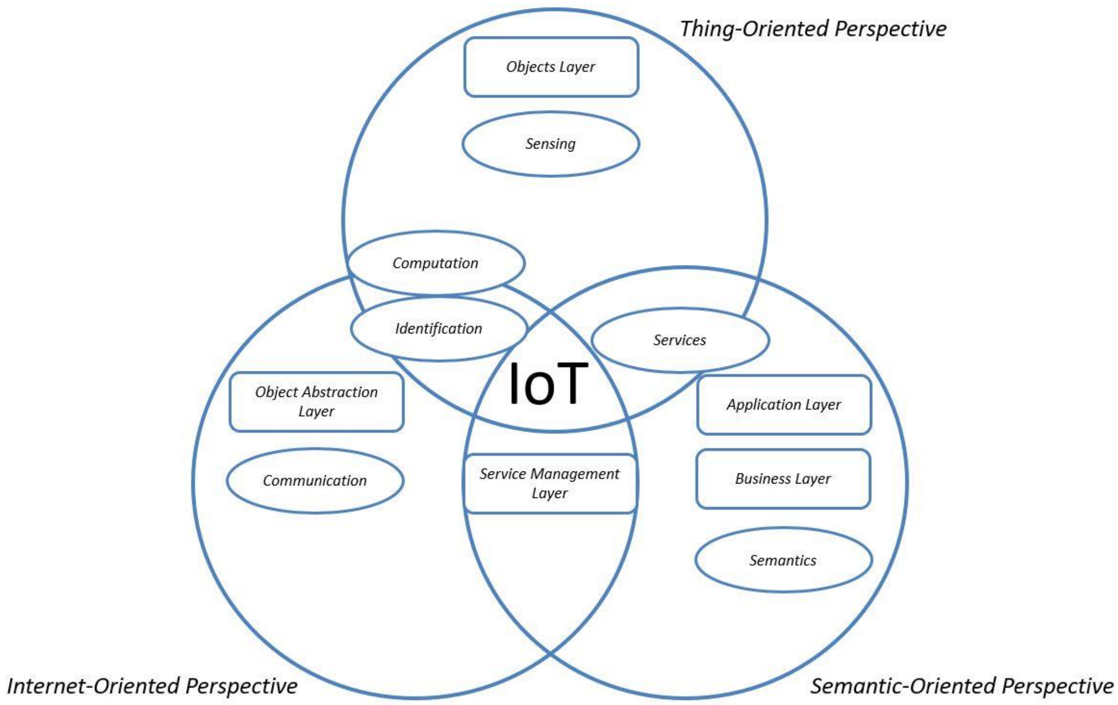

Figure 3.1: Perspectives, layers and key elements of IoT (own illustration)

Despite the large potential for several previously mentioned applications, services and visions, IoT is still in its infancy. Its constant and steady development and employment face various challenges. This is partly reasoned by the composition of the IoT vision, which depends on several enabling technologies, e.g. Wireless Sensor Networks (WSN), Machine to Machine (M2M), Cloud Computing and communication protocols. Chen et al. (2014) identify six key challenges, which need to be addressed in order to realise the vision of the Internet of Things:

- *Better Battery Life*: As sensors and other objects within the IoT are usually powered with small batteries, the energy consumption of the devices is a limiting factor for computational power, lifespan, communication and scope of utilisation.
- *Multiple Active Things*: IoT composites of many concurrent active objects which are transmitting data. The number of things can lead to severe interference among objects in terms of wireless communication.
- *Low-Cost Terminal Devices*: In order to realise the widespread adoption of IoT technology, the cost of terminal devices needs to be affordable.
- *Heterogeneous Terminal Devices*: In contrast to current wireless systems, the objects within an IoT environment are expected to exhibit a much higher level of heterogeneity in terms of functionality, technology and application fields. Therefore, IoT must be able to handle a large variety of different objects and technologies.
- *Scalability*: The IoT must be able to add new devices, services and functions for customers without negatively affecting the quality of existing services. Therefore, IoT systems must be designed in an extensible way.
- *Privacy and Security*: An essential element of IoT is the unique identification of objects. This requires an IoT system to guarantee a high level of privacy and security in order to realise a widespread adoption of IoT by customers.

Besides those key challenges, several other challenges and obstacles for the realisation of the IoT vision are discussed among researchers. These include the availability, reliability, mobility, performance, management, governance and accessibility (Garrity, 2015; Al-Fuqaha et al., 2015).

3.2 Sustainability

In order to approach the concept of sustainability, this section firstly provides an overview of general definitions, concepts and views of sustainability (section 3.2.1). Secondly, a more specific overview of the context of sustainability and Information and Communications Technology (ICT) is provided (section 3.2.2).

3.2.1 Definitions and Concepts of Sustainability

Sustainability in the context of dictionary definition simply implies that an activity or action is capable of being sustained (Brown et al., 1987). This definition does not seem to be appropriate as many highly damaging practices can theoretically be sustained throughout the timespan of the existence of human life. Planet earth's ecosystem has evolved over billions of years, providing human beings with the entirety of their needs. Against this background and timeframe, modern civilisation changes the composition and shape of this ecosystem rapidly and possibly irreversible. As there is no second planet available to satisfy our needs, human beings must incorporate the idea of treating the natural state of this ecosystem as a fixed reference point to frame development activities (Johnston et al., 2007). Therefore, sustainability as a concept is increasingly gaining attention within the agendas of policymakers, companies and researchers. The term sustainability itself originates in "soutenir", a French verb which means "to hold up or support" (Brown et al., 1987).

According to Johnston et al. (2007), there are around 300 definitions of sustainability that vary regarding their meaning, purpose and application area. McMichael, Butler and Folke (2003) characterise sustainability as a transformation of human lifestyle that optimises the likelihood that living conditions will continuously support security, well-being and health by maintaining the supply of non-replaceable goods and services. Ehrenfeld (2005) describes sustainability as the indefinite perpetuation of all life forms. Another approach to sustainability, provided by Sen (2013), centres human freedom. Sustainability is defined as the freedom of an individual to choose and live his own life according to his personal needs without compromising this freedom for future generations. This freedom includes the fulfilment of basic needs, the improvement of the current generation's capabilities and the liberty to define and pursue own goals. Sustainability is often defined in an environmental context and therefore, utilises the so-called input-output rule. This rule implies that waste emissions from a project must be within the biosphere's assimilative capacity. Furthermore, resource inputs must be within the regenerative capacity of a natural system that generates them (Goodland and Daly, 1996). In addition, the depletion of non-renewable resources should require comparable substitutes (Daly, 1980). A common definition of sustainability is the one provided by the so-called Brundtland Commission. Here sustainability is defined as *"development that meets the needs and aspirations of the present without compromising the ability of future generations to meet their own needs"* (United Nations General Assembly, 1987, p.43). However, the identification of the components of sustainability is complex as perceptions differ depending on one's view of the environment and the components which are valued (Riha, Levitan and Hutson, 1997). In order to provide an overview of the different definitions of sustainability, Brown et al. (1987) identify six categories of usage referring to the term sustainability:

- *Sustainable Biological Resource Use:* This perspective focuses on the usage of the term sustainability in terms of environmental resource usage. The usage is sustainable if the yield of a particular biological resource, e.g. wood or fish, over a defined timespan is lower or equal to the regenerative capacity of the ecosystem. This view relates to the previously described input-output rule.
- *Sustainable Agriculture:* The usage of the term sustainability in the context of agriculture focuses on the emphasis of long-term maintenance of production instead of short-term maximisation. Therefore, this view highlights the conservation of land resource base without degradation. This includes the conservation of water, soil and genetic diversity.

- *Carrying Capacity:* This approach of definition discusses the maximum population size that the environment can support. Thus, sustainability is a size of the population in a set region which is lower or equal to the number of people this given amount of land can support regarding their basic needs. The maximum capacity is not static and may vary through technological improvements, investments or imports of energy and resources.
- *Sustainable Energy:* The concept of sustainability in energy is strongly connected with the idea of renewable, nondepletable and unlimited energy. The discussion around sustainable energy emerged in the context of the rapid depletion of fossil energy resources, e.g. oil and coal. Definitions in the category of *Sustainable Energy* often utilise the aforementioned input-output rule to assess the sustainability of a specific energy resource usage.
- *Sustainable Society and Sustainable Economy:* Sustainability definitions in the context of society commonly focus on the insurance of the continued existence regarding human life on planet earth. These definitions often incorporate characteristics of *Sustainable Biological Resource Use, Carrying Capacity* and *Sustainable Energy* to conserve a viable habitat for humanity. Furthermore, some definitions in the context of sustainable societies adopt values of coexistence like empathy, compassion, equality and a sense of justice for all (Milbrath, 1984). Strongly connected to definitions of a *Sustainable Society* are definitions in the context of sustainability and economy. Views in this context differ and are split into two groups. One group argues that in order to realise a *Sustainable Society* continuing steady economic growth is essential to avoid unemployment and adapt to the growth of the human population. The other group represents the belief that a steady-state economy or zero economic growth is beneficial for the concept of a *Sustainable Society*. In this context, the term sustainable growth emerged, describing economic growth that can be supported by physical and social environments for the foreseeable future.
- *Sustainable Development:* Sustainability definitions in this category focus on developing strategies which manage a comprehensive scope of characteristics. These include natural and human resources as well as financial and physical assets in order to enhance wealth and well-being. Definitions within this category incorporate the idea that current decisions should not compromise the maintenance or improvement of living standards in the future. Therefore, this category combines the preceding categories to a certain degree.

As key elements of these different definition categories, Brown et al. (1987) identify:

1. The continued support of human life on earth.
2. Long-term maintenance of stock of biological resources and the productivity of agricultural systems.
3. Stable human populations.
4. Limited growth economies.
5. An emphasis on small-scale and self-reliance.
6. Continued quality in the environment and ecosystems.

Although over 30 years old, these key elements are still valid and can be discovered in the 2030 agenda for *Sustainable Development* provided by the United Nations General Assembly in 2015. In order to achieve the aim of this thesis, which is to provide a comprehensive view of sustainability in the context of IoT, the adoption of a definition in the context of *Sustainable Development* is the most viable. *Sustainable Development*, as previously described, combines a large set of characteristics and covers a broad scope of sustainability aspects. Therefore, the agenda of the United Nations General Assembly is useful for the further course of this thesis. The agenda recommends the adoption of 17 *Sustainable Development Goals (SDGs)* in order to move the world to a sustainable trajectory (United Nations General Assembly, 2015). The 17 *SDGs* are listed in the following:

1. End poverty in all its forms everywhere.
2. End hunger, achieve food security and improved nutrition and promote sustainable agriculture.
3. Ensure healthy lives and promote well-being for all at all ages.
4. Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all.
5. Achieve gender equality and empower all women and girls.
6. Ensure availability and sustainable management of water and sanitation for all.
7. Ensure access to affordable, reliable, sustainable and modern energy for all.
8. Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all.
9. Build resilient infrastructure, promote inclusive and sustainable industrialisation and foster innovation.
10. Reduce inequality within and among countries.
11. Make cities and human settlements inclusive, safe, resilient and sustainable.
12. Ensure sustainable consumption and production patterns.
13. Take urgent action to combat climate change and its impacts.
14. Conserve and sustainably use the oceans, seas and marine resources for sustainable development.
15. Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss.
16. Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels.
17. Strengthen the means of implementation and revitalise the Global Partnership for Sustainable Development.

These 17 goals in combination with 169 corresponding targets build the foundation to transform the world by ensuring, simultaneously, human well-being, economic prosperity and environmental protection by tackling multiple complex challenges faced by humankind (Pradhan et al., 2017). Thereby, the goals are not independent of each other but occasionally exhibit a strong interaction and correlation. Furthermore, some targets within specific goals are conflicting and may result in diverging results (Nilsson, Griggs and Visbeck, 2016). For a detailed description of synergies and trade-offs between the specific *SDGs* see Pradhan et al.'s (2017) *A Systematic Study of Sustainable Development Goal (SDG) interactions*.

Another frequently adapted approach of sustainable development is the so called *Triple Bottom Line (TBL)*, also referred to as the three pillars of sustainability (Elkington, 1998). Compared to the *SDGs*, this approach is not as detailed in terms of categorisation and therefore applicable for more general assertions concerning sustainability. This view consists of three main areas: *Environment, Economy* and *Society*. In order to accomplish the vision of *Sustainable Development*, these three aspects have to be considered. Equivalent to the relationship between the previously described *SDGs*, the three dimensions within the *TBL* are not independent of each other. They are systematically interconnected and affect each other through mutual causality and positive feedbacks (Geissdoerfer et al., 2017). Originating in the research field of economy, the concept of the *TBL* can be adapted to a broad range of different contexts and is appropriate to investigate IoT from the perspective of sustainability (Wise, 2016; Kiel et al., 2017). Discussions in the context of the *TBL* often emphasise the need for a balance between the three dimensions of *Environment, Economy* and *Society* (Geissdoerfer et al., 2017). Hilty and Aebischer (2015) contradict this view, arguing that a balance is only possible in the context of independent but connected entities. Following this argumentation, it is impossible to build a balance between the three dimensions of the *TBL* because the dimensions are nested. *Economy* isn't possible without *Society* as it forms a part of *Society. Society* itself is a part of the *Environment* and depends on it to provide the resources for its existence. Whereas, the *Environment* can exist without the other two dimensions. Hilty and Aebischer (2015) conclude that it is not possible to build a balance between the three dimensions. Figure 3.2 depicts both approaches to the *TBL*. Concept a) refers to the view that emphasises a balance, concept b) depicts the approach of nested dimensions.

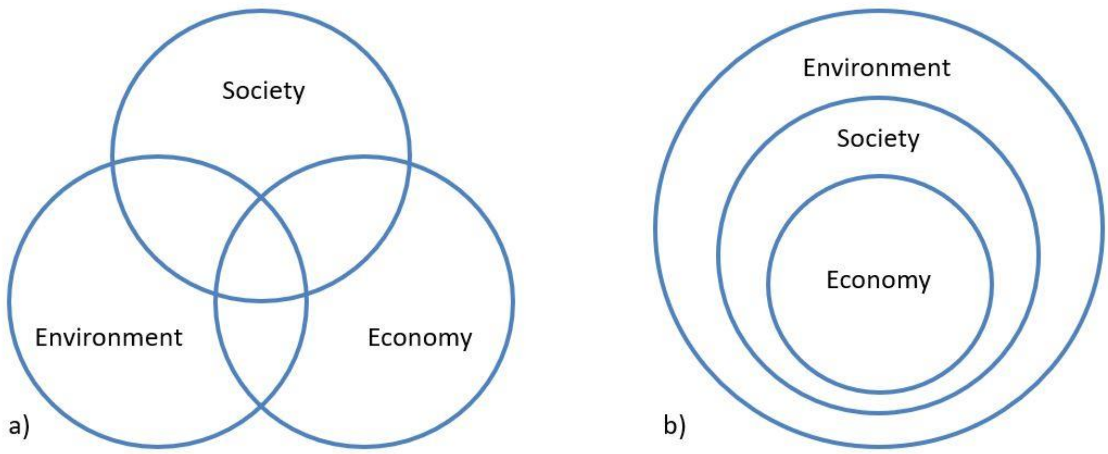

Figure 3.2: Different views of the environment, society, and the economy (adapted from Hilty and Aebischer 2015)

3.2.2 Sustainability in the context of ICT

This thesis aims to assess the sustainability of the IoT, and therefore, a part of today's Information and Communications Technology (ICT). As described in the introduction of this thesis (chapter 1), the approach of combining ICT research with concepts of sustainability is not new and has been discussed in research and practice. With the appearance of cooperation between ICT research and environmental sciences, different application concepts and definition approaches emerged. In the context of ICT and sustainability, Hilty and Aebischer (2015) identify six different research fields which connect these two worlds:

- *Cybernetics as a Precursor:* As early as 1970, ideas occurred to transform the world into a more sustainable place by using computing power. These ideas manifested, for example, in the suggestion of an automated air quality control system. The vision contained the idea that knowledge acquisition will improve the ecological crisis.
- *Environmental Informatics:* The concept of *Environmental Informatics (EI*) emerged from the need to systematically meet domain-specific requirements to information processing in the early 1990s. By that time, public authorities started building up Environmental Information systems. *EI* utilises methods from information systems in combination with simulation modelling techniques and data processing. In the context of sustainable development, *EI* contributes through the potential of shared data and the creation of a consensus on environmental strategies and policies. It is defined as a method of analysation of real-world problems in a specific environmental domain alongside the definition of requirements for information processing within this domain. Furthermore, *EI* benefits environmental sustainability by providing the opportunities of informatics methodology and tools (Page and Wohlgemuth, 2010).
- *Computational Sustainability:* This field aims to provide decision support for *Sustainable Development* policies. Therefore, it utilises methods from computer science, information science, operations research, applied mathematics, and statistics. The decision support characteristic *of Computational Sustainability* mainly focuses on the optimal management of natural resources by applying advanced algorithms. Furthermore, this research field adapts the previously described *TBL* concept and aims to balance the three dimensions.
- *Sustainable Human-Computer Interaction:* The focus of this research field is the relationship between humans and technology in the context of sustainability. It strongly focuses on the design aspects of technology and promotes sustainable design in terms of material, interaction, lifetime and responsible disposal. *Sustainable Human-Computer Interaction* deals with two basic concepts. Firstly, how sustainable lifestyles and sustainable behaviour can be supported and encouraged by the design of technology and interactive systems. Secondly, how the technology itself has to be designed in order to support a usage which is sustainable (Mankoff et al., 2007).
- *Green IT and Green ICT: Green IT* is defined as *"the study and practice of designing, manufacturing, using, and disposing of computers, servers and associated subsystems – such as monitors, printers, storage devices, and networking and communication systems – efficiently and effectively with*

minimal or no impact on the environment" (Murugesan, 2008, p.26). The main reasons and benefits of *Green IT* practices are the reduction of power consumption, lowering of costs, reduction of carbon emissions and environmental impact, improvement of systems performance and space savings. Focus areas within this research field include the design for environmental sustainability, energy-efficient computing, power management, data centre design, server virtualisation, responsible disposal and recycling, regulatory compliance, green metrics, environmental-related risk mitigation, use of renewable energy sources and eco-labelling of IT products. Consequently, *Green IT* centres the sustainability of the production and usage of IT rather than the opportunities for the deployment of IT for sustainability. The eco-friendly improvement in issues of IT itself is also called "Green for IT" or "Green IT 1.0" (Baek and Park, 2015).

- *ICT for Sustainability:* The focus area of *ICT for Sustainability* is the deployment of ICT potential to create a more sustainable society. While also adopting *Green IT* principles, it strongly emphasises the enhancement of sustainability through the utilisation of IT. This view is also referred to as "Green by IT" or "Green IT 2.0". The scope of this concept in terms of sustainability goes beyond the IT sector and aims to improve the sustainability performance of enterprises and society as well (Baek and Park, 2015). Application areas are, for example, intelligent transportation systems, eco-friendly supply chain management and building energy management systems. *ICT for Sustainability* exhibits similarities with the previously described first concept of *Sustainable Human-Computer Interaction*, the encouragement and support of sustainable lifestyles and behaviour through the utilisation of IT.

Besides these described research fields and concepts in the context of IT and sustainability other, less commonly used, definitions are discussed. Those include ICT for Development, ICT for Energy Efficiency, Energy Informatics and Digital Sustainability, to name a few (Hilty and Aebischer, 2015).

To classify impacts on sustainability, which are caused by ICT, Hilty and Aebischer (2015) suggest the LES model, which is illustrated in Figure 3.3. LES stands for the three identified levels of impact: *Life-Cycle impact*, *Enabling impact* and *Structural Impact*.

- *Life-Cycle Impact:* The *Life-Cycle impact* refers to impacts which are caused by the required actions to provide ICT hardware and services. It includes the production of raw materials for ICT hardware, the manufacturing of such, the energy consumption of ICT system usage and the recycling of hardware and disposal of non-recyclable waste. To asses *Life-Cycle Impacts* the method of *Life-Cycle Assessment* (LCA) is suggested.
- *Enabling Impact:* This impact categorisation relates to effects that are enabled by the application and usage of ICT. It assesses the sustainability of production and usage in terms of resource use. Therefore, all actions are viewed as processes of production or consumption. Three types of *Enabling Impacts* are distinguished: Process Optimisation, Media Substitution and Externalisation of Control. Process Optimisation is relevant in terms of production and consumption, whereas Media Substitution and Externalisation of Control especially refer to technological changes.

- *Structural Impact:* The highest level of abstraction describes ICT impacts, which cause significant changes at the macro level. The changes thereby originate in the actions at the micro-level and, in turn, affect these actions. Structural Impact includes the change of economic structures, such as the accumulation of capital, and institutional structures, such as law, policies or social norms.

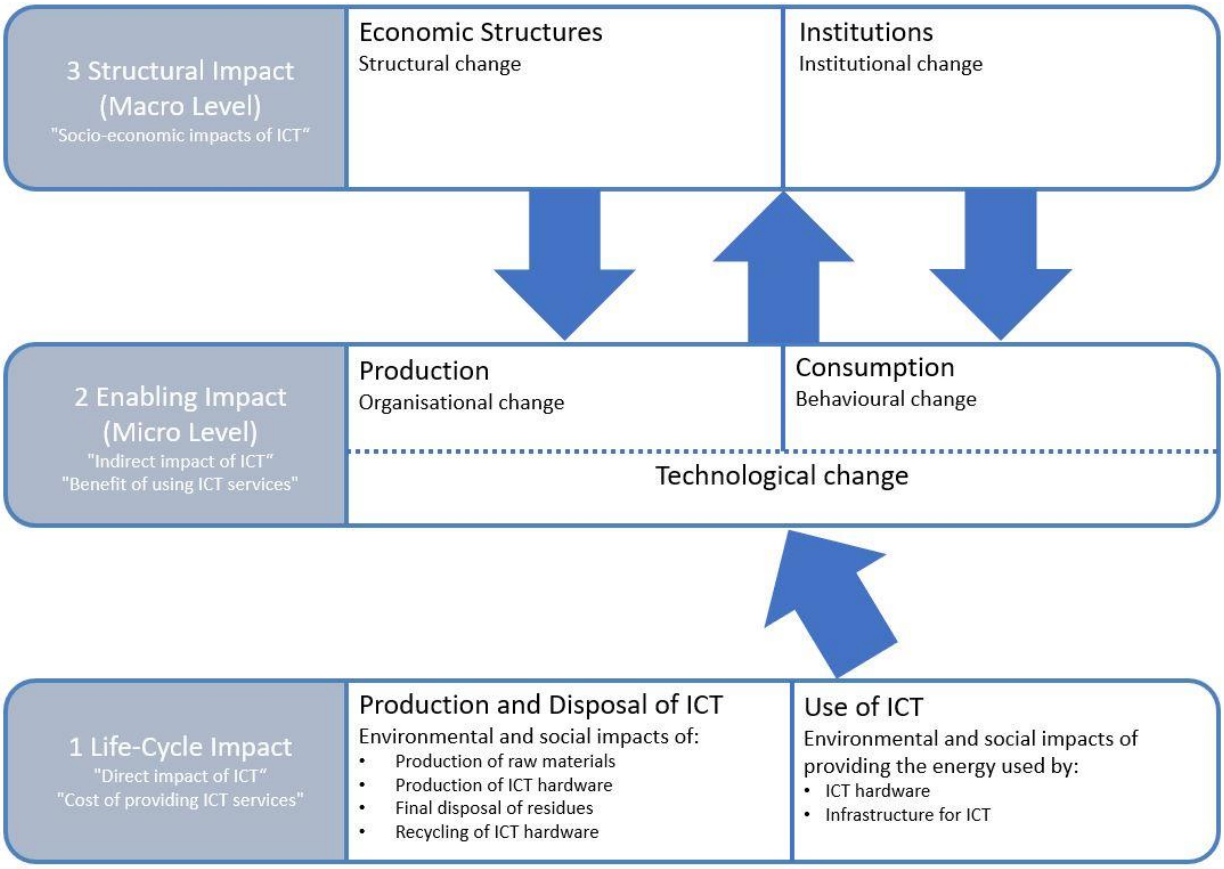

Figure 3.3: The LES model (adapted from Hilty and Aebischer 2015)

4 IoT in the context of Sustainability

This chapter analyses IoT in the context of sustainability and therefore builds the basis for the conceptual framework, which is presented in chapter five. The chapter begins with the elaboration of a definition of sustainability in the context of IoT (section 4.1). Consequently, identified aspects and components in this relation are shown and described (section 4.2). Section 4.3 reveals and details specific IoT-enabled concepts, solutions and paradigms from the perspective of sustainability. Furthermore, it provides IoT paradigms to enhance the sustainability of IoT technology. The emerged categorisations and concepts are applied to particular projects in section 4.4.

4.1 Definition of Sustainability in the context of IoT

To answer RQ1.1 and guide the further analysis of IoT concerning sustainability, a definition regarding sustainability in IoT is needed. This definition determines what is meant by referring to IoT and sustainability within this thesis. A definition of both concepts individually has been given in chapter 3. Relating to IoT the further analysis considers components of IoT along with their production, deployment, operation, maintenance and disposal. Furthermore, services or possibilities which are enabled by IoT or in which IoT takes an indispensable role are included.

In terms of sustainability, two main views emerged during the early stages of the analysis. These two views are already described in the context of sustainability and ICT (section 3.2.2) and were found to be applicable to the analysis of IoT in combination with sustainability as well. The first view relates to the previously described concept of *Green IT and Green ICT.* This view is frequently discussed in the literature within the context and commonly termed as *Green IoT. Green IoT* is defined as a set of procedures and techniques adopted by the IoT in order to reduce the environmental footprint of the IoT itself and existing services and applications. This is realised by the utilisation of particular hardware or software techniques focusing on the topics of green manufacturing, green redesign, green deployment and green recycling and disposal (Shaikh et al., 2015; Murugesan, 2008; Zhu et al., 2015). The concept of *Green IoT* mainly focuses on sustainability aspects within the technology and components of IoT itself. While often centralising energy efficiency, environmental aspects and greenhouse gas emissions resulting from the production and operation of IoT, this view is broadened within this thesis. The further analysis applies the term *Sustainability for IoT* (*Sus4IoT*). The usage of this term covers aspects focusing on the sustainability of the IoT technology itself in terms of manufacturing, components, design, maintenance, operation and disposal. This includes sustainability as a whole and thereby broadens the environment-focusing usage of G*reen IoT*. This definition was set in order to cover sustainability aspects within the IoT that might not match the definition of G*reen IoT*. The view *Sus4IoT* explicitly disregards the deployment of IoT to enhance sustainability by the usage, for example, through services or particular solutions. It only relates to the sustainability aspects of the technology and components of IoT itself. Regarding the effects, this definition refers to the category of *Life-Cycle Impacts*, suggested by Hilty and Aebischer (2015) and described in section 3.2.2. The usage of IoT services and solutions in order to enhance sustainability is covered by the second view this thesis applies. This second view relates to the previously introduced concept of *ICT for Sustainability*. Within this thesis it is applied using the term *IoT for Sustainability* (*IoT4Sus*). In contrast to *Sus4IoT* it only covers the utilisation of IoT in the context of sustainability and therefore neglects sustainability aspects of the applied technology itself. *Sus4IoT* includes services, concepts, visions, opportunities and functions of IoT which are relevant in terms of sustainability. Therefore, it covers the effect category of *Enabling Impacts*, which is described in the LES model. Regarding the classification of IoT, made in section 3.1, *Sus4IoT* mainly focuses on sustainability aspects relating to the *Thing-Oriented Perspective* and the *Internet-Oriented Perspective*, such as sensing, computation, identification and communication. In contrast, *IoT4Sus* focuses on the *Semantic-Oriented Perspective*, covering sustainability aspects of services and semantics, specifically their utilisation. To further clarify this distinction, the example of energy consumption is appropriate. If a technique or procedure is used to lower the energy consumption of the IoT system itself, e.g. sensor nodes, communication or data processing, it is considered to be appurtenant to *Sus4IoT.* If an IoT system or service is used to lower the energy consumption of devices outside its system, e.g. through the automatic shutdown of electronic devices if they are not in use, it is considered belonging to *IoT4Sus*. *Sus4IoT* covers internal sustainability aspects of IoT. *IoT4Sus* relates to external aspects.

Circumstances and aspects within these two views are considered as relevant in the context of sustainability if they have either positive or negative effects on a given situation which is pertinent to sustainability. Therefore, they are examined for consequences which affect at least one of the three dimensions of the *TBL (Environment, Economy* and *Society*) and facilitate or hamper the objectives of the *SDGs*.

The definition of sustainability in the context of IoT applied in this thesis is depicted in Figure 4.1. The depicted circle represents the system of IoT and illustrates, that *Sus4IoT* relates to relevant aspects within the IoT itself while *IoT4Sus* relates to relevant aspects regarding the deployment of IoT systems and services.

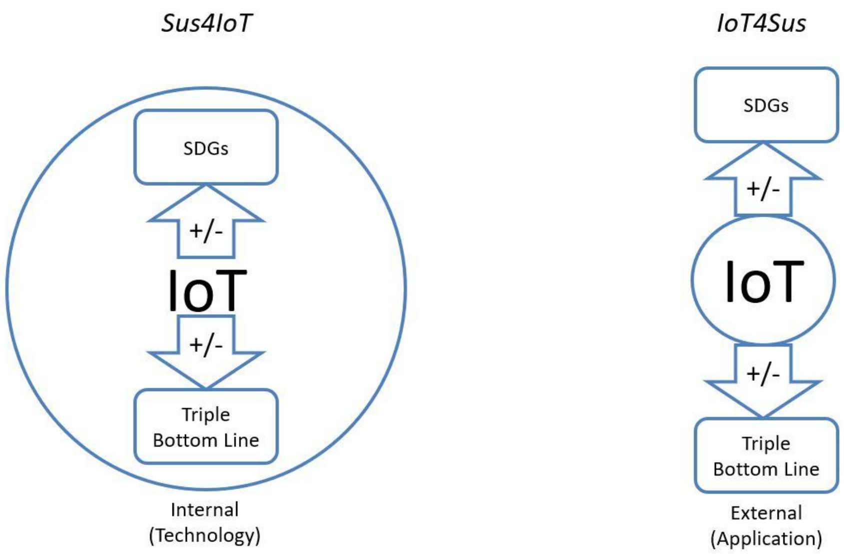

Figure 4.1: Definitions of sustainability in the context of IoT (own illustration)

4.2 Aspects of IoT in the context of Sustainability

In order to answer RQ2.1 and guide the further analysis, relevant aspects in the context of sustainability and IoT are presented in this section. These aspects emerged during the application of the previously explained research method of *Qualitative Coding* (section 2.2). Specifically, the identified aspects are pattern codes with each aspect containing a set of subcategories or subcodes. The identified aspects are *Drivers, Challenges, Effects, Indicators and measurement methods* and *Solutions, Concepts and Paradigms*. *Solutions, Concepts and Paradigms* are divided into two groups. Firstly, *IoT4Sus* concepts, which are relevant in terms of sustainability deployment. Secondly, *Sus4IoT* concepts, which refer to internal sustainability aspects of IoT technology. In the following, these aspects are described and examined further. Subsequently, they are related to the detailed examination of the aspect and *Solutions, Concepts and Paradigms* in section 4.3. The identified aspects and their relations are depicted in Figure 4.2. The rectangles represent the identified aspects. The circles represent the two focus areas of this thesis, sustainability and IoT. These areas also include a set of subcodes. In the case of IoT, these subcodes refer to components, such as hardware, communication, software. The subcodes of sustainability are represented by the dimensions of the *TBL* and the *SDGs*.

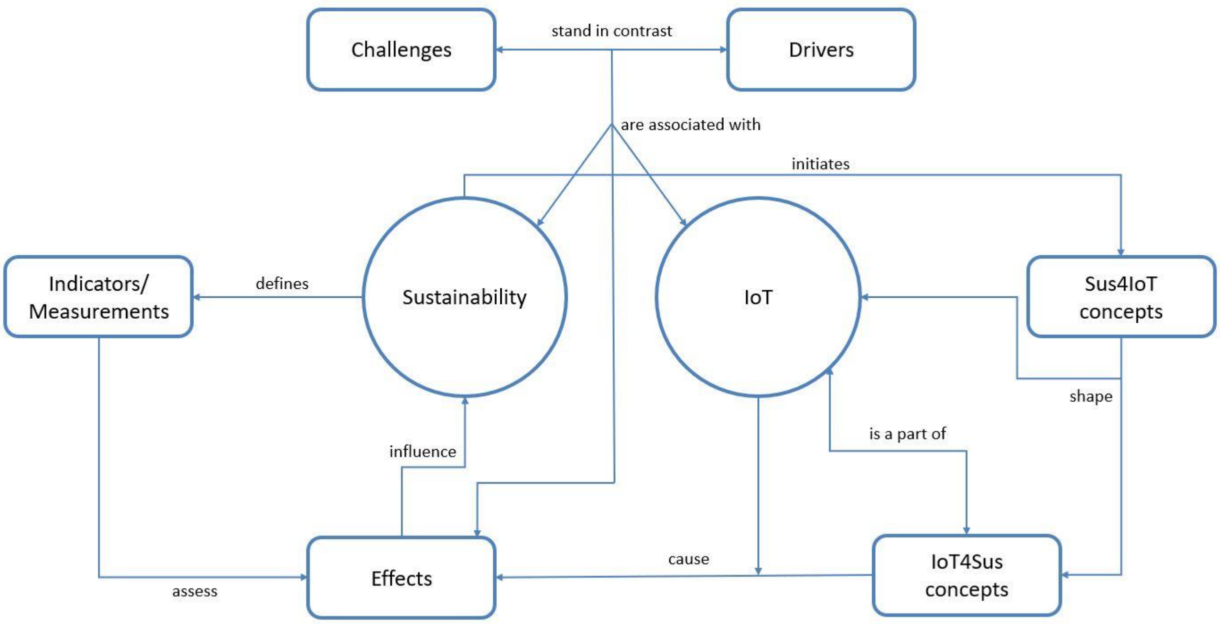

Figure 4.2: Relations of aspects within IoT and sustainability (own illustration)

4.2.1 Drivers and Challenges

In order to clarify the previously identified aspects and answer RQ2.4, this section provides *Drivers* and *Challenges* for the deployment of IoT in the context of sustainability. *Drivers* in this context are functions and aspects in the literature which were mentioned as a reason to deploy IoT systems. Considered challenges are characteristics which hamper the utilisation of IoT regarding sustainability. In contrast to the subsequently described effects (section 4.2.2), *Drivers* and *Challenges* are aspects which are associated with the consideration of the deployment of IoT systems and are explicitly not associated with immediate effects that occur during the deployment. Positive effects are also mentioned as *Drivers* in the literature, while negative effects are referred to as *Challenges*. However, effects are examined in detail in the further course of this thesis and are neglected within the aspect of *Drivers* and *Challenges.* Instead, aspects that are considered as *Drivers* and *Challenges* are mentioned as desired functionalities (*Drivers*) and undesired hypothetical consequences or barriers (*Challenges*) for the deployment of IoT systems in the context of sustainability. Identified *Drivers* (section 4.2.1.1) and *Challenges* (section 4.2.1.2) are described in the following.

4.2.1.1 Drivers

Identified *Drivers* strongly relate to functionalities of IoT which are considered as useful to tackle sustainability issues, or to support solutions and services, which positively influence aspects of sustainability. These functionalities are not independent of each other but interrelate and overlap. Identified *Drivers* in the context of sustainability and IoT are *Monitoring, Process optimisation/ Automation, Awareness Raising/ Behavioural Change, Data Acquisition/ Analysis, Tracking* and *Alerting/ Warning*. These *Drivers* and their usage are briefly described in the following.

Monitoring

Within the category of *Drivers*, *Monitoring* is mentioned most. *Monitoring* is defined as a routine, ongoing measurement activity which is used to collect information on a programme's activities, outputs, states and outcomes (Morra Imas and Rist, 2009). Regarding IoT, real-time monitoring is achieved through the adoption of sensing techniques in combination with communication (Chen et al., 2017). This functionality is highly useful to remotely acquire real-time information about variables which affect sustainability and thereby be aware of critical factors. Applications within the context of IoT and sustainability are for example the monitoring of soil moisture within *Smart Agriculture* solutions (Rivas-Sánchez, Moreno-Pérez and Roldán-Cañas, 2019) or the monitoring of energy consumption within *Smart Home* solutions (Mylonas et al., 2018).

Process Optimisation/ Automation

This driver is mentioned the second most. *Process Optimisation and Automation* describes the automatic execution of formerly manually performed tasks. The optimisation of processes relates to the enhancement of efficiency regarding a given process and the realignment of processes in order to reach a specific goal. Automation and optimisation in the context of IoT is defined as the awareness of an IoT system about what is to be done, how it is to be done and what outcomes are to be achieved without explicit instructions (Dohr et al., 2010). These functionalities are enabled by the analysis and interpretation of data, e.g. acquired from *Monitoring*. Application examples concerning sustainability are routing optimisation in the context of *Smart Logistics* (Liu et al., 2019) or intelligent, automatic production scheduling within *Smart Factories* (Müller and Voigt, 2018). Another application of *Process Optimisation* *and Automation* is the automatic control of devices, following specific governance rules, in order to lower energy consumption (Wang, 2014).

Awareness Raising/ Behavioural Change

In contrast to the formerly described driver, *Process Optimisation and Automation*, this driver relies on the human being to execute tasks which are suggested by the analysis of data. This represents an educational function which is achieved by providing users with individual data regarding their behaviour in the context of a characteristic which is relevant for sustainability. The required data is gained through the deployment of IoT systems and for example, acquired via *Monitoring*. The IoT functionality itself within this aspect plays a rather passive role as the success of its deployment is strongly dependant on the user (Garrity, 2015). An application area where users are provided with information is, for example, a service that suggests users individual activities in order to enhance their health (Li, Darema and Chang, 2017). Another possibility is to point out individual benefits for the user if he decides for a sustainability-enhancing alternative, for example, time savings by using public transport instead of a car (Davidsson et al., 2016) or cost savings by saving energy and turning off unused devices (Nonnecke, Bruch and Crittenden, 2016).

Data Acquisition/ Analysis

This driver is a summarising aspect used to capture *Data Acquisition and Analysis* techniques in case of no further particularisation. Data acquisition can be achieved through any kind of sensing or sensing technique, e.g. *Monitoring*. Analysis is the process of putting the acquired data in a context and generate insights for a respective purpose. Within this driver, a distinction between four objectives of *Data Acquisition and Analysis* is made. This distinction is adapted from the *Gartner Analytic Ascendancy Model* (Laney and Kart, 2012):

- *Descriptive Analytics:* This type of analytics centres the question of what happened or what is happening. It focuses on the observation and description of situations. An application of this type is, for example, the deployment of a *Smart Meter*, which displays the energy consumption (Nonnecke, Bruch and Crittenden, 2016).
- *Diagnostic Analytics:* Analytics in this category focus on reasoning. The objective is to explain why something happened or is happening. *Diagnostic Analytics* are, for example, utilised to explain the relationship between people's behaviour and the energy consumption of a city (Bates and Friday, 2017).
- *Predictive Analytics*: *Predictive Analytics* aim to predict what is likely to happen in the future. Therefore, different simulation and forecasting techniques are utilised. These are used, for example, to predict natural disasters like droughts, tsunamis, floods, earthquakes, wildfires and alert residents in time (Dupont et al., 2018)
- *Prescriptive Analytics:* This category focuses on the examination of how to reach a desired state or outcome and aims to identify actions which must be taken to reach this outcome. For example, these analytics are applicated to prescribe suggestions to patients at distant locations in the context of *Smart Healthcare* (Sodhro et al., 2018)

Tracking

Tracking in the context of IoT is defined as the *Monitoring* of the behaviour of persons, things or data through space and time (Chui, Löffler and Roberts, 2010). Therefore, *Tracking* represents a form of *Data Acquisition and Analysis* that is a specific entity of *Monitoring*. *Tracking* strongly relates to technologies like RFID and the Global Positioning System (GPS). Examples in the context of sustainability are the tracking of waste of electronic equipment in order to ensure appropriate disposal (Baek and Park, 2015) or the tracking of perishable goods to guarantee their intactness (Arshad et al., 2017).

Alerting/ Warning

The last and least mentioned driver that was identified is *Alerting and Warning*. This driver basically composites of *Monitoring* in combination with the dispatch of an automated message to a defined person, institution or group in case a specific variable or combination of variables exceeds a defined threshold. Examples of application are the monitoring of urban infrastructure statics and condition (Gubbi et al., 2013) and the monitoring of the continuous cooling chain in the context of food safety (Verdouw et al., 2018).

The identified *Drivers* and their relationships are depicted in Figure 4.3.

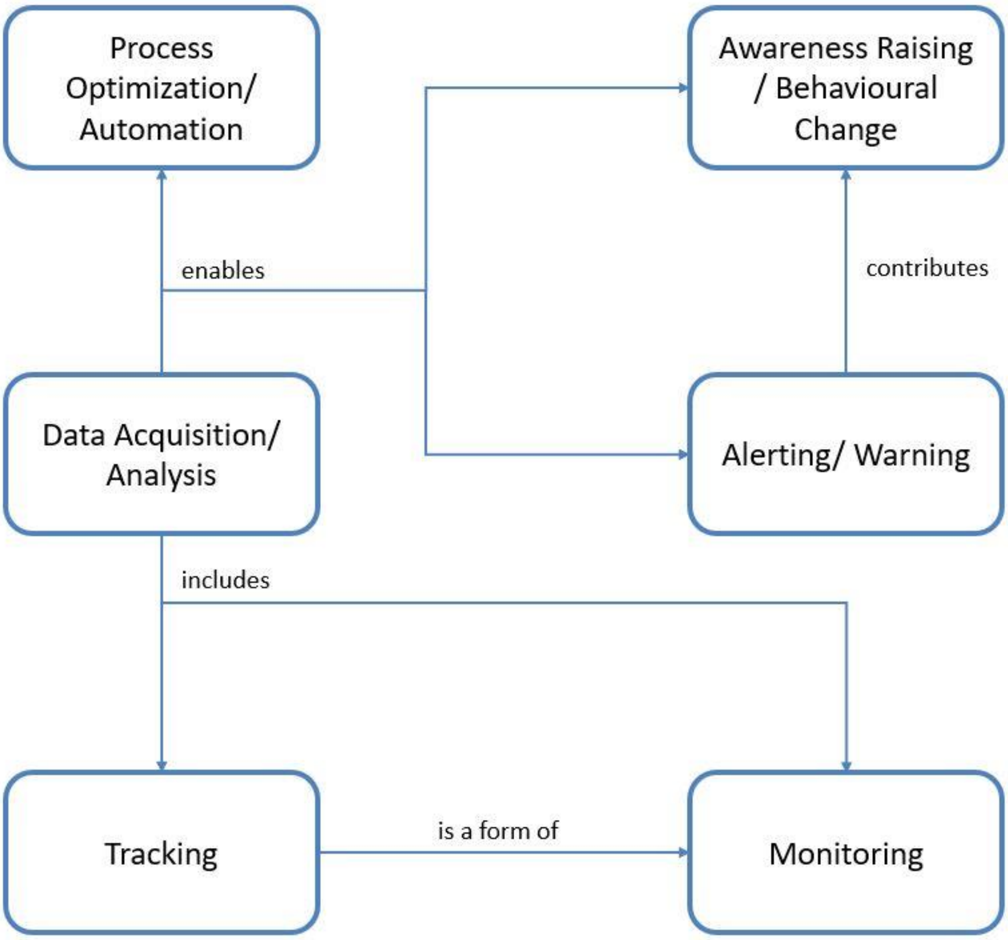

Figure 4.3: Relations of drivers of IoT in the context of sustainability (own illustration)

4.2.1.2 Challenges

The identified *Challenges* in the context of sustainability and IoT relate to characteristics of IoT, which might affect sustainability negatively or hamper the deployment of IoT to enhance sustainability aspects. Therefore, these *Challenges* represent obstacles which must be reduced and overcome to unleash the full potential of IoT for sustainability and increase IoT performance in this context. *Challenges* overlap with negative *Effects*, which are described in section 4.2.2. However, in the analysed literature, *Challenges* are mentioned explicitly as barriers which must be overcome in the future and represent learnings that arose from the observation of adverse effects. The identified *Challenges* are *Power Demand, Financial Requirements, Waste/ Disposal, Security/ Privacy, Interoperability, Air Pollution, Collective Inclusion, Production, Rights/ Law/ Politics, Raw Material Utilisation, Network Coverage* and *Technology Adoption.* These *Challenges* are briefly described in the following.

Power Demand

This barrier is related to the energy consumption of IoT systems and connected technologies, such as sensors or data centres. The aspect can be divided into several manifestations which represent a challenge for IoT regarding sustainability. Firstly, the *Power Demand* of IoT systems poses a threat to sustainability, especially if fossil resources are used to produce the required energy. An example for this *Challenge* category is the massive energy consumption of large data centres which are required to process data within IoT systems (Bonilla et al., 2018) or the *Power Demand* of the increasing number of smart devices within the IoT (Maksimovic, 2017). The second dimension which relates to this *Challenge* category is connected to sensors and devices. Those are often powered by batteries, for example in remote areas. The energy demand of battery-powered remote devices results in a shortage of lifespan or in case of highly energy-efficient usage in the limitation of utilisation. Furthermore, this aspect creates a great problem for device management and environmental protection (Wang et al., 2017). *Power Demand* is related to the intensification of other *Challenges*, namely *Financial Requirements*, *Air Pollution*, *Production* and *Raw Material Utilisation.*

Financial Requirements

This *Challenge* captures barriers for the deployment of IoT, which relate to financial expenditures. It includes initial expenses, such as the acquisition of hardware devices and infrastructure, as well as running costs, such as electricity costs, maintenance and rent payments for server space. As IoT is a relatively new technology, the success of a particular IoT system is often uncertain, which amplifies the wariness to invest in appropriate solutions (Birkel et al., 2019). One driver for the overall costs of IoT systems is the required number of expensive devices, for example, sensor nodes (Andión et al., 2018; Nagy et al., 2018). Licencing and installation costs represent another matter of expense (Verdouw et al., 2018). Furthermore, the maintenance of IoT infrastructure is named to be an essential cost factor, covering running costs and such to ensure the operability of the system (Davidsson et al., 2016). The financial barrier relates to other *Challenges*. Those are *Power Demand*, *Collective Inclusion* and *Production*.

Waste/ Disposal

The production of IoT devices, in conjunction with their prospective disposal, poses another *Challenge* for sustainability. This problem comprises several components. The deployment of IoT systems causes the obsolescence of formerly used technology and machinery as it is not always possible to equip existing systems with IoT features. Therefore, systems have to be replaced and obsolete technology requires appropriate disposal, which increases the amount of waste (Birkel et al., 2019). Furthermore, the utilisation of IoT is related to the usage of an increasing number of electronic devices, which also results in higher amounts of electronic waste (Maksimovic, 2017). This trend is intensified by the short product lifespans associated with IT (Jenkin, Webster and McShane, 2011). In addition to the increased total amount of waste, the disposal of electronic devices is very complex and often causes environmental pollution. Components of IoT, such as RFID tags, are complicated to recycle. This originates in the containing of large amounts of non-degradable material (Shuja et al., 2017; Shaikh et al., 2015). Electronic waste represents a significant part of hazardous waste in landfills, releasing substantial amounts of toxic materials, volatile chemicals and heavy metals (Pramanik, Pal and Choudhury, 2019). The challenge of *Waste/ Disposal* exhibits relations to the barriers of *Production* and *Raw Material Utilisation*.

Security/ Privacy

The challenge of assuring *Security and Privacy* within IoT systems is highly discussed among researchers. The contempt of this aspect might result in various threats to sustainability and prevent users from a widespread adaption of IoT, which hampers the opportunities of IoT for sustainable development (Chen et al., 2014). IoT devices are designed to generate large amounts of data and sense various activities, including personal data like location, medical records or behaviour patterns. Especially IoT devices which are meant to enhance sustainability are embedded in public space, for example, public transport. People thereby have no opportunity to opt-out (Nonnecke, Bruch and Crittenden, 2016). This poses a threat to the fundamental right of informational self-determination. Abuse of IoT could turn the information society into a surveillance society (Garrity, 2015). Furthermore, IoT devices are often constrained regarding computing power, which is needed for *Security and Privacy* techniques like encryption. For this reason, those devices are eminently vulnerable for manipulations like data theft or data manipulation (Baek and Park, 2015; Stetsuyk, Maevsky and Maevskaya, 2018). This could have catastrophic, costly consequences, for example, regarding IoT deployments within a nation's power grid (Szymanski, 2017). The catastrophic consequences of attacks against IoT systems include the manipulation of life-ensuring *Smart Healthcare* devices like pacemakers. Manipulation of such devices will inevitably and immediately damage the health of people (Islam et al., 2015). Consequently, *Security and Privacy* are high priority requirements and should be considered early in the design phase (Shaikh et al., 2015). This includes securing devices against unauthorised usage, ensuring the security of stored and communicated data against unauthorised access and the anonymisation of collected data (Davidsson et al., 2016). *Security and Privacy* as a barrier relates to *Power Demand* as the constrained energy availability of devices might result in a reduction of computing power and thus, possibilities to ensure *Security and Privacy*. Furthermore, this challenge is connected to *Rights/ Law/ Politics*, *Technology Adoption* and *Interoperability.*

Interoperability

The integration and networking of devices and data represents an essential challenge for IoT, not just regarding the deployment for sustainability. In contrast to preceding wireless systems, the Internet of Things composes of devices with a high level of heterogeneity. IoT communication environments contain a blend of devices that substantially differ in terms of functionality, technology and application fields (Chen et al., 2014). The difference of IoT devices is amplified by the usage of varying techniques regarding vendors (Davidsson et al., 2016). To this day, IoT architecture is still under standardisation and committees are trying to enable communication between heterogeneous networks. This includes the development and usage of standardised protocols and interfaces and the development of efficient middleware (Shuja et al., 2017). To gain information and assess such a complex construct like sustainability, numerous variables and aspects must be considered. This requires the combination of different systems, devices and data alongside the possibility to extract high-level semantic information (Bellavista, Giannelli and Zamagna, 2017). However, full *Interoperability* of devices may be more vulnerable to failure through accidental or malicious acts (Nonnecke, Bruch and Crittenden, 2016). Therefore, *Interoperability* relates to *Security and Privacy*.

Air Pollution

Greenhouse gas (GHG) emissions are among the most discussed sustainability issues these days, contributing to higher disease rates, global warming and the depletion of the ozone layer (Shuja et al., 2017). ICT, which includes IoT, is among the polluters, and emissions which originate from ICT production, maintenance and operation are increasing rapidly (Arshad et al., 2017). ICT emissions are estimated to contribute 6%-8% to the total of GHG emissions by 2020, quickly surpassing air transportation (Jenkin, Webster and McShane, 2011; Shaikh et al., 2015). These emissions arise from the high energy demands of ICT systems during production and operation, particularly if this energy is generated through fossil resources (Pramanik, Pal and Choudhury, 2019). Furthermore, the deployment of IoT systems is connected to the usage of a higher number of electronic devices. The manufacturing of billions of IoT devices, the shipment of these, operation and excess use of radio access networks will elevate the carbon emissions further (Popli, Jha and Jain, 2019). This *Challenge* is related to *Power Demand* and *Production*.

Collective Inclusion

Collective Inclusion covers the aspect of social justice regarding IoT. In order to unleash the full potential of IoT to enhance sustainability, all people on planet earth should be able to use IoT in their regions and communities. Today, the penetration level of IoT in Africa is significantly lower than in other world regions (Onyalo, Kandie and Njuki, 2015). The exclusion of certain groups of people or regions of earth from IoT-enabled opportunities will increase the gap between developed and developing countries further (Bonilla et al., 2018). The inability to utilise IoT has various reasons. Some regions or communities lack access to required knowledge about the deployment, maintenance and usage of IoT (Garrity, 2015). Other issues for providing access to IoT for a large part of the human population are the required financial expenses and the needed access to a communication network (Dupont et al., 2018). Therefore, *Collective Inclusion* relates to *Financial Requirements* and *Network Coverage.*

Production

Manufacturing of IT hardware and electronic devices, including IoT components, is connected to various hazardous consequences for sustainability. The previously described massive manufacturing of devices to realise the IoT vision entails a massive consumption of raw materials, water, power, resources and energy. Materials, which are used in the manufacturing process, are often difficult to extract from the environment, difficult to purify and handle and complex to recycle (Bonilla et al., 2018). Furthermore, the manufacturing of hardware not only requires materials which are directly incorporated but also consumes resources for the extraction of such and the process of *Production*. Those resources include large amounts of water, fossil fuels and toxic chemicals (Sarkis, Koo and Watson, 2013). Also, the manufacturing process of ICT requires significant amounts of energy. For example, the fabrication of an average computer consumes 30.000 megajoules of energy (Pramanik, Pal and Choudhury, 2019). The deployment of IoT will increase the environmental burden of *Production* as the amount of used hardware, like sensors, increases. Furthermore, the short lifespans of IT require continuous replacements and upgrades and thus continuous manufacturing (Jenkin, Webster and McShane, 2011). *Production* relates to *Power Demand*, *Raw Material Utilisation*, *Financial Requirements* and *Waste/ Disposal*.

Rights/ Law/ Politics

This *Challenge* covers issues relating to political, administrative and legal aspects of IoT deployments. Governments and legal frameworks occupy a crucial role in terms of creating a viable environment for both IoT and sustainability. This role is, for example, manifested through incentives for the promotion of commonweal or punishments of harmful activities. Regarding IoT, governments are required to set a legal framework for the utilisation of data, particularly the analysis of personal data and the transfer of data across borders (Garrity, 2015). Furthermore, governments must ensure to provide appropriate infrastructure to enable a comprehensive realisation of the IoT vision, for example, widespread broadband connectivity. The high level of interconnection, leading to global networking, requires politicians to define suitable standards at the supranational level (Birkel et al., 2019). This barrier exhibits a connection to *Security*/ *Privacy* and *Network Coverage.*

Raw Material Utilisation

Issues regarding the raw material consumption of IoT especially arise from the *Production* and maintenance of required hardware components. As previously described, the manufacturing of IoT hardware consumes large amounts of resources, such as water. These resources, if not used up during the manufacturing process, are often polluted and blended with other materials or chemicals, which results in a complex recycling process or the need of secure disposal (Pramanik, Pal and Choudhury, 2019). The extraction of raw materials directly consumes another critical resource of the global ecosystem, landmass. Extraction occupies and often pollutes areas to a degree which prevents other usages of the area, for example, as cropland (Birkel et al., 2019). Furthermore, the extraction of raw materials often takes place in conflict areas, resulting in exploitation, violence and abuse of human rights. An example is the mining of coltan, an indispensable material for capacitors within electronic devices. The most significant reserves of this material are located in the Democratic Republic of Congo, which suffered enduring and devastating civil wars along with resulting humanitarian crises during the first decade of the third millennium (Montague, 2002). The consumption of fossil fuels in order to generate energy is another aspect of this barrier (Arshad et al., 2017). *Raw Material Utilisation* relates to *Power Demand*, *Production* and *Waste/ Disposal*.

Network Coverage

An essential requirement for the deployment of a workable IoT system is access to appropriate communication networks. The vision of IoT suggests an intensive communication between sensing devices, computing power and user devices (Verdouw et al., 2018). In order to meet this requirement, comprehensive, cost-efficient, robust and flexible connectivity must be available (Popli, Jha and Jain, 2019). Currently, the available communication infrastructure hampers the deployment of large-scale IoT systems. For numerous regions on the globe, only low data rates and limited connectivity is available (Latif et al., 2017). This is especially valid for rural or remote areas and less developed countries (Dupont et al., 2018). However, even well-networked areas must consider the increasing network traffic and develop their infrastructure further (Garrity, 2015). The barrier of connectivity interrelates with *Rights/ Law/ Politics* and *Collective Inclusion.*

Technology Adoption

The barrier of *Technology Adoption* may represent the most crucial in order to enhance sustainability through the deployment of IoT. The adoption of IoT and the trust to utilise this technique and apply learnings from this utilisation depends on human behaviour. Humans are often resistant and reluctant to modify their behaviour to fit with systems, preferring that systems adapt to meet their needs (Garrity, 2015). In terms of sustainability, most, if not all, issues originate from human behaviour. Therefore, it is crucial that people trust and adopt IoT systems and gained insights to realise a minimisation of harmful activities (Elliot, 2011). This trust strongly relates to the perceived *Security and Privacy*.

The identified *Challenges* and their relations are depicted in Figure 4.4. Joins and divides of connections are represented with a circled cross accompanied by the respective direction.

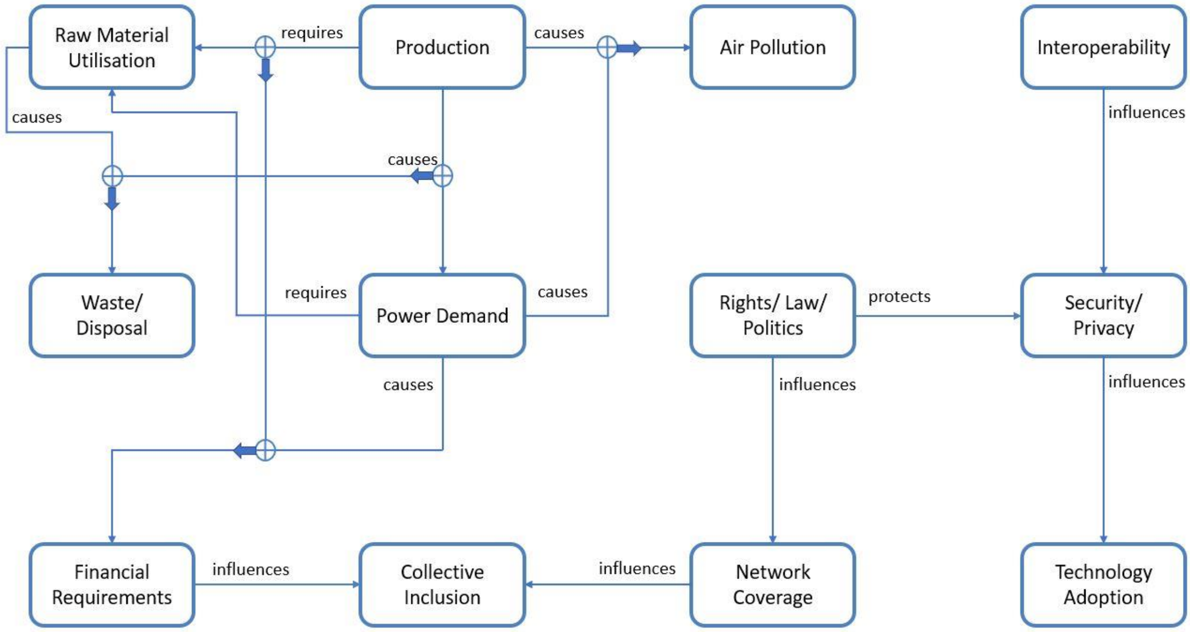

Figure 4.4: Relations of challenges of IoT in the context of sustainability (own illustration)

4.2.2 Effects

In order to set the foundation for the answer of RQ2.3 and RQ 2.4, it is essential to identify impacts on sustainability which originate in the manufacturing, operation and utilisation of IoT. These impacts origin in the utilisation of IoT (*IoT4Sus*) or sustainability aspects of manufacturing and operation of IoT (*Sus4IoT*). As previously described in section 3.2.2, impacts can be classified into three categories: *Life-Cycle Impacts, Enabling Impacts* and *Structural impacts* (Hilty and Aebischer, 2015). Therefore, manifestations of specific impacts influence sustainability aspects either negatively or positively. *Life-Cycle Impacts* are associated with negative consequences for sustainability through production, use and disposal. *Enabling Impacts* offer positive opportunities by substitution and optimisation effects and negative impacts through induction effects and obsolescence effects. *Structural Impacts* are described as negative impacts by the occurrence of rebound effects and emerging risks, while the transition towards sustainable patterns of production and consumption states positive impacts for sustainability (Hilty, 2008). In contrast to *Drivers* and *Challenges*, *Effects* are explicitly mentioned as immediate consequences of IoT deployments within the considered literature. Moreover, *Effects* cover a broader view of sustainability areas. Whereas the *Challenge* of *Raw Material Utilisation* directly refers to the resource consumption of IoT, the *Effect* on resource consumption also covers IoT-enabled solutions to reduce the consumption of other objects, e.g. cars. The identified *Effects* of IoT on sustainability are *Energy Consumption, Economy/ Costs, GHG Emissions, Human Behaviour, Resource Consumption, Amount of waste, Environment, Health, Water Consumption, Security, Social Gap/ Accessibility, Privacy* and *Human Work*. In the following, identified *Effects* are briefly described. Furthermore, these *Effects* are used to assess specific IoT solutions in section 4.3.

Energy Consumption

This aspect covers the influences of IoT on the sustainability feature of *Energy Consumption*. IoT causes impacts on *Energy Consumption* in numerous ways and influences this circumstance positively as well as negatively. Furthermore, this *Effect* captures changes in terms of overall energy utilisation and the efficiency of energy usage. Reasons for this influence arise from both the technology itself (*Sus4IoT*) and the utilisation (*IoT4Sus*). An example for a positive influence on *Energy Consumption* in terms of *Sus4IoT* is the enhancement of energy efficiency by using energy-oriented routing techniques for data communication or *Activity Scheduling* of sensor nodes (Farhan et al., 2018). A negative influence in terms of *IoT4Sus* is represented by the increase of primary energy demand, originating in the operation of data centres and processing of large data amounts, to enable industrial automation with the support of IoT (Stock et al., 2018). Positive influences on *Energy Consumption* within *IoT4Sus* is, for example, realised through energy consumption monitoring and configuration in *Smart Buildings* (Sembroiz et al., 2018).

Economy/ Costs

The economic consequences of IoT deployments are captured within this category. It covers enhancements and detractions of economic activity and prosperity as well as cost reductions or increases. As in the case of *Energy Consumption*, this aspect is influenced by IoT in several ways. An example of the positive impact of *IoT4Sus* on *Costs* is the application within *Smart Logistics*. The IoT-enabled optimisation of delivery routes and reduction of empty runs saves *Costs* and enables higher productivity (Gružauskas, Baskutis and Navickas, 2018). Within *Sus4IoT* positive influences on *Costs* can be achieved through the cheapening of certain devices and components or through specific approaches like "Do it yourself" or *Open-Source* software (Dupont et al., 2018). Negative impacts in this realm arise from the massive deployment *Costs*, which result in long and uncertain amortisation and occupation of financial resources which could be invested in other areas (Birkel et al., 2019).

GHG Emissions

The reduction of *GHG Emissions*, such as carbon dioxide, is one of the pivotal objectives to alleviate the consequences of climate change. IoT can affect *GHG Emissions* in a positive or negative way. Positive impacts from IoT mostly arise from the utilisation (*IoT4Sus*), while adverse consequences are often related to the technology itself (*Sus4IoT*). An example of the utilisation of IoT that reduces the amount of *GHG Emissions* is the utilisation within *Smart Traffic*. Travel patterns are analysed and used to optimise the providence of public transport vehicles. This results in higher occupancy rates and minimisation of deployed vehicles, thus less *GHG Emissions* (Davidsson et al., 2016). A decrease of emissions in this domain is also realised through the optimisation of traffic routes dependent on the occupancy rate, which results in a lower probability of traffic jams (Baek and Park, 2015). Negative influences, resulting from the production and usage of IoT technology, can be lowered through the usage of renewable energy to power IoT devices. This is, for example, enabled by the application of *Energy Harvesting* techniques for IoT devices, like the utilisation of solar power or kinetic energy (Zhu et al., 2018).

Human Behaviour

As previously described within the aspect of *Challenges* (section 4.2.1.2), *Human Behaviour* occupies a crucial role in transforming today's society towards more sustainability. IoT technology exhibits a high potential to contribute to improved *Human Behaviour* regarding sustainability aspects as it enables high-quality analysis and recommendations in terms of individual behaviour patterns. The impacts of IoT on this sustainability aspect are mainly manifested within the application of IoT (*IoT4Sus*). Improved *Human Behaviour* contributes to the enhancement of numerous sustainability issues by raising awareness of these issues like energy consumption or waste production (Wang, 2014). An application example for IoT, which aims to raise the user's awareness regarding a sustainability aspect is smart metering. By providing real-time feedback on energy demand of their homes, users learn about causes and tend to improve their habits (Arshad et al., 2017). Adverse influences on *Human Behaviour* caused by IoT primarily originate in the so-called rebound effect. Once people adopt more sustainable technology, they often tend to intensify the usage of this technology or worsen their behaviour regarding other sustainability aspects, which possibly voids the initial improvements (Greening, Greene and Difiglio, 2000).

Resource Consumption

The enhancement of resource efficiency, especially of limited, non-renewable resources, represents another challenge in order to improve sustainability. This *Effect* dimension includes resources except for electricity and water, which are represented by own dimensions. The Internet of Things influences *Resource Consumption* and efficiency in both ways, positive and negative. Thereby positive consequences mainly occur with the utilisation of IoT (*IoT4Sus*), while adverse impacts mostly origin in the manufacturing and usage of IoT technology itself (*Sus4IoT*). To enhance resource efficiency and lower overall *Resource Consumption*, IoT is, for example, applicated to contribute the vision of a *Circular Economy (CE)*. The concept of *Circular Economy* aims an industrial system in which resources are used in a closed cycle. It emphasises a design of products which enables to fully recover, recycle and reuse the components after usage (Murray, Skene and Haynes, 2017). IoT can contribute significantly to this vision by tracking the usage of specific materials and by monitoring the composition of particular products (Alcayaga, Wiener and Hansen, 2019). Negative impacts on *Resource Consumption* originating in the production and operation of IoT itself can also be lowered by applying *CE* principles (Arshad et al., 2017).

Amount of Waste

Related to the category of *Resource Consumption* is the aspect of waste, as waste can be prevented by an improvement of resource efficiency and the application of *CE* principles (Baek and Park, 2015). Likewise, this dimension is influenced by IoT in a positive way by the utilisation of IoT (*IoT4Sus*), while negative impacts most notably arise from the manufacturing and operation of IoT itself (*Sus4IoT*). For instance, a positive influence on waste generation through the utilisation of IoT technology is realised through the extension of product lifetime. By monitoring the wear and tear of certain products, damages of particular components can be identified and repaired before the damage spreads across other components of the product (Li, Darema and Chang, 2017). An extension of product lifetime can also be achieved by the remote monitoring and upgrading of product firmware or included digital components

(Bressanelli et al., 2018). The remote monitoring and upgrading of devices are also applicable to enhance the sustainability of IoT itself (*Sus4IoT*). Furthermore, the lifetime of IoT technology and thus the prevention of resulting waste can be enhanced by the utilisation of specific design principles, such as *Open-Source*. If users are able to repair, upgrade or customise IoT systems by their own the obsolescence of systems and devices delays (Sas and Neustaedter, 2017).

Environment

Environment is a summarising category in case of no further particularisation. The previously described dimensions of *Waste*, *Resource Consumption*, *GHG Emissions* and *Energy Consumption* are parts of IoT impacts on the *Environment*. However, this aspect captures statements where impacts on the general aspect of the *Environment* are described without a further explanation of the reasons and specific consequences. Positive impacts regarding the *Environment* especially arise from services and applications of IoT, thus *IoT4Sus*. Negative consequences regarding the *Environment* are rather related to the production, operation and disposal of IoT devices (*Sus4IoT*). For example, enhancement environmental sustainability is achieved by the deployment of *Smart Agriculture* solutions. The application of precise amounts of pesticides, water and fertiliser according to the crop's needs protects soil and groundwater from contamination and ensures a sustainable usage of agricultural land (Shaikh et al., 2015). Another application area of IoT which exhibits positive consequences for *Environment* is *Environmental Monitoring*. For instance, the monitoring of forests supports early fire detection and thereby avoids further damage to the *Environment* (Mo et al., 2009). Negative impacts especially arise during the deployment phase of IoT systems and originate in higher amounts of waste from equipment obsolescence and raw material consumption to produce required devices (Bonilla et al., 2018).

Health

IoT has great potential to enhance health services and accessibility. This potential is primarily found in the utilisation of IoT for human health. However, IoT can also affect the category of *Health* negatively. For instance, adverse impacts originating in the toxic waste and environmental pollution within the process of production and disposal pose a threat to human, botanical and animal life. Furthermore, the implementation of IoT within *Smart Factories* may have a negative influence on *Health*. Employees require additional competencies and experience a lower level of social interaction, which can result in increased stress and therefore, a negative impact on human *Health* (Birkel et al., 2019). Nevertheless, the positive impacts of IoT on *Health* dominate in the analysed literature. The application area of *Smart Healthcare* promises more individual, faster service and quicker access to services. Solutions include individual recommendations based on patient sensing data, e.g. acquired from wearables, medication management, monitoring of patient data, semantic medical access, automated emergency calls and many more (Islam et al., 2015). Large-scale implementations of *Smart Healthcare* systems will ultimately result in an increase in human life expectancy, earlier disease examination and enhancements of health service quality (Chui et al., 2017).

Water Consumption

As in the case of *Energy Consumption*, this dimension is a part of *Resource Consumption*. IoT exhibits opportunities to enhance water efficiency and lower *Water Consumption*. This is realised by functionalities and services connected with the utilisation of IoT. The technology itself, particularly the manufacturing process, consumes large amounts of water and therefore has a negative impact on *Water Consumption*. Positive impacts are achieved through monitoring and the avoidance of water wastages. Within *Smart Agriculture*, substrate water levels are monitored and precisely automatically adjusted if needed (Rivas-Sánchez, Moreno-Pérez and Roldán-Cañas, 2019). In *Smart Cities Water Consumption* affected positively by monitoring water pipes and identify leakages as well as the management of water flow, distribution and pressure (Maksimovic, 2017; Nonnecke, Bruch and Crittenden, 2016).

Security

The dimension of *Security* refers to the preservation of public order and public safety to enable a peaceful and safe life for human beings. Positive consequences of IoT in this area mostly arise from the utilisation of IoT and the functionality of monitoring. Adverse impacts originate in IoT technology itself and often relate to the vulnerability of specific devices. An example of how IoT can support *Security* is found in the arrest of the "Boston bomber", in 2013. Based on the analysis of data, gathered through smartphones, cameras and sensors, law enforcement agencies were able to identify and detain the assassin (Shuja et al., 2017). Another application area of IoT, which enhances *Security* is the prediction and warning of natural disasters like forest fires, storms or tsunamis (Li, Darema and Chang, 2017). Furthermore, IoT in the area of *Smart Vehicles* enhances traffic safety by automatic communication between vehicles and active prevention of accidents (Davidsson et al., 2016). Undesirable impacts are strongly connected with the *Challenge* of *Security and Privacy* and are discussed in section 4.2.1.2.

Social Gap/ Accessibility

The deployment of IoT in terms of *Social Gap and Accessibility* centres the inclusion of every human being into society and the access to basic needs. As already described within the aspect of *Challenges*, IoT technology also exhibits threats to this dimension, especially in terms of costs for the required technology and education to operate and maintain this technology. Positive impacts within this dimension arise from the monitoring and knowledge building about circumstances of everyday life of groups which lack access to basic needs or exhibit special needs, for example, people who depend on a wheelchair. A solution to enhance the quality of life for this groups is, for example, the tracking of routes of wheelchair users to gain knowledge about their movement patterns and disclose barriers within the infrastructure (Gilart-Iglesias et al., 2015). In order to gain knowledge about the accessibility to clean water in rural areas, water pumps can be equipped with sensors to check their functionality and performance. Areas with poor access to clean water can then be systematically targeted by governments and organisations (Garrity, 2015). Another positive impact on this dimension is generated by the possibility to replace capital intensive technology with relatively cheap IoT solutions, like in the case of weather monitoring stations (Garrity, 2015).

Privacy

As already described within the aspect of *Challenges* (section 4.2.1.2), *Privacy* is a concern of many users regarding the adaption and use of IoT technology. Those concerns relate to the analysation of their personal data and, in combination with *Security*, to the fear of unauthorised usage (Anjum et al., 2018). IoT as data acquiring technology generally poses a threat to the dimension of *Privacy* and the fundamental right of informational self-determination. However, advances in IoT technology address this issue and limit the adverse effects.

Human Work

This dimension captures impacts of IoT on the work of humans. Jobs play an essential role in both, the economic and the societal dimension of the *TBL* as they ensure income for people, which they use to satisfy their basic needs and to buy goods and services, ensuring other people's income. Discussions around the consequences of IoT deployments on jobs vary. There is no common consent if IoT will cause job losses or generate new jobs. The further automation of tasks will require more IT-related jobs, while the need for mechanical labour will decrease (Müller and Voigt, 2018). This development will result in job losses within areas where tasks fall to autonomous systems. In contrast to this, IoT supports human learning through intelligent assistance systems and provides high-quality human-machine interfaces, which may create new opportunities for people that lose their jobs to autonomous systems (Birkel et al., 2019). Educational institutions and organisations are challenged to adopt this trend in time and educate students and employees to meet the new requirements. Eventually, appropriate education and retraining will mitigate job losses and ensure the number of required workers with IT skills in the future (Bologa et al., 2017).

4.2.3 Indicators and Measurement Methods

To achieve RO2, research question 2.2 must be answered. This question deals with the measurement of sustainability impacts and the assessment of IoT influences on sustainability aspects. This is especially important to learn about the *Effects* of IoT projects on sustainability and thus substantial for developing the aimed framework within this thesis. Therefore, this section provides measurement methods which were discovered and used in the analysed literature. Indicators, in general, are defined as factors which consist of information that display changes. Those factors provide reliable and straightforward means to reflect the changes connected to an event. Therefore, indicators enable to perceive differences, improvements or developments in a particular context (Church and Rogers, 2006). Indicators are divided into two categories, *Quantitative Indicators* and *Qualitative Indicators*. *Quantitative Indicators* are measures of quantities or amounts and can be expressed numerically by direct measurements. In contrast to this, *Qualitative Indicators* are judgements or perceptions of changes which cannot be directly measured in a numerically (Church and Rogers, 2006). This categorisation is applicable for the identified *Effect* dimensions in the previous section. Assessment methods of both categories were found in the analysed literature and are provided in the following.

Quantitative Methods

Quantitative Methods are applicable for *Effect* categories which provide measurement opportunities of numeric factors. This enables a direct comparison of values before and after the deployment of IoT systems to assess the impact of IoT within this dimension. The application of *Quantitative Indicators* is appropriate to assess effects within the dimensions of *Energy Consumption*, *Economy/ Costs*, *GHG Emissions*, *Resource Consumption*, *Amount of Waste* and *Water Consumption*. These dimensions provide measurable numbers which indicate their amount. Examples are the *Energy Consumption* in joule, *Costs* in a specific currency, *GHG Emissions* in tons, *Resource Consumption* in kilograms, *Amount of Waste* in kilograms and *Water Consumption* in litres. Furthermore, certain aspects of the other dimensions can be measured and assessed based on numeric values. Examples for numeric indicators within the other dimensions are number of people who use *Smart Meters*, number of trees per hectare in a forest, the mortality rate of a specific disease, number of successful cyberattacks on an IoT system, number of people with access to clean water and unemployment rate. The required numerical values can be obtained through measurement and sensing as well as simulations, extrapolations or estimations (Farhan et al., 2018).

Qualitative Methods

To assess effects which cannot be directly measured and expressed via numeric values, *Qualitative Methods* should be applied. *Qualitative Methods* express changes in the form of characteristics which are described through assessments. Consequently, these characteristics are graded and often mapped to scales. Identified *Effect* dimensions which are suitable to be assessed with *Qualitative Indicators* are *Human Behaviour*, *Environment*, *Health*, *Security* and *Privacy*, *Social Gap/ Accessibility* and *Human Work*. Within the analysed literature, two methods of *Qualitative Methods* were identified. Bonilla et al. (2018) utilise a methodology which views sustainability as a predefined, ideal state. The impact of certain activities on sustainability is consequently measured by the perceived change of distance towards that ideal state. A particular activity is classified as beneficial for sustainability if the distance to the ideal sustainable state is decreased, while an increase of distance is rated as detrimental. Comparable to this approach is the methodology of *Comparative Analysis*, for example, used by Arshad et al. (2017). This method utilises a set of characteristics for specific solutions or states. These are compared to reveal the most beneficial option for a particular objective.

To examine a specific impact on the sustainability of IoT, appropriate indicators should be considered on an individual basis. Aspects which should be included in this consideration are the targeted element of change, influence factors, location, timeframe, measurement units or reference values/states, reliability of measurements, causality and feasibility (Church and Rogers, 2006).

4.3 Solutions, Concepts and Paradigms

This section synthesises the previously described aspects to assess the sustainability of highly discussed IoT, or IoT-enabled, solutions. It is divided into the examination of IoT deployments which affect sustainability aspects by utilisation of IoT (section 4.3.1) and the presentation of methods, solutions and advancements aiming to increase the sustainability of IoT technology itself (section 4.3.2). Both sections are essential in order to answer RQ2.3 and RQ3.2. Section 4.3.1, focusing on *IoT4Sus*, examines visions and technologies, which are enabled by the deployment of IoT technology, regarding their impacts on the previously described dimensions of sustainability (section 4.2.2). Subsequently, section 4.3.2, concentrating on *Sus4IoT*, discusses solutions to enhance the sustainability of IoT itself, referring to *Challenges*.

4.3.1 IoT for sustainability (IoT4Sus)

This first section of the examination of solutions and services focuses on the sustainability of IoT deployments. Although the primary objective of some presented visions and solutions is not the enhancement of sustainability aspects, they were found to offer opportunities and threats which influence previously described characteristics of sustainability. Furthermore, the presented concepts are highly discussed in the context of IoT and are partially already existing, which emphasises the need to assess them regarding sustainability. In order to be included, IoT must occupy an indispensable or revolutionising role within the concept. Identified visions and solutions which were found to fit the category of *IoT4Sus* are *Smart Traffic/ Vehicles, Smart Homes/ Buildings*, *Smart Grids, Smart Healthcare, Smart Meters, Smart Agriculture/ Farming, Circular Economy, Environmental Monitoring, Smart Factories, Smart Logistics* and *Smart Cities.* In the following, these concepts are explained and examined regarding their impacts on sustainability. To systematically display these concepts, the examination follows the ensuing pattern. Firstly, the particular concept is defined to clarify its shape and characteristic. Subsequently, IoT features of the concept are presented. These features enable applications, which are provided and briefly described following the features. Consequently, the *Effects* on sustainability are described and discussed. *Effects* in the area of *IoT4Sus* relate to the in section 3.2.2 introduced impact classification of *Enabling Impacts*, as they are realised through the application and utilisation of IoT. Furthermore, associated *Challenges* are provided. Finally, the respective concept is mapped to matching *SDGs*. Table 4.1 provides an overview of the analysed literature alongside described concepts.

Table 4.1: Overview of analysed literature and respective IoT4Sus concepts (own listing)

Reference/ Concept	Smart Traffic/ Vehicles	Smart Homes/ Buildings	Smart Grids	Smart Healthcare	Smart Meters	Smart Agriculture/ Farming	Circular Economy	Environmental Monitoring	Smart Factories	Smart Logistics	Smart Cities
(Wang et al., 2013)	●										●
(Shaikh et al., 2015)	●	●	●	●	●	●	●	●	●	●	●
(Bibri, 2018)	●	●	●		●			●		●	●
(Davidsson et al., 2016)	●										
(Gilart-Iglesias et al., 2015)	●										●
(Gružauskas, Baskutis and Navickas, 2018)	●									●	
(Baek and Park, 2015)	●		●	●		●	●	●			
(Liu et al., 2019)	●									●	
(Maksimovic, 2017)	●	●	●		●		●				●
(Nonnecke, Bruch and Crittenden, 2016)	●	●	●		●						
(Anawar et al., 2018)	●		●								●
(Behrendt, 2019)	●										●
(Zhu et al., 2015)		●	●	●					●		●
(Pan et al., 2015)		●	●								
(Chen et al., 2017)		●				●					
(Kolstad et al., 2018)		●					●				
(Rivas-Sánchez, Moreno-Pérez and Roldán-Cañas, 2019)		●				●					●
(Wang, 2014)		●									
(Arshad et al., 2017)		●		●	●					●	●
(Bates and Friday, 2017)		●									●

Reference/ Concept	Smart Traffic/ Vehicles	Smart Homes/ Buildings	Smart Grids	Smart Healthcare	Smart Meters	Smart Agriculture/ Farming	Circular Economy	Environmental Monitoring	Smart Factories	Smart Logistics	Smart Cities
(Yang et al., 2017)		●				●					
(Zarei, Mohammadian and Ghasemi, 2016)		●		●						●	
(Liu et al., 2018)		●				●					
(Park et al., 2015)		●									
(Mylonas et al., 2018)		●									
(Sembroiz et al., 2018)		●									
(WEF, 2018)		●									
(Bonilla et al., 2018)			●				●		●		
(Li, Darema and Chang, 2017)			●	●				●			
(Islam et al., 2015)				●							
(Shafique et al., 2018)				●							
(Chui et al., 2017)				●							
(Garrity, 2015)				●		●		●			
(Anjum et al., 2018)				●							●
(Sodhro et al., 2018)				●							
(Popli, Jha and Jain, 2019)				●		●					
(Latif et al., 2017)				●							
(Orazi et al., 2018)					●	●	●	●			
(Dupont et al., 2018)						●	●				●
(Brundage et al., 2018)							●	●			
(Bressanelli et al., 2018)							●				
(Alcayaga, Wiener and Hansen, 2019)							●				
(Marques et al., 2019)							●				●

Reference/ Concept	Smart Traffic/ Vehicles	Smart Homes/ Buildings	Smart Grids	Smart Healthcare	Smart Meters	Smart Agriculture/ Farming	Circular Economy	Environmental Monitoring	Smart Factories	Smart Logistics	Smart Cities
(Bellavista, Giannelli and Zamagna, 2017)								●			●
(Birkel et al., 2019)									●		
(Zhang, Wang and Liu, 2018)									●		
(Müller and Voigt, 2018)									●	●	
(Bologa et al., 2017)									●		
(Nagy et al., 2018)									●		
(Garrido-Hidalgo et al., 2018)									●		
(Beier, Niehoff and Xue, 2018)									●		
(Verdouw et al., 2018)										●	
(Tran-Dang and Kim, 2018)										●	
(Zhao et al., 2016)											●
(Farhan et al., 2018)											●
(Deakin and Reid, 2018)											●
(Dong et al., 2016)											●
(Andión et al., 2018)											●

4.3.1.1 Smart Traffic/ Vehicles

Definition

Smart Traffic describes a traffic system, which autonomously and efficiently controls traffic flows based on automatically gathered data. In part, the acquisition of the required data is executed by *Smart Vehicles*. Cars, trains, buses, bicycles and people travelling with those are equipped with devices, tags, sensors and actuators which log data and send information to traffic control sites. In addition, parts of traffic infrastructure, such as roads, are equipped with sensors (Shaikh et al., 2015). The increasing amount of data generated in this context is emphasised by the fact that in the first quarter of 2016, more cars than phones were newly connected to US mobile networks (Behrendt, 2019).

IoT features

As already mentioned within the definition, things, such as cars, bicycles and roads, are equipped with sensors and furthermore, transmit the acquired data to different actors like traffic control sites or vehicle manufacturers. The acquired data is processed and used to offer a set of services for users and institutions. Furthermore, in the case of autonomous traffic control, actuators are triggered based on the gathered data.

Applications

- Smart Parking: Smart Parking systems aim to increase the efficiency of parking activities through IoT technologies by reducing search activities. Therefore, such systems contribute to the reduction of air pollution, fuel waste and driver frustration (Idris et al., 2009).
- Smart Traffic Flow Management: Smart Traffic Flow Management is realised through vehicle-to-vehicle and vehicle-to-infrastructure communication, which is enabled by IoT. It aims to enhance the efficiency of traffic flows and thus reducing congestions and associated unnecessary emissions and fuel consumptions. Therefore, such systems use, for example, smart traffic lights and signals (Shaikh et al., 2015).
- Autonomous Vehicles: Vehicles equipped with sensors, cameras, GPS and wireless communication are able to drive without the need for human interaction. They relate to road assistance and safety and aim to increase the efficiency of movement. Through vehicle-to-vehicle communication, it is possible to build platoons of vehicles, where vehicles follow one another closely to reduce air resistance and thus fuel consumption and GHG emissions (Nonnecke, Bruch and Crittenden, 2016).
- Infrastructure Monitoring: The monitoring of critical urban infrastructure, such as bridges, roads and tunnels, through embedded IoT sensors enables early reactions to hazardous states regarding static and condition. This enhances security and decreases maintenance costs. (Gubbi et al., 2013).
- Road Assistance and Safety: The application within road assistance and safety relates to *Smart Vehicles* and describes IoT applications which monitor the movement of a vehicle within its surrounding. Through vehicle-to-vehicle communication, information about the traffic ahead, approaching vehicles or the possibility of a collision are gathered and processed to enhance the safety of travellers and pedestrians (Baek and Park, 2015). Furthermore, the monitoring of the condition and

structural health of vehicles enhances safety through early warnings in case of hazardous conditions (Li, Darema and Chang, 2017).

- Smart Traffic Lights and Signals: The application of IoT actuators within traffic lights and signals is a part of Smart Traffic Flow Management. Based on the processing of traffic data, intelligent decisions are made and individual instructions are given to traffic lights and signals automatically. This dynamic adjustment contributes to the reduction of congestions and accidents (Bibri, 2018).
- Traveller Information: Information services for travellers aim to provide data for users which enables them to make informed choices. Such information can relate to available transport options, prices, accessibility, average duration and environmental impact of options. The immediate comparison across several transport options is believed to enhance the attractiveness of public transport. This reduces the number of cars, and thus fuel consumption and GHG emissions (Davidsson et al., 2016).
- *Smart Logistics*: *Smart Logistics* represent an area of *Smart Traffic/ Vehicles*. Due to the detailed explanation of *Smart Logistics* in section 4.3.1.10, it is neglected at this point.
- Sharing Economy: Shared mobility technologies, like car-sharing or bike-sharing, are related to a reduction of vehicle numbers and an increase in vehicle utilisation. IoT characteristics are able to provide detailed information to customers regarding the location, condition and cost of available vehicles. The access to real-time information and booking for available shared mobility possibilities increases the usability of such concepts, and thus decreases fuel consumption, GHG emissions and amount of vehicles (Nonnecke, Bruch and Crittenden, 2016).

Effects

The associated *Effects* on sustainability within the analysed literature are consistently positive. 36.17% of the mentioned impacts describe a reduction of *GHG Emissions*. The decrease of *Resource Consumption*, especially fuel, is another positive effect on sustainability and ranks second among effects with a share of 17.02%. The third most described effect is represented by a positive impact on *Economy/ Costs* with a frequency of 12.77%. *Security* (10.64%), *Human Behaviour* (8.51%) and *Energy Consumption* (6.38%) are also mentioned as sustainability dimensions which are positively influenced by *Smart Traffic and Vehicles*. Furthermore, positive impacts concerning *Amounts of Waste*, *Health* and *Social Gap/ Accessibility* are described, whereas those *Effects* are just infrequently stated, accounting for 2.13% of associated impacts each.

Challenges

Identified *Challenges* in the realm of *Smart Traffic/ Vehicles* are *Financial Requirements*, *Interoperability*, *Network Coverage*, *Rights/ Law/ Politics* and *Security*/ *Privacy*.

Related SDGs

In terms of the previously described *Sustainable Development Goals* (section 3.2.1), the concept of *Smart Traffic and Vehicles* can contribute to *SDG11 – Sustainable cities and communities* and *SDG13 – Climate action.*

4.3.1.2 Smart Homes/ Buildings

Definition

A *Smart Home* or *Building* is a home environment which is equipped with numerous sensors and actuators, which are communicating with each other and networks outside of the home/ building (Sembroiz et al., 2018). This concept strongly relates to the remote and automatic monitoring and operating of home appliances like air conditioning, heating and computers (Arshad et al., 2017). Reasons for the deployment of *Smart Home* technologies are especially the reduction of energy consumption and associated costs as well as the enhancement of life quality (Shaikh et al., 2015).

IoT features

IoT features in the area of *Smart Homes and Buildings* are represented by the equipment of home appliances with sensors, actuators and communication possibilities. This enables users to remotely monitor and control different aspects within their home environment, such as lighting, temperature and energy consumption (Wang, 2014). Furthermore, some home devices communicate with specific institutions or organisations. An example is the previously described Smart Fridge, which triggers grocery orders in case their stock is running low (section 3.1).

Applications

- *Smart Home* Devices: A Smart Fridge represents an example of *Smart Home* Devices. Such a device is equipped with, to an IoT system connected, sensors or actuators and relates to the other two application areas, home automation and *Smart Metering*. Almost all home appliances can be smart, for example, microwaves, ovens and air conditioners (Zhu et al., 2015). Smart devices are used to either monitor their usage and energy consumption, control them remotely or both. Furthermore, smart home devices are utilised in the area of assisted living, for example, to automatically trigger emergency calls in case they register a hazardous event.
- Home Automation: Home Automation describes the automatic control of smart devices. Thereby, the automatic adjustment follows rules which are defined by users or achieved through data analysation (Bibri, 2018). An example of Home Automation is location-based automated and networked energy control for home appliances (Pan et al., 2015).
- *Smart Meters*: *Smart Meters* are an essential part of *Smart Home* and *Building* solutions as they sense and communicate the consumption of resources like energy and water (Sembroiz et al., 2018). However, *Smart Meters* are detailly explained in section 4.3.1.5, and thus neglected at this point.

Effects

Just as in the case with *Smart Traffic*, *Smart Home*s are described continuously as positive for sustainability. Although privacy concerns are mentioned, those are stated as hypothetical threats, not as immediate consequences. In terms of immediate positive *Effects*, *Energy Consumption* is accountable for a large share of associated impacts (47.37%). Furthermore, *Smart Homes and Buildings* contribute to *Human Behaviour*, which represents 15.79% of *Effect* mentions. Decreases in operational *Costs* are also strongly connected to this concept (10.53%). Further positive *Effects* are mentioned regarding *Health*

(8.77%), *Environment* (7.02%) and *GHG Emissions* (7.02%). A loose association exists with *Water Consumption* and *Amount of Waste*, which account for 1.75% of mentions each.

Challenges

Smart Homes and Buildings are especially relevant to the *Challenge* of *Security and Privacy* due to the comprehensive and detailed monitoring of residents and home appliances.

Related SDGs

The concept of *Smart Homes and Buildings* contributes to *SDG3 – Good health and well-being, SDG11 – Sustainable cities and communities* and *SDG13 – Climate action.*

4.3.1.3 Smart Grids

Definition

Smart Grids are power grids that enable real-time decisions regarding the choice of energy sources. Based on flow monitoring, *Smart Grids* allow to automatically switch to renewable energy sources depending on the availability and real-time costs of such (Burritt and Christ, 2016). Furthermore, *Smart Grids* can react flexibly to power fluctuations which are associated with renewable energy sources. The integration of customer consumption data enables such grids to enhance the balance between energy consumption and production (Li, Darema and Chang, 2017).

IoT features

In order to achieve the targeted functionality, *Smart Grids* utilise an extensive network of *Smart Meters*, actuators and sensors along with the communication and processing of generated data. The real-time monitoring of consumption and available power production options provides the basis for decisions regarding the composition of power supply. These decisions trigger actuators within the network to increase or reduce the power supply of particular sources (Maksimovic, 2017).

Applications

- *Smart Meters*: *Smart Meters* are an indispensable component of *Smart Grids*. They monitor and communicate the energy flow from different sources, like windmills and solar plants. Furthermore, *Smart Meters* exhibit the current demand for energy and provide valuable information for energy providers. *Smart Meters* are explained in detail in section 4.3.1.5.
- Smart Devices: The integration of smart objects into the *Smart Grid* network poses another essential component. Smart objects are a hypernym and include, for example, *Smart Meters*, consumer appliances, infrastructure and generation machinery, equipped with IoT features (Shaikh et al., 2015).
- Power Automation: Power Automation describes the automatic decision making of *Smart Grids* regarding the amount of power supply and from which sources to obtain the required energy. The real-time collection and analysis of enormous data amounts from power sources and consumer devices enables the automatic compilation of the most efficient energy mix regarding costs and sustainability (Bibri, 2018).

Effects

Within the literature, *Smart Grids* are solely related to positive impacts regarding sustainability. The results emphasise the fundamental aim of this concept. 42.86% of *Effect* mentions relate to a decrease in *Energy Consumption*. In addition, reduced *Resource Consumption*, resulting from the usage of fossil fuels to generate energy, is the second most described effect, accounting for 28.57%. Lower *GHG Emissions* are also associated with *Smart Grids* (14.29%). Furthermore, enhancements in the dimensions of *Amount of Waste*, *Environment* and *Human Behaviour* are mentioned with a share of 4.76% each.

Challenges

The concept of *Smart Grids* exhibits *Challenges* regarding *Financial Requirements* and *Interoperability*. Those *Challenges* origin from the massive investments which are required to transform a large-scale grid into a *Smart Grid* and the incorporation of numerous technologies.

Related SDGs

Smart Grids contribute to *SDG7 – Affordable and clean energy, SDG12 – Responsible consumption and production* and *SDG13 – Climate action*.

4.3.1.4 Smart Healthcare

Definition

The vision of *Smart Healthcare* aims to ameliorate health through the prevention, treatment and examination of physical damage, mental damage, illness, injury and disease with the support of ICT (Chui et al., 2017). Through the deployment of IoT technology, doctors, clinics and health insurances can remotely monitor the physiological conditions of patients in real-time and trigger suitable actions (Zhu et al., 2015).

IoT features

The concept of *Smart Healthcare* utilises several IoT functionalities. Patients are equipped with smart devices, such as wearables, which gather relevant data in the context of patient's health. Smart sensors and devices attached to a patient build a Wireless Body Area Network (WBAN) (Popli, Jha and Jain, 2019). Data gathered within the WBAN is communicated with institutions or services, such as health facilities or recommendation services to assess the patient's health. Consequently, suitable actions are triggered, for example, the adjustment of medication or useful recommendations to enhance the health status (Sodhro et al., 2018).

Applications

- Remote Disease Diagnosis and Treatment: One promising application area for *Smart Healthcare* is represented by the possibility of remote diagnosis and treatment. Doctors can remotely monitor certain physical conditions without the need for direct contact with the patient. Data, gathered by wearables and sensors, exhibits relevant information regarding hypothetical diseases. Furthermore, the diagnosis of certain diseases can be executed automatically. As a result of this, doctors can enhance the efficiency and quality of health services, while comfort and treatment time for patients is improved (Sodhro et al., 2018). IoT technology also facilitates remote treatment of diseases, for example, medication adjustments or even remote surgery (Rohokale, Prasad and Prasad, 2011).

- Smart Medical Devices: Smart devices applicated in the context of healthcare are intended for the gathering of physical characteristics, which are relevant to assess the patient's health condition. Such characteristics are, for example, glucose level, activity, blood pressure, body temperature and heart rate. Respective devices are smartphones or specific wearables (Islam et al., 2015). The further progressing of technology even allows to place sensors within the patient's body, for example embedded in pacemakers (Latif et al., 2017).
- Health Supporting Information Services: Supporting information services are automated services which provide useful information to users regarding enhancement possibilities of their health. The required data is obtained through smart devices and processed to provide individual recommendations, such as activities which should be taken or avoided. Therefore, such services raise the awareness of users concerning their health status (Garrity, 2015).
- Ambient Assisted Living: Ambient Assisted Living describes the application of IoT in order to offer specialised services to older people. The utilisation of IoT allows an extension of individual, autonomous life for those people and assists in case of problems (Islam et al., 2015).
- Medication Management: Medication Management is meant to enhance the noncompliance problem in medication. Through smart medication packing the intake and combination of medication is monitored, and misuse is avoided. An example of medication management is a box which contains several medications. The provision of specific medication is controlled by a doctor, who is able to monitor intake and to remotely adjust the combination. (Islam et al., 2015).
- Smart Wheelchair: Smart Wheelchairs represent a part of smart medical devices and a part of *Smart Vehicles* (section 4.3.1.1) at the same time. IoT technology is used to monitor the vitals of the individual user, contributing to remote disease diagnosis and treatment. Furthermore, Smart Wheelchairs gather data about the user's surroundings and movements to assess the accessibility of a location (Islam et al., 2015).
- Public Health Surveillance: IoT technology enhances the government's assessment of public health, which improves the ability of early notifications in case of health risks. This is realised through massive data processing from different sources. For example, a commencing epidemic can be revealed by data regarding individual behaviour changes, sickness notes, online inquiries for medical information and specific sound patterns like coughing. The monitoring and processing of such indicators can be used to generate alerts in case of disease outbreaks (Li, Darema and Chang, 2017).

Effects

Within the literature, *Smart Healthcare* is continuously associated with positive *Effects* regarding sustainability aspects. Although threats are mentioned in terms of privacy, those are described as hypothetical and avoidable. *Smart Healthcare* exhibits strong positive impacts on the dimension of *Health*, which account for 44.44% of *Effect* descriptions. Through the possibility of remote and early diagnosis, positive impacts on the *Economy/ Costs* category are realised (22.22%). Furthermore, remote health monitoring and treatment enhances the *Accessibility* of health services, in particular for older people and people who live in rural areas. These *Effects* account for 16.67% of mentions. Positive impacts on *Human Behaviour* represent 16.67% of associated implications and are realised through the utilisation of health-supporting information services.

Challenges

Smart Healthcare is related to several *Challenges*. *Power Demand* of smart medical devices, especially within a patient's body poses one of them (Sodhro et al., 2018). *Financial Requirements*, needed to implement large-scale *Smart Healthcare* solutions, are also mentioned. *Human Behaviour* and adaption of this technology, as well as the *Network Coverage* of rural areas, might hamper the performance of this concept also. Furthermore, the monitoring and transmission of sensitive personal data require high standards regarding *Security and Privacy* (Islam et al., 2015).

Related SDGs

The associated *Effects* emphasise the suitability of *Smart Healthcare* to support *SDG3 – Good health and well-being*. Furthermore, *SDG10 – Reduced inequalities* is undergirded through the enhancement regarding the accessibility of health services.

4.3.1.5 Smart Meters

Definition

Smart Meters are meters which are equipped with communication technologies. They are used to provide homeowners with real-time feedback about resource consumption like water, energy, gas and heat, and thus raise awareness. *Smart Meter* data is also used to automatically control and minimise consumption (McKerracher and Torriti, 2013). Furthermore, data is transmitted to utility companies for billing purposes and consumption monitoring, which is utilised in the context of *Smart Grids* (Fan et al., 2010).

IoT features

The incorporation of IoT technologies into meters is represented by the automatic communication of sensed data with other devices and institutions. Data is transferred and processed in order to reveal real-time consumption to residents or utility companies. Moreover, consumption data is communicated with other devices, such as actuators, to trigger specific control activities (Maksimovic, 2017).

Applications

- Resource Consumption Monitoring: *Smart Meters* are incorporated into wirings, pipes or smart devices to measure the resource flow. Consequently, the raised data is transmitted using wireless communication technologies (Arshad et al., 2017). The granularity of data, in case of energy consumption, can reach from a whole district to a single bulb, depending on the objective (Bibri, 2018). Gathered data and respective analytics are, for example, utilised to adjust the consumption patterns of residents and reveal high consumption devices. Furthermore, measurement results are used to reveal leakages within supply networks, such as water pipes (Nonnecke, Bruch and Crittenden, 2016).

- *Smart Grid*: The previously described concept of the *Smart Grid* (section 4.3.1.3) utilises *Smart Meters* to obtain data about real-time energy consumption. This data is utilised to adjust the power supply and to decide which sources can and should be used to satisfy the demand.
- *Smart Homes/ Buildings*: As explained in section 4.3.1.2, *Smart Homes and Buildings* employ *Smart Meters* for different purposes, such as home automation.

Effects

Associated *Effects* regarding *Smart Meters* mostly relate to enhancements in *Energy Consumption* and *Human Behaviour*, each accounting for 31.25% of described impacts. These outcomes are realised through increased awareness, adjusted consumption patterns and automated savings. The decrease of *Energy-*, *Water-* and *Resource Consumption* constitutes positive effects in the area of *Costs*, which represent 18.75% of mentioned implications. Consequently, decreases in *Water Consumption* (12.50%) and *Resource Consumption* (6.25%) are described, although not as numerous as reductions in *Energy Consumption*.

Challenges

In terms of *Challenges*, *Smart Meters* are related to *Interoperability* due to the different technologies and utilisations.

Related SDGs

Smart Meters support *SDG12 – Responsible consumption and production* and *SDG13 – Climate action*. Furthermore, they indirectly contribute to *SDGs* associated with *Smart Homes/ Buildings* and *Smart Grids*.

4.3.1.6 Smart Agriculture/ Farming

Definition

The deployment of IoT technology in the area of agriculture and farming is called *Smart Agriculture* or *Smart Farming*. This concept aims to increase the productivity and quality of crops and animal farming by the utilisation of IoT. The enhancement of productivity is necessary to ensure the nutrition of the growing human population, which is believed to reach 9.8 billion by 2050 (Dupont et al., 2018). Furthermore, *Smart Agriculture* and *Smart Farming* are envisioned to improve the storage and distribution of food (TongKe, 2013).

IoT features

Smart Agriculture is associated with the continuous monitoring of several influencing factors for the quality and productivity of crops and animal farming. Such influence factors are, for example, represented by weather and soil moisture. Through monitoring, gained data is transmitted and processed to assess the condition and analyse options for actions. Furthermore, the required actions, like fertilising or irrigation, are executed automatically based on sensed data (Tzounis et al., 2017).

Applications

- Urban Gardening: Urban Gardening refers to the efficient cultivation of plants in urban areas. Besides the objective of food supply, this application is connected to cleaner air, positive psychological effects and aesthetic improvements (Rivas-Sánchez, Moreno-Pérez and Roldán-Cañas, 2019). Due to constrained resources like space, soil and direct sunlight within urban areas, this concept requires an efficient utilisation (Chen et al., 2017).
- Smart Input Management: The above-mentioned efficient utilisation of resources is realised through Smart Input Management. Inputs in the context of agriculture and farming are for example water, fertiliser, insecticides and forage. Through the real-time monitoring and analysis of conditions required quantities of those inputs can be determined precisely. As a result, productivity is maximised, while inputs are minimised (Dupont et al., 2018).
- *Environmental Monitoring*: This application builds the foundation of required data for *Smart Agriculture/ Farming* and refers to the comprehensive and accurate observation of environmental circumstances like temperature, soil moisture and health of livestock. This application is examined further in section 4.3.1.8.
- Food Supply Chain Monitoring: In order to assure food safety and quality, the monitoring of food along the whole supply chain, from grower to customer, is a viable instrument. In recent years customers have shown increasing interest regarding the origin, processing and transportation of their food. Furthermore, specific products require special conditions, like closed cooling chains. These demands can be satisfied with the incorporation of IoT technologies, for example, RFID tags, into the food supply chain (Tzounis et al., 2017).
- Autonomous Vehicles: The previously described application of IoT within vehicles supports the further automation of agriculture and farming and enhances efficiency. For example, Autonomous Vehicles can support the seeding and harvesting of crops based on *Environmental Monitoring*, and thus with the right timing, at the right place with the right conditions (Tzounis et al., 2017).

Effects

The concept of *Smart Agriculture and Farming* is related to positive and negative *Effects* regarding sustainability. Adverse impacts, accounting for 6.06% of mentions, occur in the dimension of the *Social Gap* and originate in the high financial expenditures, which are required to realise this concept. While developed countries can increase their agricultural productivity further through this technology, developing countries often cannot afford to invest the required sums (Dupont et al., 2018). Positive *Effects* associated with this concept are mostly described in the area of *Water Consumption* (30.30%). The enhanced availability of information regarding the food supply chain results in improved *Health* (24.24%). This is realised through more consciousness of food consumption, which also results in improved *Human Behaviour* (12.12%). *Environment* and *Economy/ Costs* are also influenced positively by *Smart Agriculture/ Farming*, accounting for 9.09% each. In addition, decreases in *Resource Consumption* (3.03%), *GHG Emissions* (3.03%) and *Energy Consumption* (3.03%) are associated with this concept.

Challenges

Smart Agriculture and Farming are related to high initial *Financial Requirements* (Dupont et al., 2018). In addition, these expenditures amplify the *Challenge* of *Collective Inclusion*. Furthermore, rural areas in which agriculture and farming are mostly located often lack appropriate *Network Coverage*.

Related SDGs

In terms of *Sustainable Development Goals* this vision supports *SDG2 – Zero hunger, SDG3 – Good health and well-being* and *SDG12 – Responsible consumption and production.* Through the associated increment of the social divide, it might hamper *SDG10 – Reduced inequalities.*

4.3.1.7 Circular Economy

Definition

The vision of a *Circular Economy* is defined as a system which is restorative and regenerative by design. It aims to maintain products, components and materials at their highest utility and value (Geissdoerfer et al., 2017). Consequently, this concept contrasts linear economy. The linear process consists of the manufacturing of products from raw materials, the sale and usage, and following, the disposal as waste (Bressanelli et al., 2018). The objective is a decoupling of economic growth from environmental losses and resource extraction through a closed loop of reuse, remanufacturing and recycling (Braungart, McDonough and Bollinger, 2007).

IoT features

IoT technology offers suitable functionalities to realise the vision of a *Circular Economy*. The application of sensors turns products into smart connected ones. This enables monitoring of a product's status, usage, location and condition (Geissdoerfer et al., 2017). Also, certain parts of a product, like firmware, maybe upgraded remotely in order to enhance lifespan. Components of a product, which are equipped with sensors like RFID, can be traced. This tracking contributes to the collection of end-of-life products and waste management, and thus the possibility to reuse, remanufacture and recycle (Bressanelli et al., 2018).

Applications

- Material Tracking: IoT enables the tracking of materials in order to achieve closed resource loops. Products or specific components can be equipped with RFID tags and other sensors. Consequently, products can be collected and recycled appropriately. Furthermore, it is possible to prevent inappropriate disposal through backtracking of materials and appropriate penalties for polluters (Bressanelli et al., 2018).
- Product Monitoring: Closely related to the application of Material Tracking is Product Monitoring. Through the knowledge about status, location, condition and usage of products sharing solutions, which maximise the utilisation rate, are enabled. Furthermore, customers can assess the condition of their product and take respective actions regarding maintenance (Bressanelli et al., 2018).

- Product Management: Product Management refers to manufacturer-sided Product Monitoring. The acquisition of data regarding usage patterns allows companies to enhance their products by adjusting to the real deployment and eliminating weak spots, for example, through remote software upgrades. Besides, they can provide customers with individual information to prevent premature obsolescence. Manufacturer-sided monitoring also enables individual billing and simplifies the maintenance and refurbishment of products (Alcayaga, Wiener and Hansen, 2019).
- Smart Waste: Smart Waste is strongly connected with Material Tracking and thus appropriate disposal and maximisation of recyclability. Furthermore, Smart Waste Management utilises smart devices, such as smart waste bins, for the assessment of waste amounts and their composition. The application of IoT technology within waste management enhances the efficiency of disposal and recycling operations by data acquisition and automation (Marques et al., 2019).

Effects

The deployment of IoT to support the concept of a *Circular Economy* is described alongside several positive *Effects* within the analysed literature. Positive implications are especially realised in terms of *Amount of Waste* by the reuse of discarded materials (33.33%). The resulting decrease of *Resource Consumption* accounts for 25.00% of mentioned implications. Recycling of materials and increased waste management also positively influences the dimension of *Economy and Costs* (16.67%). Furthermore, the *Circular Economy*, supported by IoT technology, is linked with the reduction of *Environmental Destruction* (8.33%) and harming *Human Behaviour* (8.33%). Enhancements regarding *GHG Emissions* (4.17%) and *Health* (4.17%) are also mentioned.

Challenges

Equipping products and materials with comprehensive IoT technology results in increased *Power Demand* of products (Bressanelli et al., 2018).

Related SDGs

The *Circular Economy* can support *SDG12 – Responsible consumption and production*. Furthermore, through the reduction of required hazardous resource extraction activities, it also contributes to *SDG15 – Life on land*.

4.3.1.8 Environmental Monitoring

Definition

Environmental Monitoring describes the process of data acquisition regarding critical environmental aspects, such as air quality, weather, soil condition and water quality. The assessment of environmental factors is advantageous for several uses, such as agriculture, crisis detection and environmental protection (Bibri, 2018).

IoT features

IoT technology enhances the granularity and simplifies the acquisition of environmental data. Through automatic sensing and communication, users can remotely monitor different characteristics real-time

(Shaikh et al., 2015). Furthermore, the merging and processing of different environmental data is used to trigger automated actions, such as warnings in case of hazardous weather conditions (Li, Darema and Chang, 2017). The installation of smart devices into different environments replaces the need for manual observations and thus raises efficiency and extends possibilities regarding the scope and period of monitoring (Bellavista, Giannelli and Zamagna, 2017).

Applications

In the domain of *Environmental Monitoring,* numerous applications with a wide range of objectives exist. Per definition, *Environmental Monitoring* covers a broad scope of data acquisition activities and constitutes a part of other concepts, such as *Smart Traffic/ Vehicles* or *Smart Agriculture* (Baek and Park, 2015). Therefore, this thesis only provides exemplary applications of *Environmental Monitoring*.

- Air Quality Monitoring: Applications of IoT technology, matching the definition of *Environmental Monitoring*, are found in the domain of air quality assessment. Sensors which measure the composition of atmospheric gases at different locations can be used to identify hotspots of pollution. For instance, those insights are utilised to adjust the traffic flow within the cities to avoid hazardous air pollution (Bibri, 2018).
- Weather Monitoring: Weather Monitoring refers to the collection of data regarding different aspects which impact weather conditions. Precise assessment and prediction of weather is, for instance, utilised in the domain of agriculture. Furthermore, weather forecasts can reveal upcoming hazardous events, like hurricanes. In case of such an event, residents are alerted and enabled to prepare and protect themselves (Li, Darema and Chang, 2017).
- Wildlife Monitoring: Remote monitoring is also utilised in order to assess the conditions of wildlife populations. Acquired data is central regarding the protection of animal populations as it reveals population numbers and possible threats like diseases or poaching. The utilisation of smart devices to acquire particular data has another significant advantage over manual observation, as the penetration of humans into wildlife habitats often scares away wild animals or changes their behaviour (Shaikh et al., 2015).
- *Smart Agriculture*: *Environmental Monitoring* constitutes an essential part of the previously described *Smart Agriculture* (section 4.3.1.6). Relevant environmental parameters in this context are the weather, soil condition and presence of pests (Tzounis et al., 2017).

Effects

As diverse as its application areas are the described *Effects* within the analysed literature, although uniformly positive. The sturdiest connections are found in the dimensions of *Environment* and *Human Behaviour* (23.53% each). Furthermore, *Environmental Monitoring* contributes to *Health* (11,76%) and *Security* (11,76%) and decreases *Resource Consumption* (11.76%). Additional positive *Effects* are described in reductions of *GHG Emissions* (5.88%), *Energy Consumption* (5.88%) and *Water Consumption* (5.88%).

Challenges

Challenges for this concept arise from the increase of *Power Demand* by the deployment of comprehensive sensing infrastructure. Furthermore, devices are often installed in rural areas without any access to electricity. The *Network Coverage* of such rural areas represents another challenge for *Environmental Monitoring* (Baek and Park, 2015).

Related SDGs

The broad scope of *Environmental Monitoring* utilisation is also represented by the associated *SDGs*. Potential contributions relate to *SDG2 – Zero hunger, SDG3 – Good health and well-being, SDG6 – Clean water and sanitation, SDG13 – Climate action, SDG14 – Life below water* and *SDG15 – Life on land*.

4.3.1.9 Smart Factories

Definition

Smart Factories, also referred to as the Industrial Internet of Things (IIoT), describes the integration of Internet of Things technologies into the industrial value creation processes. This vision aims real-time, intelligent networking of people, machines and objects as well as information and communication systems to dynamically control complex systems and increase productivity and costs (Kiel et al., 2017). This internal networking is complemented with external networking through the whole supply chain (Bonilla et al., 2018).

IoT features

The above-described vision requires a high level of interconnection within value creation processes. IoT technology provides a broad set of functionalities to satisfy these requirements. The combination of smart sensors, devices, actuators, products and wearables alongside appropriate wireless communication technologies supports the realisation of this concept (Beier, Niehoff and Xue, 2018). Additionally, acquired data is analysed and immediately integrated into these networks (Nagy et al., 2018).

Applications

- Industrial Automation: Industrial Automation refers to the increment of automatic data-driven execution of tasks, which formerly required human interaction. Machine operations, functionalities and output rates are automatically controlled and monitored (Zhu et al., 2015). Moreover, the collaboration between automated machines is enhanced by following a data-driven smart scheduling approach. Thereby, a maximum share of value creation is automatically executed by machines. For instance, purchases, manufacturing, and commissioning (Müller and Voigt, 2018).
- Workplace Safety: Where human interaction is indispensable, IoT technology can be used to enhance the safety of workers. Movement of workers is monitored and combined with machine operation data to prevent accidents or immediately stop machines in case of hazardous events. Moreover, vital signs of workers can be monitored to ensure their physical fitness for particular tasks and prevent health risks. IoT technology can also be applicated to enhance human-machine interaction (Garrido-Hidalgo et al., 2018).

- Employee Monitoring: The above-described monitoring of employees can also be utilised for other objectives than security. Monitoring and analysis of movements and executed tasks provide insights regarding the efficiency of employees and enable comparisons reasoned by data (Garrido-Hidalgo et al., 2018)
- Market Research: As described within the applications for the *Circular Economy* (section 4.3.1.7), smart products can be used to gain valuable information about product usage patterns and customer behaviour. This information can be exploited to enhance offered products and services, and thus gain advantages over competitors (Nagy et al., 2018).

Effects

Smart Factories, and thus, the automatic execution of tasks formerly carried out by humans, is related to job losses. The negative impacts regarding the dimension of *Human Work* account for 14.29% among all mentioned effects. In contrast to this negative consequence, *Smart Factories* are strongly associated with benefits for *Economy/ Costs* once the high initial investments amortised (28.57%). This is partly reasoned by decreases in *Energy Consumption*, which represent 19.05% of consequence descriptions. Further decreases are reported regarding *GHG Emissions* (9.52%) and *Resource Consumption* (9.52%). Increasements are identified within the domains of *Human Behaviour* (14.29%) and *Health* (4.76%).

Challenges

Challenges for the realisation of *Smart Factories* are especially posed by the high *Financial Requirements* which are needed to acquire suitable equipment. The acquisition of new machinery makes machines that cannot be upgraded obsolete and generates wastage in case no buyer is found, which amplifies *Waste/ Disposal* (Birkel et al., 2019).

Related SDGs

Smart Factories support *SDG8 – Decent work and economic growth, SDG9 -Industry, innovation and infrastructure* and *SDG12 – Responsible consumption and production*. The support of *SDG8 – Decent work and economic growth* is disputable due to the associated job losses. As already described within the *Effects* (section 4.2.2), job opportunities are rather shifted towards IT-related jobs than being lost.

4.3.1.10 Smart Logistics

Definition

The deployment of IoT technology in supply chain and logistics systems and vehicles is called *Smart Logistics*. Vehicles and products are equipped with identification, sensing and communication technology. Furthermore, delivery routes and logistic systems are monitored and analysed in order to enhance efficiency, pace and transparency of logistic processes. *Smart Logistics* aim to enhance service quality and reduce resource consumption and negative environmental impacts alike (Verdouw et al., 2018).

IoT features

IoT functionalities within this concept are represented by the incorporation of smart sensors into products and vehicles, the monitoring of routes and logistic systems and the respective data analysation processes to enhance the efficiency of logistic processes. The application of IoT thereby creates a network which contains information about manufacturers, suppliers, goods, logistics companies, customers, delivery routes and options and furthermore supply and demand to facilitate efficient, flexible and fast services (Liu et al., 2019).

Applications

- Route and Freight Optimisation: A major opportunity regarding IoT deployments within logistics is represented by the optimisation of routes and cargo. IoT based real-time information of logistics resources and freight is shared among companies in order to build a dynamic freight allocation system. Through the automatic allocation and maximised utilisation of logistics resources in combination with optimised navigation efficiency of services is enhanced and unloaded drives are avoided (Liu et al., 2019). As a result of this, fuel consumption and associated GHG emissions are reduced, and freight costs are decreased. Furthermore, monitoring and automatic cargo allocation avoid wrong deliveries (Müller and Voigt, 2018).
- Quality Management: Smart logistics exhibit quality securing opportunities. Globalisation realised the interconnection of national economies throughout the entire globe, which often results in high distances between production sites and consumer locations. Therefore, long travel distances for perishable goods require special conditions, for instance, a continuous cooling chain. Smart vehicles and product sensors support the monitoring of these conditions, enabling assessments about quality and expiration dates. In case of inappropriate conditions for specific goods, IoT services can alert customers and logistics companies alike to take corresponding actions (Verdouw et al., 2018).
- Autonomous Vehicles: The concept of *Smart Logistics* also incorporates autonomous vehicles, which were described concerning *Smart Traffic and Vehicles* (section 4.3.1.1). Today, Autonomous Vehicles are already utilised within warehouses and execute commissioning and loading tasks (Gružauskas, Baskutis and Navickas, 2018).

Effects

The *Smart Logistics* concept is primarily associated with positive *Effects* originating in efficiency optimisation. Strong ties are described with reductions in *Costs* (29.41%), *GHG Emissions* (26.47%) and *Resource Consumption* (20.59%). The positive consequences regarding *Resource Consumption* and associated emissions result in positive effects on the *Environment*, which account for 11.76% of mentions. Additional positive implications are stated in connection with *Energy Consumption* (5.88%) and *Health* (5.88%).

Challenges

Challenges regarding *Smart Logistics* are posed by the high initial *Financial Requirements* to build the aimed infrastructure and the *Interoperability* regarding such an infrastructure, as many different companies, vehicles and goods should be included. Furthermore, *Network Coverage* poses a challenge for moving vehicles.

Related SDGs

Smart Logistics support the *Sustainable Development Goals SDG8 – Decent work and economic growth*, *SDG9 – Industry, innovation and infrastructure* and *SDG13 – Climate action*.

4.3.1.11 Smart Cities

Definition

A short description of a *Smart City* is a human settlement which utilises previously addressed concepts. It contains a combination of different smart domains like *Smart Traffic and Transportation*, *Smart Homes* and *Smart Healthcare*. Thereby, a *Smart City* aims to offer new and useful services to citizens, companies and public administrations (Zanella et al., 2014). Furthermore, *Smart Cities* employ IoT technology to address challenges like rapid urban growth, increasing energy consumption and air pollution (Anawar et al., 2018).

IoT features

Smart Cities apply the previously mentioned concepts, and thus their IoT functionalities in order to achieve their aim. Citizens, companies and administrations are provided with easy access and interaction with a wide variety of IoT devices. Those include home appliances, surveillance cameras, monitoring sensors, actuators, displays and vehicles. The resulting large network and respective data processing and semantics build the foundation for a set of offered services (Zanella et al., 2014).

Applications

Applications within *Smart Cities* are represented by the previously described concepts and thus not repeatedly described at this point. Especially relevant in the context of *Smart Cities* are *Smart Traffic and Vehicles, Smart Homes/ Buildings*, *Smart Grids*, *Circular Economy*-related Smart Waste Management, *Environmental Monitoring* and *Smart Meters* (Zanella et al., 2014).

Effects

Associated *Effects* regarding *Smart Cities* are continuously positive. Furthermore, the integration of a large variety of services constitutes a broad scope of positive impacts. The most relevant implications, which are mentioned in the analysed literature, are improvements regarding *Energy Consumption* (26.92%) and *GHG Emissions* (26.92%). Positive impacts within the dimensions of *Social Gap/ Accessibility* (11.54%) and *Environment* (11.54%) are also described frequently. Further positive consequences are stated for the dimensions of *Water Consumption*, *Amount of Waste*, *Economy/ Costs*, *Health*, *Human Behaviour* and *Resource Consumption*, each accounting for 3.85%.

Challenges

Challenges of *Smart Cities* strongly relate to previously provided *Challenges* of the contained concepts. A particular *Challenge* of *Smart Cities* is represented by the *Collective Inclusion*. *Smart Cities*, which offer a large variety of innovative services for citizens, are estimated to amplify gentrification due to higher land prices and rents. This poses a threat as low-income residents might get forced out and thus excluded from the opportunities offered by *Smart Cities* (Deakin and Reid, 2018).

Related SDGs

Equally to the formerly described aspects, contributions of *Smart Cities* in terms of *SDGs* are the sum of incorporated concepts. However, *Smart Cities* especially support *SDG11 – Sustainable cities and communities*.

Table 4.2 summarises the described *Effects* of *IoT4Sus* concepts on identified sustainability aspects. A plus thereby implies a positive *Effect*, such as a reduction of *GHG Emissions* or an improvement regarding *Health*. A minus displays negative impacts such as a worsening of *Human Behaviour* or an increase of *Energy Consumption*.

Table 4.2: Effects of IoT4Sus concepts on sustainability aspects (own listing)

Concept / Effect	Energy Consumption	Economy/ Costs	GHG Emissions	Human Behaviour	Resource Consumption	Amount of Waste	Environment	Health	Water Consumption	Security	Social Gap/ Accessibility	Privacy	Human Work
Smart Traffic/ Vehicles	+	+	+	+	+	+		+		+	+		
Smart Homes/ Buildings	+	+	+	+		+	+	+	+				
Smart Grids	+		+	+	+	+	+						
Smart Healthcare		+		+				+			+		
Smart Meters	+	+		+	+				+				
Smart Agriculture/ Farming	+	+	+	+	+		+	+	+		-		
Circular Economy		+	+	+	+	+	+	+					
Environmental Monitoring	+		+	+	+		+	+	+	+			
Smart Factories	+	+	+	+	+			+					-
Smart Logistics	+	+	+		+		+	+					
Smart Cities	+	+	+	+	+	+	+	+	+		+		

4.3.2 Sustainability for IoT (Sus4IoT)

This section concentrates on solutions and advancements which aim to improve sustainability aspects regarding IoT technology itself. Therefore, they provide methods to overcome sustainability issues and *Challenges*, associated with components and operation of IoT technology. *Challenges* relate to the previously described impact classification of *Life-Cycle Impacts* (section 3.2.2). *Sus4IoT* solutions aim to reduce this negatively associated impacts. To be included into this section a method or advancement regarding technology, deployments and operation must provide a significant improvement in one of the previously posed *Challenge* categories (section 4.2.1.2), for instance, *Power Demand* or *Waste/ Disposal*. The analysed literature commonly describes such concepts with the term greening (Shaikh et al., 2015). Respective methods and paradigms which were identified in the analysed literature are *Energy Harvesting, Algorithm Optimisation, Activity Scheduling, Open-Source, Hardware Optimisation, Efficient Routing, Data reduction, Recycling, Retrofitting* and *Crowdsensing*. Furthermore, the paradigm of *Utility Expansion* is suggested, although not discussed in the literature. These concepts are described in the following. To systematically display identified methods, the examination follows the ensuing pattern. Firstly, a definition for the respective solution is given. Secondly, the relevance within IoT is described. Subsequently, different characteristics and application options are provided and briefly explained. Consequently, the sustainability improvements regarding IoT *Challenges* are shown. Table 4.3 provides an overview of the analysed literature alongside described methods and paradigms, as *Utility Expansion* is not discussed in the literature but suggested within this thesis it is neglected in this overview.

Table 4.3: Overview of analysed literature and respective Sus4IoT paradigms (own listing)

Reference/ Paradigm	Energy Harvesting	Algorithm Optimisation	Activity Scheduling	Open-Source	Hardware Optimisation	Efficient Routing	Data Reduction	Recycling	Retrofitting	Crowdsensing
(Zhu et al., 2015)	●	●	●		●	●	●			
(Chen et al., 2014)	●					●				
(Shuja et al., 2017)	●	●	●			●		●		
(Arshad et al., 2017)	●	●	●		●	●	●	●		
(Shaikh et al., 2015)	●							●		
(Shaikh and Zeadally, 2016)	●									
(Zhu et al., 2018)	●		●			●				
(Shafique et al., 2018)	●									
(Kallam et al., 2017)	●	●								
(Nan et al., 2017)	●	●								
(Wang et al., 2017)	●	●								
(Liu and Ansari, 2017)	●					●				
(Maksimovic, 2017)	●		●		●			●		
(Pramanik, Pal and Choudhury, 2019)	●	●	●		●	●		●		●
(Stergiou et al., 2018)		●								
(Bibri, 2018)		●								
(Dupont et al., 2018)		●	●	●	●					
(Li et al., 2017)		●								
(Anjum et al., 2018)		●								
(Wang, Hu and Liu, 2017)		●	●			●				
(Sodhro et al., 2018)		●	●							
(Ismail and Materwala, 2018)		●	●		●					
(Stetsuyk, Maevsky and Maevskaya, 2018)		●								
(Farhan et al., 2018)			●							

Reference/ Paradigm	Energy Harvesting	Algorithm Optimisation	Activity Scheduling	Open-Source	Hardware Optimisation	Efficient Routing	Data Reduction	Recycling	Retrofitting	Crowdsensing
(Huang, Wu and Tang, 2018)			●			●				
(Huang et al., 2018)			●			●	●			
(Popli, Jha and Jain, 2019)			●			●	●			
(Rivas-Sánchez, Moreno-Pérez and Roldán-Cañas, 2019)				●						
(Sas and Neustaedter, 2017)				●				●		
(Mylonas et al., 2018)				●						
(Jara et al., 2014)						●				●
(Sembroiz et al., 2018)						●				
(Wong and Wong, 2016)								●		
(Müller and Voigt, 2018)								●	●	
(Birkel et al., 2019)									●	
(Bates and Friday, 2017)									●	
(Deakin and Reid, 2018)									●	
(Pan et al., 2015)										●

4.3.2.1 Energy Harvesting

Definition

Energy Harvesting describes a mechanism to generate energy from networks ambient resources to provide continuous power supply for a specific sensor node and the overall WSN. The actual utilisation of an environmental source to harvest energy strongly depends on the availability at the respective location and includes sources like kinetic energy, wind energy, thermal energy and solar power (Zhu et al., 2018).

IoT components

This paradigm is especially relevant for WSNs and linked sensor nodes which are located in remote areas without direct access to conventional electricity supply and energy grids. To solve the issue of power availability, sensor nodes mostly incorporate battery power. However, the utilisation of batteries entails several problems and disadvantages. Extreme weather conditions may destroy batteries, which results in chemical leakages and environmental pollution. Furthermore, the charge of batteries is limited, hampering their suitability for sensor nodes which should operate over a long period. *Energy Harvesting* provides the opportunity to continuously power sensor nodes based on available, unlimited environmental resources. Thereby, sensor nodes gain a certain degree of autonomy and independence from human interactions, like the replacement of batteries (Shaikh and Zeadally, 2016).

Application

As previously mentioned the specific utilisation of this method strongly depends on the surroundings of the device which should be powered. Shaikh and Zeadally (2016) provide a comprehensive overview for *Energy Harvesting* sources which may be utilised in WSNs. They distinguish between the ambient environment and external sources. Thus, ambient sources include radio frequency, solar and thermal energy sources. Additionally, wind and hydro flow can be utilised to generate electricity for the operation of sensor nodes. External sources are divided into two subcategories, mechanical and human sources. Mechanical sources contain power generation opportunities through the exploitation of vibration, pressure and stress-strain. Human sources refer to the utilisation of the human body to generate electricity and are especially relevant in the domain of *Smart Healthcare*. Energy may be harvested from human activity, such as motions, or through physiological sources like body heat and blood flow. For detailed descriptions of the single methods and respective energy capturing technologies see Shaikh and Zeadally's (2016) *Energy Harvesting in wireless sensor networks: a comprehensive review.* However, Shafique et al. (2018) argue that even efficient energy harvester devices struggle to deliver sufficient power to sensor nodes continuously. Some sources, such as solar energy, tend to fluctuate regarding their intensity. To balance the energy supply with the power demand, energy should be collected nonstop, whereas the device should be operated in intervals. It is essential to acknowledge that *Energy Harvesting* utilises renewable energy to power sensor nodes. This approach can also be extended to power more extensive, more energy thirsty structures of IoT, like data centres (Maksimovic, 2017).

Improvements regarding sustainability

Besides the improved autonomy of sensor nodes, *Energy Harvesting* benefits aspects of sustainability. The shift of energy supply from conventional methods to renewable energy sources saves fossil resources like coal or gas, which are used to generate power and emit GHG. Therefore, *Energy Harvesting* supports the overcoming of *Air Pollution* and *Raw Material Utilisation.* Furthermore, the harvested energy is free, which results in decreased operational costs once the financial expenditures for the integration of *Energy Harvesting* technology have amortised, reducing *Financial Requirements*. In addition, the avoidance of batteries within sensor nodes protects the *Environment* from harmful pollutions in case of damages (Shaikh et al., 2015).

4.3.2.2 Algorithm Optimisation

Definition

The method of *Algorithm Optimisation* describes the development and refinement of device and communication algorithms concerning their energy efficiency. The aim is to optimise the balance between energy consumption and computation or transmission power, and thus fulfilling the respective objective with a minimum input of energy (Stetsuyk, Maevsky and Maevskaya, 2018). Furthermore, this method refers to the inclusion and appropriate execution of energy-saving methods, which are explained subsequently in this section, for instance, *Activity Scheduling*.

IoT components

Algorithms are sets of instructions and used to solve classes of problems or perform computations. Therefore, algorithms are found in every computing device and thus, in every part of an IoT system. This enables the application of energy-efficient algorithms for all components of IoT systems, such as sensing devices, data centres, semantic applications and communication technology (Zhu et al., 2015).

Application

Since algorithms build a central and indispensable element of every computing device, the application of energy-efficient algorithms covers a broad scope. For this reason, this thesis only exemplifies some applications within the domain. Software design paradigms which focus on efficient software with minimum resource utilisation are for instance used in cloud computing and data centre design, as data processing often poses a large share of energy consumption, and thus operation costs (Zhu et al., 2015). An example of the application within data centres is given by Peoples et al. (2013). The proposed architecture uses an orchestration agent in a client-server model, which evaluates servers in the context of energy efficiency. The usage within communication protocols provides energy efficiency, for instance, through dynamic adjustment of transmission power, optimisation of tag estimation and avoidance of tag collision and overhearing (Shaikh et al., 2015). In the context of smart sensors efficient algorithms are used to prevent high power consumption in idle states. This is, for example, realised by the subsequently described method of *Activity Scheduling* (Shuja et al., 2017). Furthermore, a programming language named EPDL was developed in the context of energy efficiency. EDPL enables non-experts to write energy policies for smart environments (Arshad et al., 2017). Another example of energy-efficient algorithms within IoT is represented by *Efficient Routing* techniques and focused later in this section.

Improvements regarding sustainability

The application of *Algorithm Optimisation* is strongly associated with the improvement of energy efficiency. Therefore, this method reduces *Power Demand*, associated *Air Pollution* and *Raw Material Utilisation*.

4.3.2.3 Activity Scheduling

Definition

Activity Scheduling refers to a method of energy consumption reduction by the application of an efficient algorithm. It aims to cut down energy usage if the device is in an idle state, for instance not in use or if no data of the particular device is needed at a given time. Furthermore, the aim is to identify the ideal trade-off between utility and energy consumption (Zhu et al., 2018).

IoT components

As *Activity Scheduling* is an algorithm-enabled method, it is hypothetically applicable for a broad scope of computation devices. For instance, the shutdown of a smartphone display or a laptop, after a certain amount of time without interaction, can be classified as *Activity Scheduling*, aiming a decrease of energy consumption. Within IoT networks, the application of this method is especially suitable for WSNs and M2M communication. This is due to the reason that sensor data, as well as M2M communication, is often not needed continuously but rather with the occurrence of certain events or activities. The dispensability of their steady full performance for the overall functionality of an IoT system represents a potential for energy savings (Zhu et al., 2015).

Application

To applicate *Activity Scheduling* and realise a decrease in power demand within these components, two major states of devices are implemented, the active state and the sleep state. While in the active state, devices employ their full performance to sense and communicate data. Accordingly, the duration of the active state should be kept to a minimum to save as much energy as possible (Wang, Hu and Liu, 2017). In contrast to the active state, the device cannot perform any function except for a wake-up timer in the sleep state. Compared to the activity state, the energy consumption of a device in the sleeping state is 1/100 – 1/1000, and thus significantly lower (Gui and Zhou, 2016). The switching between sleep state and activity state usually follows a predefined periodic rule. This entails the disadvantage of the so-called sleeping delay. The sleeping delay describes a situation where the transmission of data is prevented because one of the involved nodes is in sleep mode. Furthermore, this poses a problem if the sleeping node is embedded in the transmission structure for active data transmission (Huang, Wu and Tang, 2018). However, this problem can be solved by advanced schemes, like the radio frequency watchdog scheme. With this, a sensor listens to a particular signal but turns off its radio module in case there is no need to transmit data (Lee, Bae and Choi, 2013; Popli, Jha and Jain, 2019).

Improvements regarding sustainability

Activity Scheduling represents a suitable opportunity to decrease the *Power Demand* of sensor nodes. Furthermore, to energy consumption related *Air Pollution* and *Raw Material Utilisation* are reduced. In the case of battery-powered sensor nodes, the improved energy efficiency might result in a longer lifespan and thus, supports the overcoming of *Waste/ Disposal* (Dupont et al., 2018).

4.3.2.4 Open-Source

Definition

Open-Source describes a decentralised software-development model, which emphasises collaborative development. In order to enable public participation and collaboration, source code, blueprints and documentation of software or software-containing products is freely available for everyone. Therefore, this paradigm stands in contrast to commercial, proprietary models where users buy a finished product without having access to large parts of the deployed source code (Levine and Prietula, 2014).

IoT components

The application of the *Open-Source* paradigm is possible for every computation device which contains an algorithm. Therefore, it is hypothetically adequate for every component of an IoT system. Applications of *Open-Source* models and related DIY concepts in the area of IoT mostly refer to sensor devices, their compositions, source codes and operation. Furthermore, this aspect refers to IoT-related services, such as cloud or IoT platforms, which are free of charge and customisable by users (Dupont et al., 2018).

Application

Applications of this paradigm within IoT environments are mostly realised by the utilisation of *Open-Source* IT platforms and microcontrollers like Arduino or Raspberry Pi. Arduino, offering *Open-Source* hardware as well as software, is suitable for developing autonomous and connected objects. The basic microcontroller can be equipped with numerous sensors, actuators and communication devices. Consequently, functions, operation and communication with other devices or networks can be implemented by users according to their objectives. (Rivas-Sánchez, Moreno-Pérez and Roldán-Cañas, 2019). Thereby, the *Open-Source* model offers a set of advantages compared to commercial IoT solutions. Firstly, the costs of *Open-Source* microcontrollers, like Arduino, and additional components are relatively low. Furthermore, users are enabled to fully customise their products regarding their deployment purposes and environments. Through the open design, these DIY products are easy expandable and repairable at relatively low costs (Dupont et al., 2018). Besides, this concept allows users to learn new skills and test them with a usable product by following manuals provided by other, experienced users. This educational effect of DIY was found to motivate people to value and develop an attachment to their handmade artefacts. Consequently, users tend to repair and maintain their products, rather than discard them in benefit for new ones (Sas and Neustaedter, 2017).

Improvements regarding sustainability

Through the providence of low-cost DIY opportunities and knowledge, *Open-Source* solutions mainly contribute to a reduction in the *Social Gap* and improved access to technology. This is especially relevant for low-income countries, as commercial IoT solutions are often unaffordable for large parts of their population and economy (Dupont et al., 2018). Furthermore, the high degree of low-cost customisability and repairability may result in longer lifespans of products and thus, reduce *Waste/ Disposal*. The increased attachment of users regarding products they built by their own results in a higher degree of trust and *Technology Adoption*.

4.3.2.5 Hardware Optimisation

Definition

Hardware Optimisation methods refer to paradigms, which aim to decrease sustainability issues within IoT technology by the utilisation of appropriate hardware. Furthermore, this method emphasises the design of hardware which provides long lifespans and a high degree of upgradability and repairability to prevent large amounts of waste. In addition, the efficiency of utilised hardware should be maximised in order to achieve a particular objective with a minimum amount of hardware (Maksimovic, 2017).

IoT components

As in the case of algorithm and software optimisation, *Hardware Optimisation* is applicable for every device within an IoT system. Through efficient hardware design and employment, energy savings can be achieved. The design of hardware which incorporates a minimum amount of hazardous material is especially relevant for sensor nodes which are embedded directly in the environment, for instance in lakes, forests or agricultural land. Possible damages of such IoT devices immediately result in environmental pollution, for example, through leaking batteries (Shaikh and Zeadally, 2016).

Application

There are various methods and opportunities to enhance sustainability aspects of IoT hardware. For example, Zhu et al. (2015) propose the application of green RFID tags. RFID tags should be reduced in size to decrease the amount of nondegradable material which is used during their manufacturing. Furthermore, fully degradable tags are suggested, such as printable RFID tags and paper-based RFID tags. In general, hardware solutions should be designed with a focus on energy consumption. This not only enhances the sustainability but also reduces operational costs (Zhu et al., 2015). Furthermore, hardware should be designed and deployed according to their specific objectives. For instance, sensor nodes which only transmit small amounts of data over a short distance should be equipped with low power communication hardware like NFC or Zigbee instead of Wi-Fi or LTE (Pramanik, Pal and Choudhury, 2019). To contribute to the previously described concept of the *Circular Economy* (section 4.3.1.7), hardware for IoT systems should be designed in a way which enables easy recycling and recovery of valuable limited materials (Bressanelli et al., 2018). Also, hardware should be customisable, easy to repair and upgradable to enhance the lifespan and thereby prevent early obsolescence and associated waste (Sas and Neustaedter, 2017).

Improvements regarding sustainability

The application of enhanced hardware exhibits the opportunity to decrease *Power Demand*. Furthermore, the extension of lifespan reduces the amount of associated *Waste/ Disposal*. Environmental pollution may also be decreased through the minimisation of hazardous materials regarding the composition and manufacturing of hardware. Thus, the *Challenge* of *Raw Material Utilisation* is diminished.

4.3.2.6 Efficient Routing

Definition

Data transmission within IoT networks involves large amounts of energy consumption. Therefore, *Efficient Routing* schemes aim to maximise the efficiency of data transmission. Sensor networks within IoT usually consist of sensor nodes and base stations to which sensed data is transferred. This transfer should happen with a minimum of energy consumption while securing the arrival and validity of data (Pramanik, Pal and Choudhury, 2019).

IoT components

Efficient Routing methods within IoT are especially relevant for WSNs and M2M communication as they focus the maximisation of data transmission efficiency. Therefore, they rely on algorithms which aim to select the most efficient paths regarding energy efficiency. This is realised through specific routing protocols which are responsible to compute, establish and maintain the routes among sensor nodes and base stations. Thereby, the routing usually happens in an ad hoc manner where data is transferred from a sensor node to the base station through other sensor nodes within the network (Zhu et al., 2015).

Application

The application of *Efficient Routing* schemes realised through the implementation of several algorithms for sensor nodes. These routing schemes differ in their focus and structure. Examples are multipath based routing, mobility based routing, hierarchical routing, location-based routing and data-centric routing (Zhu et al., 2018). Regarding sustainability, applied routing schemes should target a maximum degree of energy efficiency. This can be realised through different paradigms or combinations of paradigms. Pramanik, Pal and Choudhury (2019) and Farhan et al. (2018) promote a path selection approach which minimises the number of hops and thereby involved nodes in the data transmission process. As every node consumes a certain amount of energy to forward data, the reduction of involved nodes decreases the overall power demand. Wang, Hu and Liu (2017) extend this approach by the integration of information regarding energy availability. Following this approach, nodes with high energy availability should be preferred over such with less remaining energy. This contributes to the energy balance within the sensor network, prevents early obsolescence of specific nodes and thus enhances the lifespan of the network. Besides, the application of *Efficient Routing* and sensor placement techniques enables the reduction of the network size and thereby required nodes and overall energy consumption (Arshad et al., 2017). The decision regarding a specific routing scheme should always be made according to the objectives and requirements of the respective IoT network, as a focus on power demand often comes at the expense of link reliability and delay (Wang, Hu and Liu, 2017).

Improvements regarding sustainability

Efficient Routing contributes to a reduction of *Power Demand* and associated *Air Pollution* and *Raw Material Utilisation*. Furthermore, the consideration of energy balance results in an extended lifespan of the network. Therefore, it prevents a certain degree of *Waste/ Disposal*.

4.3.2.7 Data Reduction

Definition

The method of *Data Reduction* refers to the reduction of sensing activities and associated transmissions. Therefore, it incorporates two different aspects, namely the amount of data which is sensed and stored by a sensor node and the amount of data which is sent to the base station. The primary aim of this method is to reduce energy consumption, which is associated with the acquisition and transfer of information (Zhu et al., 2015).

IoT components

Data Reduction methods are especially relevant in the context of WSNs and M2M communication since initial data generation and transmission origins within these components. However, the reduction of data affects the whole ensuing processing and thus, the whole IoT system. This is caused by the lower amount of data which must be handled (Popli, Jha and Jain, 2019).

Application

The basic idea of *Data Reduction* regarding sensing activities is selective sensing. It proposes only to acquire data which is needed in a particular situation. Thereby, energy savings are realised through the avoidance of unnecessary sensing and transmission activities (Arshad et al., 2017). Zhu et al. (2015) recommend the usage of mechanisms such as aggregation, adaptive sampling, linear network coding and compression to reduce the amount of data which must be transmitted. Furthermore, data fusion is a useful instrument to reduce the amount of transferred data. Information about multiple events is fused to avoid redundancy, eventually resulting in a decreased number of data packages (Huang et al., 2018).

Improvements regarding sustainability

The application of *Data Reduction* techniques enhances the *Power Demand* of sensor nodes and linked computing activities. Thereby, also positive effects regarding *Power Demand* related *Air Pollution* and *Raw Material Utilisation* are achieved.

4.3.2.8 Recycling

Definition

Recycling is the process of converting waste and discarded objects into reusable material. The usage of recycled material decreases the need for new extraction and thus the ecological destruction and adverse societal effects, which are often affiliated with mining (Alcayaga, Wiener and Hansen, 2019).

IoT components

To achieve a high level of sustainability within IoT components, the change method of *Recycling* is another viable instrument. This change method is related to the previously described vision of a *Circular Economy*. IoT components are made from some of the scarcest natural resources, such as copper and coltan (Arshad et al., 2017). *Recycling* is applicable for every component of an IoT system which is tangible and has to be produced.

Application

An example for the application of *Recycling* in IoT is given by Wong and Wong (2017). The development of a reusable RFID luggage tag, manufactured with recycled materials, exhibits the suitability of this method to produce high-quality IoT components. To gain enough material from discarded devices, several aspects must be considered. People must be incentivised to properly dispose of electronic devices which are no longer in use. For example, an estimated 23 million unused mobile phones are present in Australian households (Foteinos et al., 2013). The contained resources must be made available for

Recycling and manufacturing. In addition to the usage of recycled material to produce IoT components, these components itself should be designed in a way which makes them easy to recycle. The blend and combination of materials within electronic components often results in a difficult recovery of incorporated materials. To enhance the recyclability of devices, this aspect should be considered early in the design phase. Another aspect of *Recycling* is represented by the possibility of easy upgradability. Devices, which are suitable to be upgraded, customised and repaired by the users exhibit a longer lifespan, preventing them from early obsolescence (Sas and Neustaedter, 2017).

Improvements regarding sustainability

Recycling as a method supports the overcoming of the *Challenges Power Demand*, *Raw Material Utilisation*, *Production*, *Waste/ Disposal* and *Air Pollution*.

4.3.2.9 Retrofitting

Definition

The method of *Retrofitting* represents the activity of upgrading existing devices and infrastructures with components that enable integration into an IoT system. Therefore, it makes the production and acquisition of comprehensive, new equipment unnecessary. *Retrofitting* offers a set of advantages regarding sustainability (Bates and Friday, 2017).

IoT components

Retrofitting it applicable for every tangible part of an IoT system. The device must feature the possibility to upgrade it in order to include it into the IoT network. Requirements for existing devices could be interfaces, which transform the acquired data regarding interoperability and communication technology to transmit the data.

Application

However, the integration of existing devices in IoT environments is not always possible and poses a complex task (Shuja et al., 2017). Moreover, the inclusion of different outdated devices into IoT, alongside different technologies, amplifies the challenge of *Interoperability*. If a device, system or infrastructure is suitable for *Retrofitting* depends on the objectives of the integration, the technology of the device and the effort required to retrofit (Bates and Friday, 2017). As in the case of *Recycling*, *Retrofitting* should be considered as early as the design phase of product development. High upgradability of devices supports this method and enables users to adjust devices to new standards, communication technologies and fields of application.

Improvements regarding sustainability

The application of this method decreases the need for new devices, diminishes *Financial Requirements* and with *Production* associated *Raw Material Utilisation*, *Air Pollution* and *Power Demand*. Furthermore, existing devices can be maintained and are prevented from the disposal, which assists to overcome *Waste/ Disposal* (Bonilla et al., 2018).

4.3.2.10 Crowdsensing

Definition

Crowdsensing, also referred to as participatory or opportunistic sensing represents another method to change IoT deployments towards more sustainability. Comparable to *Retrofitting*, it aims to utilise existing resources and devices to achieve specific objectives, whereas *Crowdsensing* does not require any upgrades or additional components to integrate them. This method describes the utilisation of personal devices, such as smartphones, for sensing and computing purposes (Yang et al., 2012).

IoT components

Tasks, for which an ordinary IoT deployment requires the installation of numerous sensors in combination with computing resources, are outsourced to personal devices of a group of people (Pramanik, Pal and Choudhury, 2019). Therefore, *Crowdsensing* is primarily applicable for IoT components which fulfil the task of sensing.

Application

In terms of sensing, computing and communicating data, smartphones are highly useful as they provide all required functionalities. Smartphones, as a ubiquitous technology, can sense ambient light, noise, location and movement (Pan et al., 2015). Even though the computational power of a single smartphone is significantly lower compared to data centres, the cumulative processing power of smartphones is high enough to execute complex computational jobs. Furthermore, computing resources can be increased easily through the inclusion of more smartphones if needed (Pramanik, Pal and Choudhury, 2019). The quintessence of *Crowdsensing* is to manage extensive sensing and computation tasks by segmenting the task into smaller microtasks, which are carried out by available, suitable personal devices. This collectively sensed, computed and shared data enables the extraction of information regarding phenomena of common interest (Ganti, Ye and Lei, 2011).

Improvements regarding sustainability

With the application of *Crowdsensing*, the manufacturing, acquisition, deployment and maintenance of sensing devices become superfluous. Therefore, *Crowdsensing* contributes to decreases in *Raw Material Utilisation*, *Energy Consumption*, *Financial Requirements, Production* and *Waste/ Disposal*.

4.3.2.11 Utility Expansion

Definition

This method suggests expanding the extent of IoT systems to capture opportunities which are not targeted initially but related to the primary objective of the deployment. Therefore, it aims to exploit the full extent of functionalities and opportunities of IoT deployments to enhance sustainability. This method is not mentioned in the analysed literature but emerged during the analysis as targeted effects and required data of IoT systems often overlap.

IoT components

As *Utility Expansion* aims to exploit existing IoT infrastructure to the greatest possible extent it is applicable for every component of an IoT system, such as WSNs, computing resources and network infrastructure.

Application

Utility Expansion should be realised by partnerships across organisations and institutions, which aim to deploy IoT systems with overlapping or relating purposes. An example could be a device in the area of *Smart Agriculture* which senses the moisture of agricultural land. In addition, this device could be equipped with motion or air quality sensors for *Environmental Monitoring* purposes. The acquired data could be shared or sold to governmental institutions which are charged with the assessment of wildlife and air quality.

Improvements regarding sustainability

The consistent application of this method would decrease the need for IoT devices and therefore negative effects on sustainability associated with the *Production, Power Demand, Financial Requirements* and *Waste/ Disposal*. *Utility Expansion* emphasises synergy to avoid redundant deployments.

Table 4.4 summarises the described impacts of *Sus4IoT* paradigms on identified *Challenges* (section 4.2.1.2). A plus thereby implies a positive contribution to overcome the respective *Challenge* by applying methods of the paradigm.

Table 4.4: Effects of Sus4IoT paradigms on challenges (own listing)

Paradigm / Challenge	Raw Material Utilisation	Production	Waste/ Disposal	Power Demand	Financial Requirements	Collective Inclusion	Network Coverage	Rights/ Law/ Politics	Air Pollution	Interoperability	Security/ Privacy	Technology Adoption
Energy Harvesting	+		+		+				+			
Algorithm Optimisation				+								
Activity Scheduling				+								
Open-Source			+		+	+						+
Hardware Optimisation	+	+	+	+					+			
Efficient Routing				+								
Data Reduction				+								
Recycling	+	+	+						+			
Retrofitting	+	+	+		+				+			
Crowdsensing	+	+	+	+	+				+			
Utility Expansion	+	+	+		+				+			

4.4 Project Examples and Classification

The previously figured aspects and solutions contribute to RQ2.1. This section applies emerged concepts and classification possibilities to project examples which were found within the analysed literature. Therefore, section 4.4.1 provides project examples along with respective descriptions. Section 4.4.2 lists the examined projects and classifies them within specific categories.

4.4.1 Project Descriptions

In order to exemplify the classification and examination of IoT projects regarding their impacts on sustainability aspects, this section describes a set of projects. These projects originate from the literature, which was analysed in this thesis. To be included, a project must exhibit IoT features which enable or actively contribute to their functionality. Furthermore, included projects show aspects and effects which are relevant regarding sustainability.

iHome Healthcare

This project is provided by (Yang et al., 2014). iHome Healthcare aims to enhance healthcare services, especially for older citizens. It consists of an IoT bio patch, the iMedBox, iMedPacks, respective communication functionalities and a database system for the doctor. The bio patch is attached to the patient's body and acquires vital signs, such as heart rate and temperature. The acquired data is communicated with the iMedBox, processed and finally sent to the monitoring system of the doctor or hospital. Furthermore, iMedBox automatically sends an emergency alarm in case of serious issues. The doctors who use this system are enabled to assess the patient's health and monitor all critical aspects remotely. Additionally, they can issue e-prescriptions in case the patient needs a specific drug. The medication is delivered to the patient's home and inserted into the iMedBox, which automatically reminds the patient and dispenses the respective dose. Through the automatic dispensing and monitoring of intake, misuse is prevented, the intake of the right dose is secured, and medication can automatically be re-ordered.

Smart Wardrobe

The smart wardrobe is proposed by Kolstad et al. (2018) and aims to increase the recycling habit of people regarding clothes. This is relevant as for every pound of recycled textile, more GHG emissions are prevented than for every pound of glass, plastic and paper combined (Chavan, 2014). For this reason, clothes are equipped with an RFID tag which enables the tag sensor within the wardrobe to register the usage of specific garments. Semantic cloud applications can compute the users taste and include other data, such as weather forecasts. Based on this information, a related smartphone app recommends individual combinations of garments, new styling ideas and clothes which are not used and should be recycled. Therefore, this project can prevent the purchase of goods which do not match the user's style and motivates the user to recycle clothes which are not used.

Alpha Washing Machines

The Alpha Washing Machines project is described by Bressanelli et al. (2018). Alpha, a north European household appliance retailer, provides highly efficient low energy washing machines on a pay-per-month scheme. The fee includes the acquisition, transportation, installation costs and maintenance, which poses a significant reduction of the initial investment costs. Provided washing machines are equipped with sensors to monitor their usage regarding frequency, load, usage time and more. Furthermore, the appliances monitor themselves regarding their condition and performance. The collected data is transmitted to the company and processed for several objectives. Alpha gains information about the actual usage of their appliances, which allows them to adapt and adjust their offerings according to customer needs. The combination of usage and performance information is used to provide customers with recommendations regarding their usage habits, for instance, load optimisation, timing, additive usage and avoidance of habits which may harm the device. Monitoring of the device itself enables Alpha to precisely assess the condition and repair parts before their malfunction harms other components. Furthermore, the firmware of washing machines can be updated remotely to further increase usage efficiency. These monitoring activities improve the lifespan of the devices. In case a machine is broken, Alpha disassembles the device and recovers functioning components for the maintenance of other devices. Broken parts which cannot be used anymore are discarded appropriately.

Smart Aquaculture in Ghana

Introduced by Dupont et al. (2018), this project addresses the productivity of aquacultures to ensure sufficient food supply for the growing global population. Furthermore, this project deals with some special requirements for IoT deployments in rural areas of low-income countries, like inadequate network coverage and limited financial resources. Therefore, a DIY low-cost sensor device and a DIY low-cost LoRa gateway are utilised, data is processed through open source applications like ThingSpeak. Furthermore, the user interface can communicate data via available and commonly used technologies within this region, such as SMS and Facebook. The sensor device is attached to a buoy which floats in a fish pond. It acquires data regarding the pH value, oxygen level and temperature. Consequently, this data is provided to users in combination with recommendations regarding optimisation strategies to enhance productivity. In addition to the increased productivity, this system prevents environmental pollution caused by inappropriate use of fertiliser or pesticides.

Smart Hand Pump in Kenya

In Africa, water service reliability strongly correlates with extreme poverty and water insecurity in rural areas. To address this problem, approximately one million hand pumps are deployed across the continent, supplying water for over 200 million people. However, one-third of these pumps are thought to be broken. To enhance the awareness of broken pumps and identify areas with significant water supply issues, handpumps within the Kyuso district in Kenya were equipped with smart sensors. The sensors communicate data regarding the flow rate of a respective pump via SMS. This enables to monitor the usage, performance, seasonality and demand peaks of water supply within a region. Acquired data is used to identify areas where action is needed to ensure sufficient water supply to the population. This enhances the effective maintenance of hand pumps and thus the accessibility to clean water. The project is described by Garrity (2015).

Urban Route Accessibility Analyser for Disabled People

This project, presented by Gilart-Iglesias et al. (2015), aims to improve the accessibility of cities for wheelchair drivers. The sensor network consists of RFID tags and respective readers. The RFID tags are distributed to wheelchair users as well as citizens who are not dependant on a wheelchair. The RFID readers are attached to numerous components of the city infrastructure and register passages of tag equipped citizens. These passages are collected and processed to obtain movement patterns. Consequently, movement patterns of wheelchair users are compared to those of non-users. This process reveals inappropriate and problematic infrastructure parts, which can be addressed by the city administration to enhance accessibility. The use of RFID tags instead of smartphone location services is due to the ensured anonymity as only information is provided regarding whether a wheelchair is used or not.

ASSET Platform

The ASSET Platform is a solution aiming to enhance the consumption patterns of customers according to their individual preferences and is described by Klinglmayr et al. (2017). Customers have individual preferences regarding characteristics of consumer goods, for instance, fair labour conditions during production, organic ingredients or local cultivation. ASSET enables customers to adapt their consumer behaviour to their individual preferences without the exhausting process of information gathering and detailed product assessment. Therefore, it consists of three connected main elements: a smartphone application, a tracking system within the supermarket and a comprehensive database that contains information about several sustainability aspects of products and their respective components. Once the user entered his individual preferences into the application, he receives useful information about products concerning his attitudes. This is realised through the tracking system which monitors the exact location and direction of the customer resulting in recommendations about products the user faces.

IOMVT

The IoT-enabled dynamic optimisation method for smart vehicles and logistics tasks (IOMVT), described by (Liu et al., 2019), is developed to improve the efficiency of logistics services and ultimately achieve green and sustainable logistics. To fulfil this aim, the project incorporates a comprehensive set of data. A central element is represented by the joined database of different logistic companies. This database contains information about a company's logistic tasks, such as freight, timeframe, location and destination. Furthermore, information about available vehicles is integrated, including location, destination, route, utilisation rate of cargo capacity and features of the vehicle. The continuous monitoring of logistic resources, freight and orders enables the system to orchestrate the logistics activities across different companies by calculating ideal routes and cargo combination. This results in a highly efficient logistics system which maximises the utilisation of logistic resources, and thus saves fuel, reduces GHG emissions, decreases the number of required vehicles and prevents empty runs.

GreenIS Factory

GreenIS Factory, presented by Garrido-Hidalgo et al. (2018), aims to enhance the security of employees in working environments with hazardous aspects. Therefore, a WSN is installed within the factory, which monitors employees and machines. In addition, workers are equipped with WBANs and smart safety equipment, such as helmets or ear protectors. The WBAN wristband monitors vital signs of the employee to ensure his physical capability for specific tasks and environments. Additional smart equipment is registered by the WBAN and ensures the right security equipment for specific tasks or working environments. If the employee is about to start a task without wearing the required equipment or showing unsuitable physical conditions, respective machines do not start, and a supervisor is notified. The machinery itself is also equipped with smart sensors and communication technology. During the work, the respective machine continuously communicates with the WBAN, checking for the required equipment and monitoring the movements of the employee. If the employee executes movements which cause danger for himself, for instance, moving his hand to close to a saw, the machine immediately stops to prevent accidents. Also, smart machinery supports employees to fulfil particular tasks by providing recommendations regarding their execution.

Location-Based Automated Energy Control

Described by (Pan et al., 2015), this project aims to reduce energy consumption in the context of *Smart Homes* automatically. The system contains different actuators which can control electronic devices within the user's home, such as lightning, entertainment devices and kitchen appliances. Trough a user interface, inhabitants can monitor their energy consumption, define different energy rules and are provided with rule recommendations based on their consumption patterns. Following these rules, the system automatically applies them and controls the energy consumption of devices based on the actual location of the user. Therefore, the user's location is tracked through GPS location of his smartphone. Furthermore, inhabitants are enabled to control the energy supply for connected devices remotely.

4.4.2 Project Classifications

The previously described projects are classified in this section by the application of four characterisation categories. Application area relates to the *IoT4Sus* concepts identified in section 4.3.1. IoT objective emphasises the utilisation of IoT and describes project characteristics according to *Drivers* which were mentioned in section 4.2.1.1. *Effects*, referring to section 4.2.2, describe implications on sustainability. As no adverse *Effects* are described within the literature, potential negative impacts are set in brackets. Those possible negative impacts especially arise in the dimension of *Privacy* through the acquisition and processing of personal data. *SDGs* are used to map projects to respective sustainability goals. The classification of the projects, according to these categories, is shown in Table 4.3 – Table 4.6.

Table 4.3: Classification of project examples (Application area) (own listing)

Project Name / Application area	Smart Traffic/ Vehicles	Smart Homes/ Buildings	Smart Grids	Smart Healthcare	Smart Meters	Smart Agriculture/ Farming	Circular Economy	Environmental Monitoring	Smart Factories	Smart Logistics	Smart Cities
iHome Healthcare				●							
Sustainable Wardrobe		●									
Alpha Washing Machines							●				
Smart Aquaculture in Ghana						●		●			
Smart Hand Pump in Kenya					●						
Urban Route Accessibility Analyser for Disabled People											●
ASSET Platform											●
IOMVT	●									●	
GreenIS Factory									●		
Location-Based Automated Energy Control		●									

Table 4.4: Classification of project examples (IoT objective) (own listing)

Project Name / IoT objective	Tracking	Monitoring	Data Acquisition/ Analysis	Alerting/ Warning	Process Optimisation/ Automation	Awareness Raising/ Behavioural Change
iHome Healthcare		●	●	●		●
Sustainable Wardrobe		●	●			●
Alpha Washing Machines		●	●		●	●
Smart Aquaculture in Ghana		●	●	●		●
Smart Hand Pump in Kenya		●	●			●
Urban Route Accessibility Analyser for Disabled People	●		●			●
ASSET Platform	●		●			●
IOMVT	●	●	●		●	
GreenIS Factory	●	●	●	●	●	
Location-Based Automated Energy Control	●	●	●		●	●

Table 4.5: Classification of project examples (Effects) (own listing)

Project Name / Effects	Energy Consumption	Economy/ Costs	GHG Emissions	Human Behaviour	Resource Consumption	Amount of Waste	Environment	Health	Water Consumption	Security	Social Gap/ Accessibility	Privacy	Human Work
iHome Healthcare		+						+			+	(-)	
Sustainable Wardrobe			+	+	+							(-)	
Alpha Washing Machines	+	+		+		+					+	(-)	
Smart Aquaculture in Ghana					+		+				+		
Smart Hand Pump in Kenya											+		
Urban Route Accessibility Analyser for Disabled People											+		
ASSET Platform				+								(-)	
IOMVT		+	+		+								
GreenIS Factory				+				+		+		(-)	(-)
Location-Based Automated Energy Control	+			+								(-)	

Table 4.6: Classification of project examples (SDGs) (own listing)

Project Name / SDG	SDG1 – No poverty	SDG2 – Zero hunger	SDG3 – Good health	SDG4 – Education	SDG5 – Gender equality	SDG6 – Clean water	SDG7 – Clean energy	SDG8 – Work and economy	SDG9 – Industry, Innovation	SDG10 – Reduced inequalities	SDG11 – Sustainable cities	SDG12 – Consumption/ Production	SDG13 – Climate action	SDG14 – Life below water	SDG15 – Life on land	SDG16 – Peace and justice	SDG17 - Partnerships
iHome Healthcare			●														
Sustainable Wardrobe												●	●				
Alpha Washing Machines									●			●	●				
Smart Aquaculture in Ghana		●								●							
Smart Hand Pump in Kenya		●				●				●							
Urban Route Accessibility Analyser for Disabled Peo-ple										●	●						
ASSET Platform												●					
IOMVT									●				●				
GreenIS Factory			●					●	●								
Location-Based Automated Energy Control											●		●				

5 Framework Development

Chapter five of this thesis synthesises the preliminary findings into a conceptual framework and will accomplish RO3 and corresponding research questions RQ3.1, RQ3.2 and RQ3.3. To develop and illustrate the framework. Section 5.1 emphasises the objectives of the framework and derives respective requirements. These requirements are met by the integration of several aspects and dimensions into the framework, which are presented in section 5.2. Ultimately, the conceptual framework is developed and presented in section 5.3.

5.1 Objectives and Requirements

To achieve the aim of this thesis, this section emphasises the objectives and requirements for the conceptual framework. Section 5.2 captures those requirements and derives concrete components of the framework. The main objective of the framework is to increase the knowledge and awareness of sustainability aspects in the context of IoT. Also, the framework aims to provide useful information to practitioners and researchers by suggesting methods to enhance the sustainability of IoT. This is achieved through an illustration which depicts relevant aspects in this context along with their relations in a comprehensible and meaningful manner. Therefore, the framework must fulfil requirements regarding the inclusion of relevant aspects, the inclusion of relevant relations and the design. Requirements within these categories are described in the following.

The illustration of relevant aspects of IoT regarding sustainability necessitates the inclusion of possibilities to enhance IoT technology concerning sustainability, possibilities for improving sustainability through the utilisation of IoT, effects and aspects in terms of sustainability, aspects and perspectives regarding IoT and challenges which hamper the utilisation of IoT in terms of sustainability.

In order to ensure a high level of comprehension and information, relations must be illustrated in the framework. Multiple relations were found to be necessary to provide a holistic overview of this multidisciplinary topic. The relation between *IoT Layers* and *Concepts and Paradigms*, the relation between *Challenges* and *Concepts and Paradigms*, the relation between *Challenges* and *IoT Layers* and consequently, the relationship between *Effects* and *Concepts and Paradigms*.

The presentation of these aspects and relations in a useful framework requires a design which is comprehensible and understandable. At the same time, the design should be able to depict comprehensive information in a complex context. Therefore, relations should be assessable consistent and quickly. Furthermore, the framework should be designed in a way which prevents ambiguousness. As the framework aims to suggest activities which enhance the sustainability of IoT projects, a clear, explicit structure and direction of reading must be provided alongside a respective quick assessment of the given suggestions.

5.2 Components, Relations and Design

The preceding section briefly described the requirements for the framework. The outline of the framework in order to achieve those requirements is elaborated within this section. Therefore, the following describes the shape of the framework regarding the components, the relations and the design.

Components

To achieve a comprehensive overview of relevant aspects regarding IoT in the context of sustainability, the proposed framework consists of four components: *IoT layers, Challenges, Paradigms and Concepts* and *Effects on sustainability*. Those components are described in the following.

- *IoT Layer*: This component refers to the perspectives and layers of IoT, which are introduced in section 3.1. The different layers are inspired by the perspectives which are provided by Atzori, Iera and Morabito (2010) and the layers described by Al-Fuqaha et al. (2015). In the context of the provided framework, three layers are illustrated: *Objects, Network* and *Application*. *Objects* refer to devices which are included in an IoT system, such as sensors, smart devices and actuators. Furthermore, the definition of *Objects* within the framework includes all physical, tangible objects in an IoT system like data centres and computing devices. The *Network* layer describes the connectivity of these devices. Therefore, it includes communication protocols, communication techniques and the transmission of data between objects. This layer explicitly does not contain the hardware which is required to achieve the network infrastructure as hardware is covered by the *Objects* layer. The A*pplication* layer describes the usage of the preceding described layers. It represents information which is gained through the acquisition, analysis and communication of data. Furthermore, it includes the application of this information to achieve specific objectives. Therefore, it contains the interpretation and utilisation of insights gained by IoT technology. The three layers are not to be seen as independent as their functionality depends on each other and the Internet of Things represents a composition of them.
- *Challenges*: *Challenges* refer to the emerged aspects which are described in section 4.2.1.2. They are included in the framework to raise awareness regarding potential barriers for the deployment of IoT systems. Described *Challenges* hamper the application of IoT systems to achieve specific objectives. Some strongly relate to IoT infrastructure and technical aspects, like *Network Coverage*. Whereas other *Challenges* can affect sustainability aspects negatively if they are not overcome or reduced, for example, *Power Demand*. Both types of *Challenges* are included in the framework and should be considered as they pose possible threats to sustainability itself or IoT systems which aim to enhance sustainability aspects.
- *Paradigms and Concepts*: Referring to described solutions and concepts in section 4.3, this component of the framework illustrates IoT paradigms, which are relevant in terms of sustainability. The depiction of concepts is split into the previously described categories *IoT4Sus* and *Sus4IoT*. Both categories offer opportunities to enhance sustainability aspects regarding the technology itself (*Sus4IoT*) or the utilisation of technology (*IoT4Sus*). The category of *IoT4Sus* is relevant in terms of the *Application* layer. This is due to the utilisation of gained information to affect sustainability

aspects positively, either through human interpretation or automatic activities which are executed by objects of the IoT system. In contrast, *Sus4IoT* refers to the network and *Objects* layer by containing concepts which enhance aspects of both layers and thus focusing on IoT technology itself instead of utilising information to improve external facets. To enhance knowledge and suggest activities, this component contains widely discussed concepts of both realms.

- *Effects*: This area illustrates the implications that were identified and described in section 4.2.2. *Effects* are included to show the potential consequences of IoT deployments in terms of sustainability. Therefore, this component distinguishes between two categories of IoT impacts on sustainability, which are adapted from the LES model, proposed by Hilty and Aebischer (2015) and described in section 3.2.2. The framework utilises the *Life-Cycle Impact* tier and the *Enabling Impact* tier. *Life-Cycle Impacts*, as effects occurring with the providence of IoT services, relate to the areas of *Objects*, *Network* and *Sus4IoT* as they describe impacts which origin in the manufacturing and operation of IoT technology and components. Those impacts are described as costs and thus negative impacts on sustainability aspects (Hilty, 2008). In contrast, *Enabling Impacts* refer to the IoT layer of applications and the concept area of *IoT4Sus*, describing consequences which are caused by the utilisation of information gained from IoT technology. Those impacts are mostly beneficial in terms of sustainability aspects, as stated by Hilty and Aebischer (2015) and described in section 4.3.1 in this thesis.

Relations

To achieve the aim of the framework, it is essential to illustrate the relations between the previously described components. The depiction of linkages and interrelations concerning single components supports the comprehension of the relation regarding IoT and sustainability and thus poses a central element of the framework. A suitable presentation of the complex and multidisciplinary relations requires the application of several relation depiction methods for this framework. Therefore, relations are illustrated by the usage of three different methods: *Colouring, Placement* and *Arrows*. The specific application of these methods and their meaning for this framework is described in the following:

- *Colouring:* The method of *Colouring* serves different purposes for the provided framework. Firstly, it demarcates the described component areas from each other. Secondly, the colour reveals some relations which are central to the comprehension of the relations between and within component areas. The area of *IoT Layers* is coloured in light grey, which exhibits no special meaning and can be neglected. In contrast, the component area of *Challenges* is coloured in gradient red. The selection of red is due to the hampering effects which *Challenges* possibly pose to IoT deployments in the context of sustainability and enables a quick comprehension of this relation. The gradient is used to express, that contained *Challenges* do not relate to a fixed *IoT Layer* but may affect more than one layer. The fluent transition supports the understanding of this aspect. Furthermore, the gradient reveals that the placement within this area should be considered. For this reason, the area of *Sus4IoT* within the component of *Paradigms and Concepts* also exhibits a gradient colouring. Concepts, which are depicted in this area, can relate to more than one layer with varying intensity. In contrast, *IoT4Sus* concepts consistently describe solutions which belong to the *IoT Layer* of *Application*. To show this aspect, the area of *IoT4Sus* concepts is coloured in one shade, which slightly differs. Regarding the *Effects*, red is used to highlight the negative impact of implications which are mapped to the *Life-Cycle Impact* area. Furthermore, the usage of red implies a relation to the component of *Challenges*. Both areas contain aspects which negatively influence the sustainability of IoT and the utilisation of IoT in this context. Consequently, the area of *Enabling Impact* is highlighted in green to emphasise that contained impacts positively influence sustainability.

- *Placement:* As briefly mentioned in the description of *Colouring*, the *Placement* of elements is also used to show relations and affiliations. The *Placement* of specific objects or areas thereby refers to the determining component of *IoT Layers* and thus expresses their belonging. Elements within an area of gradient colour are mapped regarding their classification within the *IoT Layers*. For example, the challenge of *Security*/ *Privacy* is relevant for both the network and the objects in an IoT system. Therefore, this element is mapped close to both layers. In contrast, the challenge of *Technology Adoption* strongly refers to the application of IoT and is mapped to this lane. However, this poses only an approximate classification and should not be seen as definite. Areas which are coloured consistently are mapped to the *IoT Layers* as a group. The *Placement* of a specific element within the area can be neglected and does not provide any additional information about the element. *Sus4IoT* solutions are mapped to the *Application* layer, as they provide services, which are enabled through the information functionality of IoT. *Sus4IoT* concepts refer to the technology itself and thus are depicted relating to the *Objects* and *Network* layer. *Enabling Impacts* are realised through the utilisation of *IoT4Sus* solutions and mapped accordingly. In contrast, *Effects* belonging to the *Life-Cycle Impact* are caused by the providence of IoT technology and thus refer to the *Objects* and *Network* layer.
- *Arrows:* The arrows represent the relations which should be minded in order to maximise the sustainability of an IoT project. Therefore, they suggest concrete activities to enhance the sustainability of IoT projects. Furthermore, in combination with textual elements, the arrows specify the reading direction and application of the framework. Targeted solutions within *IoT4Sus* areas, like *Smart Healthcare*, should consider *Challenges* which might be relevant for the specific project to be successful and realise a maximum of positive *Effects*. Furthermore, they should apply *Sus4IoT* concepts to overcome respective *Challenges* and reduce the *Life-Cycle Impact* of IoT, which is associated with adverse *Effects* on sustainability. This suggestion poses the quintessence of the framework and supports the understanding of linkages while simultaneously providing specific activities.

Design

In addition to the already mentioned design aspects, like the *Colouring* and the *Placement* of areas, some other design features are applied for the framework. To enable quick, intuitive comprehension of the framework, one version is provided that utilises icons (Figure 5.2). This version is meant to provide a quick overview, rather than a comprehensive understanding. The used icons represent respective elements within the component areas and capture their central meaning. Furthermore, a version which contains textual elements is provided (Figure 5.1).

An overview of the components, their description, design and relations is given in Table 5.1.

Table 5.1: Overview of framework components, design and relations (own listing)

Component	Subcomponent	Colour	Description	Relations
IoT Layer	Application	light grey	Services and information gained through IoT deployment and interpretation of these.	The *Application* layer contains *Challenges*, *IoT4Sus* concepts and *Enabling Impacts*.
	Network	light grey	Network features of an IoT system, responsible for the transmission of data and integration of objects.	The *Network* layer includes *Challenges*, Sus4IoT concepts and *Life-Cycle Impacts*.
	Objects	light grey	Physical, tangible objects in an IoT system, such as sensors, actuators, smart devices and data centres.	*Objects* comprise *Challenges*, *Sus4IoT* concepts and *Life-Cycle Impacts*.
Challenges	-	gradient red	Aspects which hamper the deployment and utilisation of IoT technology in terms of sustainability.	*Challenges* concern all *IoT Layers*, hamper the deployment of *IoT4Sus* concepts and can be overcome through the application of *SuS4IoT* concepts. Furthermore, they hamper *Enabling Impacts* and are partly reasoned by *Life-Cycle Impacts*.
Paradigms and Concepts	IoT4Sus	light blue	Concepts which are enabled by IoT and affect sustainability by the usage of information gained through IoT technology.	*IoT4Sus* concepts refer to the *Application* layer, are affected by *Challenges*, cause *Enabling Impacts* and should utilise *Sus4IoT* concepts.
	Sus4IoT	gradient blue	Concepts which refer to sustainability aspects of IoT technology itself.	*Sus4IoT* concepts concern the *Network* and *Objects* layer, can support the overcoming of *Challenges*, reduce *Life-Cycle Impacts* and should therefore be applied by *IoT4Sus* solutions.

Effects	Enabling Impact	light green	Positive *Effects* which are enabled by information that is gained through the application and usage of IoT technology.	*Enabling Impacts* are realised by the application of *IoT4Sus* solutions. The intensity of impacts can be hampered by *Challenges*.
	Life-Cycle Impact	light red	Negative *Effects* which are caused by the providence of IoT technology through manufacturing and operation.	*Life-Cycle Impacts* are reasoned by the manufacturing and operation of IoT technology and relate to the N*etwork* and O*bjects* layer. They partly cause *Challenges* and can be reduced through the usage of *Sus4IoT* concepts.

5.3 Comprehensive Conceptual IoT Sustainability Framework (CCIS)

The textual version of the proposed framework is shown in Figure 5.1. The icon version is depicted in Figure 5.1. Appendix 1 provides a legend for the icon version and describes the explicit meaning of the respective icons.

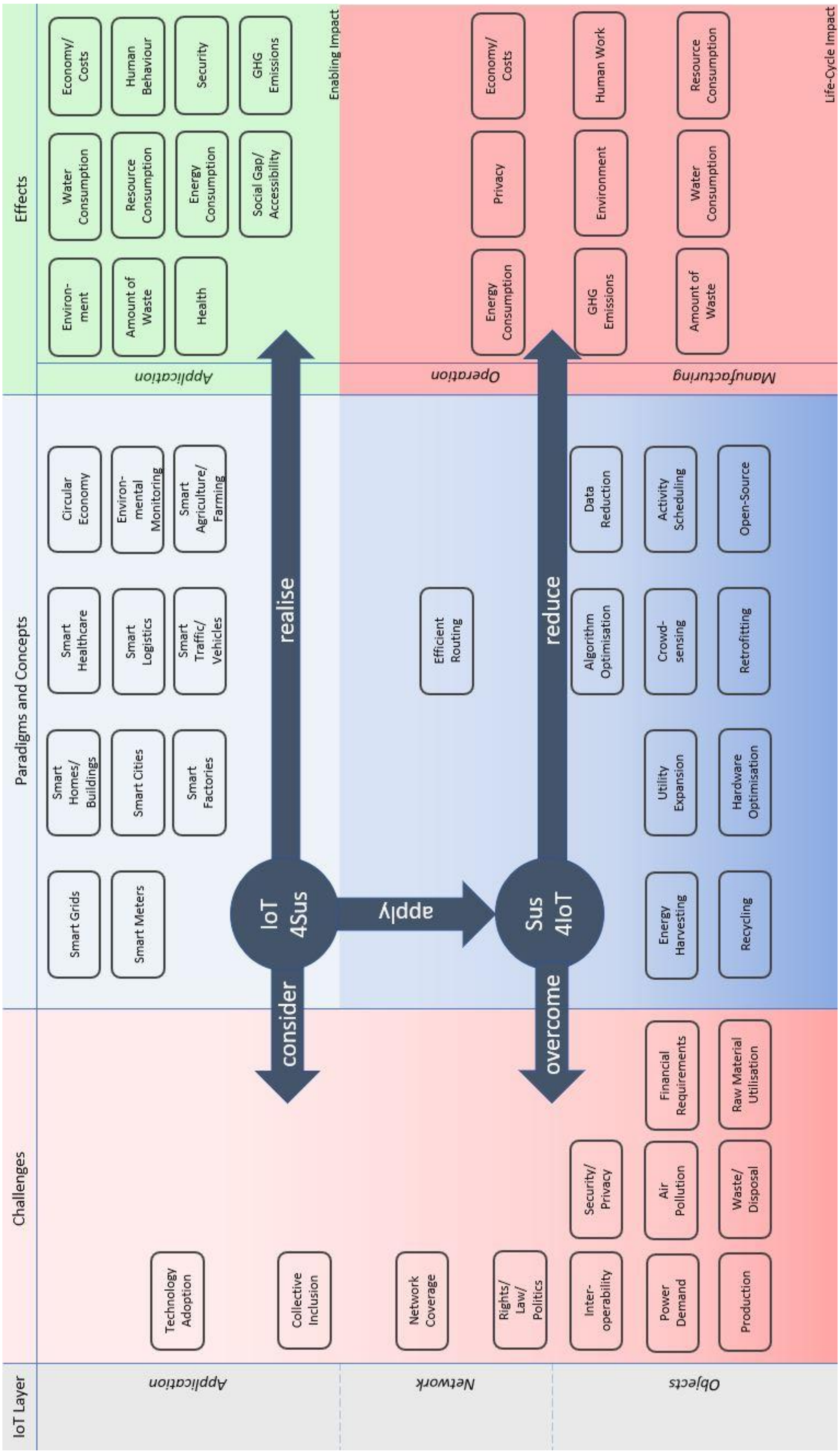

Figure 5.1: CCIS Framework - Textual version (own illustration)

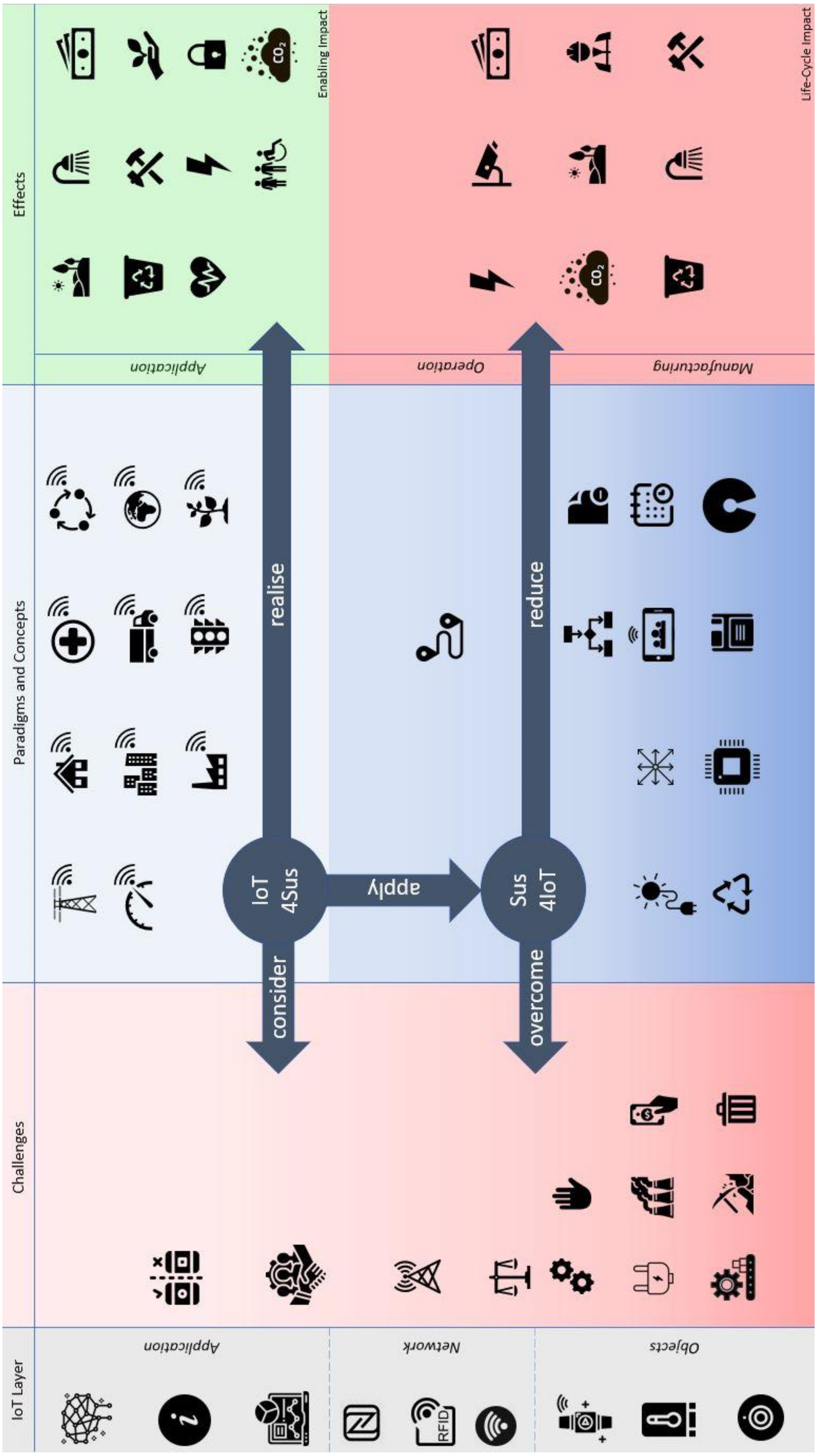

Figure 5.2: CCIS Framework - Icon version (own illustration)

6 Conclusion

The final chapter of this thesis provides a summarisation of the findings. Section 6.1 addresses and answers the research questions, which were described in section 1.2. The contribution of this thesis is emphasised in section 6.2. Subsequently, the limitations of the executed research are presented in section 6.3. The chapter concludes with implications for further research in this area (section 6.4).

6.1 Findings on Research Questions

This section describes the findings of this thesis along the, at the outset defined, research questions (section 1.2). Therefore, the answer for each research question is briefly described and referenced to the respective section of this thesis, where detailed assessments are provided.

RO1: Identification of a suitable definition and capturing of relevant aspects and characteristics of sustainability in the context of IoT.

RQ1.1: How is sustainability defined in the context of IoT?

Definitions of sustainability concerning ICT in the analysed literature vary and strongly depend on the focused area of sustainability, for instance, the environment. Section 3.2.2 provides an overview of these differing views of sustainability in relation to ICT and IoT. Regarding this thesis, sustainable actions are defined as such that enhance aspects of the *Triple Bottom Line* dimensions or are beneficial for the achievement of the *Sustainable Development Goals (SDGs*), provided by the United Nations General Assembly (2015). Referring to IoT, two concepts emerged and are explained in detail in section 4.1. Firstly, the concept of *IoT4Sus*, covering the application and usage of IoT technology in order to gain information, which is used to enhance sustainability aspects through respective activities. These activities can be executed by humans or automatically by the IoT system itself, for example through actuators. Secondly, *Sus4IoT* is defined. This definition focuses on sustainability aspects of the applied technology itself, for instance, the resource consumption of the manufacturing process and the energy consumption of IoT operation. *Sus4IoT* contains solutions that are applicable in an IoT system to reduce negative impacts on sustainability, which are associated with the providence of IoT technology.

RQ1.2: Which aspects and characteristics need to be considered in the context of IoT and sustainability?

The literature review revealed several aspects which should be considered when addressing the sustainability of the Internet of Things. Those aspects build the central elements for chapter 4 and are accordingly detailed in the respective sections of this chapter. *Drivers and Challenges,* described in section 4.2.1, are essential for the success of IoT projects and exhibit opportunities and threats in terms of sustainability. Following the precautionary principle proposed by Harremoës et al. (2001), *Effects* of IoT technology on sustainability are the essential element of interest and should be considered and examined before the deployment to prevent hazardous outcomes. A detailed description is provided in section 4.2.2. In order to assess those *Effects*, suitable *Indicators and Measurement Methods* should be applied. Methods are described in section 4.2.3 and need to be set individually to evaluate the sustainability performance of an IoT deployment. Ultimately, *Solutions, Concepts and Paradigms* of IoT need to be conceived as they produce positive and negative effects on sustainability. Concepts relating to *IoT4Sus* are described in section 4.3.1. The concepts in the are of *Sus4IoT* are posed in section 4.3.2. Furthermore, relations between identified aspects are depicted in Figure 4.2.

RO2: Examination of the link between IoT concepts and sustainability.

RQ2.1: How can IoT characteristics and solutions be classified in terms of sustainability?

Solutions and components of IoT can be classified into the categories of *IoT4Sus* and *Sus4IoT* and respective concepts to learn about their effects, opportunities and threats for sustainability. The classification of projects and components into the specific concepts of both categories provides a first overview regarding affected sustainability aspects. Furthermore, features and concepts can be classified in terms of the caused *Effects*. Therefore, the classification regarding the affected *SDG*, the dimension of the *Triple Bottom Line* and impact category of the LES model are suitable. Detailed explanations of the *SDGs* and the *Triple Bottom Line* are given in section 3.2.1, the description of the LES model is found in section 3.2.2.

RQ2.2: What are suitable indicators and measurement methods to assess the effects of IoT on sustainability?

Indicators for the assessment of effects in this context strongly depend on the specific objective and the measured effect. The analysed literature describes both, *Qualitative* and *Quantitative* methods to examine specific effects caused by IoT. *Quantitative* methods are applicable for the assessment of effects which are explicitly measurable through numeric values, for example, energy consumption. However, other effects of IoT are more complex to assess and require additional examinations through *Qualitative* methods, for instance, the effect on the social gap. In general, sustainability can be seen as an ideal state and activities which reduce the distance to this aimed state are classified as beneficial, while actions that increase the distance are described as detrimental. The detailed description of identified indicators and measurement methods is provided in section 4.2.3.

RQ2.3: What are the effects of certain IoT features and solutions on sustainability characteristics?

The effects of specific IoT solutions differ and strongly relate not only to the respective concept but the particular objective. Identified effects are impacts regarding *Energy Consumption, Economy/ Costs, GHG emissions, Human Behaviour, Resource Consumption, Amount of Waste, Environment, Health, Water Consumption, Security, Social Gap/ Accessibility, Privacy* and *Human Work*. Those impacts are described in section 4.2.2. An examination of particular IoT concepts concerning those impacts is provided in section 4.3.1 and summarised in Table 4.2. Furthermore, two categories for the tendency of impacts are described. *Enabling Impacts*, realised through the application and utilisation of IoT, affect sustainability aspects for the greater part positively. *Life-Cycle Impacts*, caused by the manufacturing and operation of IoT, influence sustainability aspects mostly negative.

RQ2.4: What are key drivers and challenges for the deployment of IoT in the context of sustainability?

Drivers are relevant to the relation of IoT and sustainability as they describe why and how IoT can be utilised to realise positive effects on sustainability aspects. The analysed literature provides drivers which are strongly connected to the acquisition, analysis and utilisation of large amounts of data. The identified drivers are *Monitoring, Process Optimisation/ Automation, Awareness Raising/ Behavioural Change, Data Acquisition/ Analysis, Tracking* and *Alerting/ Warning*. A detailed description of these drivers is provided in section 4.2.1.1. An illustration of the interrelations is depicted in Figure 4.3. Challenges are essential to consider as they potentially hamper the success of IoT deployments that aim to enhance sustainability aspects. Furthermore, some challenges pose a threat to sustainability and refer to negative effects in the category of *Life-Cycle Impacts*. The found challenges for IoT regarding sustainability are: *Power Demand, Financial Requirements, Waste/ Disposal, Security/ Privacy, Interoperability, Air Pollution, Collective Inclusion, Production, Rights/ Law/ Politics, Raw Material Utilisation, Network Coverage* and *Technology Adoption.* These challenges are described in detail in section 4.2.1.2. Relations between the challenges are depicted in Figure 4.4.

RO3: Development of a conceptual framework, which can be used to address sustainability in the context of IoT.

RQ3.1: What are general rules and aspects to consider when addressing sustainability in the context of IoT?

General rules are such, which were found multiple times in the literature and that were not just mentioned once regarding an isolated case. Aspects which are continuously described as relevant for sustainability in IoT are *Challenges, Concepts and Paradigms* and *Effects.* Furthermore, those areas are related to specific perspectives and *IoT Layers.* Therefore, these aspects are included in the proposed framework and build the illustrated components. Additional general rules are the included elements of the particular components. Depicted elements and relations are described multiple times and thus are considered as validated, except for the within this thesis suggested *Sus4IoT* concept of *Utility Expansion*. The specific application of these facets is described in section 5.2 and summarised in Table 5.1.

RQ3.2: How can the sustainability of IoT deployments and projects be enhanced?

During the course of this thesis, multiple opportunities to enhance the sustainability of IoT projects are described. The framework synthesises these different opportunities into a best practice suggestion. In order to realise positive and minimise adverse sustainability effects of IoT projects, this thesis suggests to early consider challenges for *IoT4Sus* solutions and to apply *Sus4IoT* concepts, which support the overcoming of challenges and reduce negative impacts on sustainability aspects associated with the manufacturing and operation of IoT components. This suggestion is depicted in the CCIS framework (Figure 5.1 and Figure 5.2).

RQ3.3: How can the findings be presented in a suitable manner?

To illustrate the findings and intricate relations of specific components swimlanes are utilised. Furthermore, relations are depicted with colours, placement of elements and labelled arrows. To enable a quick, intuitive comprehension, an icon version of the framework is provided (Figure 5.2). Furthermore, a version which depicts contained concepts in a textual way is given (Figure 5.1). Therefore, the CCIS framework is comfortably understandable while containing comprehensive information and relations of sustainability and IoT.

6.2 Research Contribution

This thesis provides several contributions to the research area of IoT and sustainability. Regarding the research gap, stated in the introduction of this work (section 1.1), a comprehensive, holistic overview of sustainability aspects in the context of IoT is developed. Therefore, this thesis provides a detailed and reflected assessment which includes a broad view on sustainability and pays attention to various aspects of IoT technology and usage. Furthermore, linkages between aspects of both areas are revealed and described to gain knowledge about the impacts of IoT deployments.

The detailed examination of the relations regarding this multidisciplinary topic in chapter 4 further clarifies the linkages between IoT and sustainability, and thus supports the precautionary principle to avoid hazardous impacts for humankind and environment. Furthermore, the examination reveals specific activities which should be taken to maximise the positive impacts of sustainability and reduce adverse consequences and challenges in this context. This is enabled through a detailed, comprehensive description, assessment and summarisation of concepts for the enhancement of sustainability aspects by the utilisation of IoT (*IoT4Sus*) as well as opportunities and paradigms to enhance sustainability aspects of IoT technology itself (*Sus4IoT*).

The findings are aggregated in the proposed CCIS framework, introduced in chapter 5. This framework poses a useful tool to conceive the linkages, impacts, reasons and concepts of IoT and sustainability. Furthermore, it is applicable for both researchers and practitioners to identify areas of interest, opportunities, threats, challenges and interrelations of specific IoT concepts. Moreover, the CCIS framework highlights suggested activities to enhance the sustainability of IoT projects by providing a general best practice method which emerged during the course of this thesis. Ultimately, the developed framework supports the awareness regarding sustainability aspects of the pervasive IoT technology and thus represents a constitutive element of future IoT developments and actions to enhance sustainability.

6.3 Limitations

The conducted work and the captured findings underlie some limitations, which are described in this section. The interpretation of the presented findings should consider that the selected research methodology of *Grounded Theory* based on a literature review utilises existing literature and does not involve own studies to verify and confirm provided statements. Therefore, the findings strongly depend on the collection and analysation of secondary data. Furthermore, the selection of data for the conducted work included some limitations, which are described in section 2.4. The included data represents only a part of possibly relevant data in this context and does not claim to be completely comprehensive. Moreover, the detailed examination of particular aspects which are relevant to this topic but outside the research area was neglected. This neglection includes, for example, the specific material composition of IoT components and their toxicity regarding the environment. In addition, the conducted work disregards detailed investigations of specific aspects and concepts to a certain degree in benefit for a comprehensive overview.

Regarding the analysed literature, the consistent emphasising of the positive effects of IoT on sustainability stood out. In contrast, the examination of adverse impacts is often neglected. The assertion that research within this context often focuses on isolated impacts of IoT on sustainability, described in the introduction of this thesis, confirmed during the course of analysis. Moreover, statements regarding impacts on sustainability are often given casually and vague. For instance, positive impacts of IoT applications in the area of the environment are frequently described without further particularising how these impacts occur and which aspect of the environment is affected.

The preceding described limitations transfer to the proposed framework. The CCIS framework provides a general subsumption in the context of IoT and sustainability and is suitable to procure first insights into relations, concepts and aspects. However, the application for specific projects is limited and requires further interpretation, refinement and adaption on an individual basis.

6.4 Implications for Further Research

Regarding future researches, this thesis revealed several implications. Relating to the preceding described limitations, future works in this area should adopt a broad view on sustainability rather than focusing on single aspects or dimensions. Furthermore, researches that aim to assess the effects of IoT on sustainability should include a comprehensive perception of IoT technology, including the manufacturing, operation, application, maintenance and disposal. This comprehensive perception is needed to provide detailed, reflected and holistic assessments of IoT in the context of sustainability.

In addition, the holistic assessment in this context requires further development and refinement of classifications and frameworks regarding single aspects, concepts and relations. The development of reliable, suitable indicators and measurement methods poses another requirement, which is essential for further research in this area to gain comprehensive and reflected insights regarding the sustainability impacts of IoT. To develop those indicators and examine the opportunities and threats of IoT technology further, a collaborative approach of ICT research and sustainability research is vital.

The previously described indicators and assessment methods are required to test and confirm the proposed effects further. Researches in this field often make vague statements and suggest opportunities for potential IoT deployments. This is partly reasoned by the novelty of IoT technology. However, the predicted impacts of IoT technology on sustainability should be underpinned by researches and real-world observations as soon as possible to prevent unforeseen adverse outcomes.

Ultimately, researches in the area of *Sus4IoT* concepts should be expanded and consider the entirety of IoT-related challenges. The overcoming of these challenges will unleash the full potential of IoT for sustainability by reducing the hampering, negative *Life-Cycle Impacts*.

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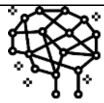
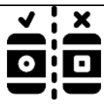
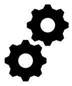
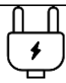
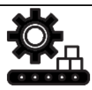
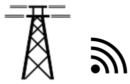
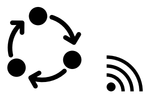
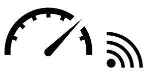
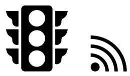
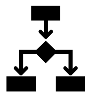
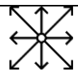
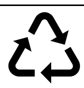
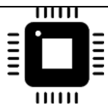
Appendix

Appendix 1: Legend for the framework

Component	Icon	Designation
IoT Layer		Interpretation
		Information
		Service
		Near-Field Communication (NFC)
		Radio Frequency Identification (RFID)
		Wi-Fi
		Smart wearable device
		Temperature sensor
		Sensor
Challenges		Technology Adoption
		Collective Inclusion
		Network Coverage

		Rights/ Law/ Politics
		Interoperability
		Security/ Privacy
		Power Demand
		Air Pollution
		Financial Requirements
		Production
		Raw Material Utilisation
		Waste/ Disposal
Paradigms and Concepts		Smart Grids
		Smart Homes/ Buildings
		Smart Healthcare
		Circular Economy
		Smart Meters
		Smart City

		Smart Logistics
		Environmental Monitoring
		Smart Factories
		Smart Traffic/ Vehicles
		Smart Agriculture/ Farming
		Efficient Routing
		Algorithm Optimisation
		Data Reduction
		Energy Harvesting
		Utility Expansion
		Crowdsensing
		Activity Scheduling
		Recycling
		Hardware Optimisation
		Retrofitting

		Open-Source
Effects		Environment
		Water Consumption
		Economy/ Costs
		Amount of Waste
		Resource Consumption
		Human Behaviour
		Health
		Energy Consumption
		Security
		Social Gap/ Accessibility
		GHG Emissions
		Privacy
		Human Work

Appendix 2: Coding Catalogue

BAR-SUS: Barriers for the deployment of IoT regarding sustainability aspects:

- BAR-SUS: Power Demand
- BAR-SUS: Security/Privacy
- BAR-SUS: Waste/Disposal
- BAR-SUS: Financial Requirements
- BAR-SUS: Interoperability
- BAR-SUS: Raw Material Consumption (other than energy)
- BAR-SUS: Rights, Legal, Politics
- BAR-SUS: Air Pollution
- BAR-SUS: Production
- BAR-SUS: Collective Inclusion
- BAR-SUS: Technology Adoption
- BAR-SUS: Network coverage
- BAR-SUS: Others

DIM-SUS: Dimension of sustainability:

- DIM-SUS: Environment
- DIM-SUS: Economy
- DIM-SUS: Society
- DIM-SUS: SDG1-No Poverty
- DIM-SUS: SDG2-Zero Hunger
- DIM-SUS: SDG3-Good Health and Well-Being
- DIM-SUS: SDG4-Quality Education
- DIM-SUS: SDG5-Gender Equality
- DIM-SUS: SDG6-Clean Water and Sanitation
- DIM-SUS: SDG7-Affordable and clean energy
- DIM-SUS: SDG8-Decent Work and economic growth
- DIM-SUS: SDG9-Industry, Innovation and Infrastructure
- DIM-SUS: SDG10-Reduced Inequalities
- DIM-SUS: SDG11-Sustainable Cities and Communities
- DIM-SUS: SDG12-Responsible Consumption and Production
- DIM-SUS: SDG13-Climate Action
- DIM-SUS: SDG14-Life below Water
- DIM-SUS: SDG15-Life on Land
- DIM-SUS: SDG16-Peace, Justice and strong Institutions
- DIM-SUS: SDG17-Partnership for the Goals

DRI-SUS: Drivers for/ functions of IoT in the context of sustainability:

- DRI-SUS: Monitoring
- DRI-SUS: Data acquisition and analysation
- DRI-SUS: Process optimization/automation
- DRI-SUS: Awareness raising/behavioural change
- DRI-SUS: Tracking
- DRI-SUS: Alerting/Warning

IMP-SUS: Implications on sustainability aspects:

- IMP-SUS: Energy Consumption
- IMP -SUS: Health
- IMP -SUS: Economy/Costs

- IMP -SUS: GHG emission
- IMP -SUS: Environment → applied if no further particularisation
- IMP -SUS: Amount of Waste
- IMP -SUS: Human Behaviour
- IMP -SUS: Resource Consumption (other than energy and water)
- IMP -SUS: Security
- IMP -SUS: Social Gap/ Accessibility
- IMP -SUS: Privacy
- IMP-SUS: Water Consumption
- IMP-SUS: Human Work

Sus4IoT-SOL: Solutions focusing on sustainability of IoT itself

- Sus4IoT-SOL: Efficient Algorithms/Protocols
- Sus4IoT-SOL: Energy Harvesting
- Sus4IoT-SOL: Data Reduction
- Sus4IoT-SOL: Efficient Routing
- Sus4IoT-SOL: Hardware Optimisation
- Sus4IoT-SOL: Activity Scheduling
- Sus4IoT-SOL: Efficient Infrastructure
- Sus4IoT-SOL: Open-Source
- Sus4IoT-SOL: Retrofitting
- Sus4IoT-SOL: Recycling
- Sus4IoT-SOL: Crowdsensing

IoT4Sus-SOL: Solutions to improve sustainability aspects by deployment of IoT

- IoT4Sus-SOL: Environmental Monitoring
- IoT4Sus-SOL: Smart Traffic/Vehicles
- IoT4Sus-SOL: Circular Economy
- IoT4Sus-SOL: Smart Homes/Buildings
- IoT4Sus-SOL: Smart Meters
- IoT4Sus-SOL: Smart Logistics
- IoT4Sus-SOL: Smart Cities
- IoT4Sus-SOL: Smart Factories
- IoT4Sus-SOL: Smart Grids
- IoT4Sus-SOL: Smart Healthcare
- IoT4Sus-SOL: Smart Agriculture/Farming

ASP-IOT: Aspects of IoT

- ASP-IoT: RFID
- ASP-IoT: Algorithms/Protocols
- ASP-IoT: WSN
- ASP-IoT: M2M
- ASP-IoT: Hardware
- ASP-IoT: Policies
- ASP-IoT: Cloud Computing
- ASP-IoT: Architecture
- ASP-IoT: Identification
- ASP-IoT: Sensing
- ASP-IoT: Communication
- ASP-IoT: Semantics
- ASP-IoT: Objects
- ASP-IoT: WBAN

- ASP-IoT: Storage
- ASP-IoT: Service/ Application
- ASP-IoT: Actuators

Rel: Relations

- Rel: enables
- Rel: hampers
- Rel: uses
- Rel: improves
- Rel: reduces
- Rel: worsens
- Rel: supports
- Rel: contrasts
- Rel: contradicts
- Rel: requires
- Rel: contains
- Rel: is a part of
- Rel: causes
- Rel: influences
- Rel: protects
- Rel: excludes