Designing Human-Centered Systems for the Internet of Things

Design-Case Study inspired Concept for End-User Data Work for tailorable information visualizations and analysis of IoT and IIoT Data

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Abstract

The Internet of Things (IoT) and the Industrial Internet of Things (IIoT) are fast-growing emerging topics of technical, social, and economic significance that not only affect work practices but also daily routines and habits. The IoT and IIoT comprise a network of smart physical things and devices (such as production machines and home appliances). The number of "things" connected via the internet or the intranet is constantly increasing. It is estimated that approximately 20 billion IoT devices will be online by 2020 [179].

Internet of Things and IIoT devices communicate with one another through software technology with the aim of making them more autonomous and cooperative [334]. In addition to technological advances in hardware for the efficient acquisition and communication of context and status data, software solutions in particular offer great potential for influencing many areas of everyday life and work; to this end, humans should be taken into account when designing new digital systems. The central element here is the use of digital data, which are now available in greater quantities and at a better quality than ever before. Currently, the amount of data produced daily is 2.5 quintillion bytes–this will continue to increase in coming years [366]. These data contain much valuable information, which can only be obtained through appropriate data analyses and visualization and correct embedding in their context.

The term "data work" has evolved as a superordinate area that combines all aspects of work with data to derive meaningful information, such as data consolidation, data processing, data refinement, data analysis, and data visualization [119]. This thesis focuses on end-user data work in the context of IoT and IIoT systems that supports users using their digital data by providing tailorable information visualizations and data analysis. From a Human Computer Interaction (HCI) perspective, this thesis examines how IoT and IIoT systems have to be designed to enable end-users to make digital data meaningful and usable. In this regard, and combining the areas of IoT

system design, end-user development (EUD) and information visualization, the main goals of this thesis are:

- To gain a deeper understanding of the use and appropriation of IoT and IIoT technology in different contexts,
- To gain insights about the use of digital data for daily routines, habits and work practices; and
- To evaluate possibilities for the development of a system design for end-user data work.

This work is based on empirical field studies that investigate different settings (domestic and industrial) in the context of IoT and IIoT. Seen through the lens of appropriation [37, 99, 102, 291, 337], relevant practices for deploying and using IoT and IIoT technology, especially the practices of working with digital data to support routines, habits, and processes, are identified and discussed for different application areas. This has resulted in the development of system requirements to support the process of making abstract digital data accountable and meaningful for users in their everyday life and work practices.

Grounded in these results, a concept of an end-user data work tool that allows the consolidation of digital data across system boundaries, lets users adjust the system to their context, supports flexible data visualizations, and empowers collaborative data work is presented.

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Related Publications

Parts of this dissertation have already been published as conference or journal papers.

- **Part II.I.4**: Castelli, N. Pinatti de Carvalho, F., Vitt, N., Taugerbeck, S., Tolmie, P., Stevens, G. and Wulf, V. 2019. On Technology-Assisted Energy Saving: Challenges of Digital Plumbing in Industrial Settings. (HHCI Journal *in review – revised version*).
- **Part II.I.5**: Castelli, N., Schönau, N., Stevens, G., Schwartz, T. and Jakobi, T. 2015. Role-based Eco-info Systems: An Organizational Theoretical View of Sustainable HCI at Work. ECIS 2015 Completed Research Papers.
- **Part II.I.6**: Castelli, N., Taugerbeck, S., Stein, M., Jakobi, T., Stevens, G. and Wulf, W. 2020. Eco-InfoVis at Work: Role-based Eco-Visualizations for the Industrial Context. PACM on Human-ComputerInteraction4, GROUP, Article 02 (January 2020)
- **Part II.II.7**: Castelli, N., Stevens, G. and Jakobi, T. 2019. Information Visualization at Home: A literature survey of consumption feedback design. *International reports on socio-informatics*. 16, 1 (2019).
- **Part II.II.8**: Castelli, N., Ogonowski, C., Jakobi, T., Stein, M., Stevens, G. and Wulf, V. 2017. What Happened in My Home?: An End-User Development Approach for Smart Home Data Visualization. Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems (New York, NY, USA, 2017).
- **Part II.II.9**: Castelli, N., Stevens, G., Jakobi, T. and Schönau, N. 2016. Beyond Eco-feedback: Using Room as a Context to Design New Eco-support Features at Home. Advances and New Trends in Environmental and Energy Informatics. J.M. Gomez, M. Sonnenschein, U. Vogel, A. Winter, B. Rapp, and N. Giesen, eds. Springer International Publishing. 177–195.

Additionally, these publications contribute to the presented topic. However, they are not included as chapters of this book.

- Castelli, N. and Stevens, G. 2016. Das Zuhause verstehen: Eine Literaturstudie zur Visualisierung von Verbrauchsdaten. *WISSENSCHAFT TRIFFT PRAXIS*. (2016), 58.
- Castelli, N., Ogonowski, C., Stevens, G. and Jakobi, T. 2014. Placing Information at Home: Using Room Context in Domestic Design. *Proceedings of the 2014 ACM International Joint Conference on Pervasive and Ubiquitous Computing: Adjunct Publication* (New York, NY, USA, 2014), 919–922.
- Castelli, N., Stevens, G., Jakobi, T. & Schönau, N., (2014). Switch off the light in the living room, please! –Making eco-feedback meaningful through room context information. In: Gómez, J. M., Sonnenschein, M., Vogel, U., Winter, A., Rapp, B. & Giesen, N. (Hrsg.), Proceedings of the 28th Conference on Environmental Informatics - Informatics for Environmental Protection, Sustainable Development and Risk Management. Oldenburg: BIS-Verlag.
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- Jakobi, T., Ogonowski, C., Castelli, N., Stevens, G. and Wulf, V. 2017. The Catch(Es) with Smart Home: Experiences of a Living Lab Field Study. *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems* (New York, NY, USA, 2017), 1620–1633.
- Ludwig, T., Stein, M., Castelli, N. and Hoffmann, S. 2018. Sicherheitskritische Mensch-Maschine-Interaktion bei Industrie 4.0. *Sicherheitskritische Mensch-Computer-Interaktion*. Springer Vieweg, Wiesbaden. 229–251.
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1. Introduction

The Internet of Things (IoT) is a fast-growing trend of technical, social, and economic significance that not only affect work practices but also daily routines and habits. The term IoT describes networks of "smart" physical things and devices that are also often referred to as a cyber-physical system (CPS; connected devices such as production machines and home appliances). Internet of Things devices communicate with each other and with software services running on the Internet with the aim to make themselves more autonomous and cooperative [334]. The number of IoT devices is constantly increasing. It is estimated that approximately 20 billion will be online by 2020 [179].

1.1. Motivation

IoT technology is the biggest driver of current digitalization strategies and procedures. The fields of application are diverse. For example, in the areas of home automation, home security, healthcare, and smart vehicles, as well as connecting industrial machines to optimize production processes in the so-called Industrial Internet of Things (IIoT). Smart objects such as fitness trackers have become an integral part of everyday life and are still spreading as extensions of the smartphones that have become ubiquitous in the last decade.

In addition to technological advances in hardware that allow the efficient acquisition and communication of context and status data, software solutions in particular offer considerable potential for influencing practices of everyday life and work. The central element here is digital data, which are now available in higher quantities and at higher quality than ever before. The current amount of data that are produced every day is estimated to be 2.5 quintillion bytes, and this is set to continue increasing in coming years [366].

While there is a growing body of work that deals with the data collection process and the associated infrastructural challenges [219], studies dealing with the harnessing of data remain rare and focus mostly on a very technical level [65, 213, 314]. The data contain a great deal of valuable information, but they can only be extracted through appropriate data analyses, data visualizations and the correct embedding in the context. Current literature has mainly focused on automated analysis [100, 226, 254]; however, the views of users who are faced with an ever-increasing amount of data has been largely neglected so far [213].

Additionally, as stressed by End-user development (EUD), Human-Computer Interaction (HCI) and computer supported cooperative work (CSCW) research, it is important to understand people's sensemaking of new technologies; this has been described with the term appropriation. The same is necessary for data, that is, studying people in the process of their sense making of and interacting with digital data [213]. Lack of understanding increases mistrust of such systems, which has a negative effect on their usefulness that can even extend to nonuse [334, 343]. Moreover, while machines can process large quantities of data efficiently, people are much better at analyzing and assigning and recognizing patterns of data [64, 267, 381]. Providing transparency and keeping humans "in the loop" allows them to better reflect on own activities and processes, make better decisions, and explore new areas of application [119, 293, 336]. This is particularly important for the IoT and IIoT, as these are increasingly finding their way in many areas of life. Therefore, people need to be given opportunities to work with the data.

An approach that combines all aspects of working with data to derive meaningful information is called "data work" [119]. Data work includes all activities that are associated with the process of making sense of data, such as data consolidation, data processing, data refinement, data analysis, and data visualization.

Currently, data work is mostly conducted by data scientists. Data scientists are experts in working with data and have the skills to prepare, consolidate, visualize, analyze and handle amounts of data in order to answer particular questions (such as those concerning the identification of unusual patterns or trends in the data) [105]. Data scientists are often assigned in large companies only, as small and medium-sized enterprises often do not have the financial resources. In the domestic context there are not even professional data scientists so far. Additionally, data scientists often lack explicit contextual knowledge of the specific context and therefore often leave potential use cases untapped. People who are directly affected by IoT and IIoT systems, such as employees working at machines or residents of a smart home, often do not have much technical knowledge and lack the skills to approach the data and to visualize and analyze them in order to make sense of them (here, these people are referred to as end-users). But, they have practical knowledge of practices, processes, procedures or work steps through their daily actions and experiences.

Hence, the fundamental challenge is to create environments that allow end-users who do not have the relevant (technical) skills to work with digital data to use them for their everyday activities through the linkage with one's own experience. This would allow them to reflect on their own activities and production processes, gain information about the use of resources, develop an awareness about the environment, build more trust in the system, and make better-informed decisions. Currently, some software tools already exist that support users to analyze and visualize digital data (see Subsection 2.2.2); however, these tools are aimed at data experts in companies and mostly rely on static data than on IoT and IIoT data.

1.2. Areas of Contribution

This thesis contributes to the field of IoT and IIoT by developing concepts to support the data work of end-users. In doing so, it understands digital data work as an emerging topic of research that is closely linked to three fields of research: IoT system design, end-user development, and information visualization.

Internet of Things and IIoT engineering deals with the generic, context-independent design of IoT systems and infrastructures. It includes the levels of hardware/device, infrastructure, applications, and services engineering [389]. While the design of hardware/devices and infrastructure are beyond the scope of this work, this thesis demonstrates how IoT and IIoT software can provide the necessary basis for enabling data work by end-users.

The research field of EUD aims to empower end-users to work with (software) systems and to adapt these systems to their specific needs [224]. By creating new layers of abstraction, EUD intends to enable users to easily and intuitively tailor a system without having a deep understanding of the underlying complexity of the software system. This thesis transfers this concept and approach to the IoT and IIoT context and shows how EUD can be implemented to provide users with the tools to engage in end-user data work and thus make better use of their digital data.

Finally, information visualization is an interdisciplinary field of research that has the goal of making information from data visible. Information visualization deals with "the use of computer-supported, interactive visual representations of data to amplify cognition" [52] and comprises various methods and approaches for generating target-oriented and application-

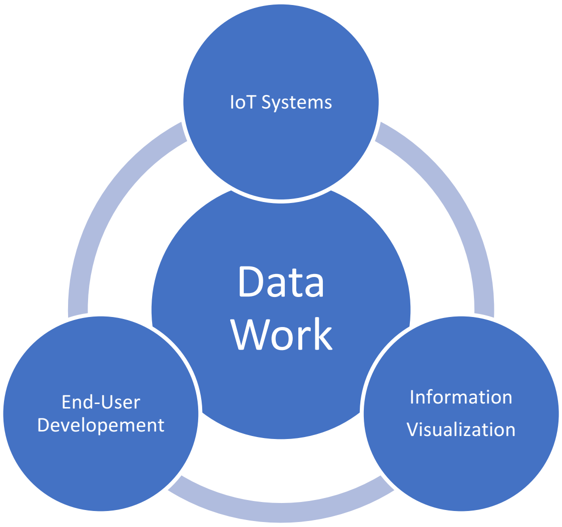

Figure 1. Research areas and their interaction within the thesis

oriented data visualizations. This thesis shows how these techniques can be made available to end-users so that the added value of the digital material (*the data*) can be converted into usable and valuable information.

This work focuses on end-user data work in the context of IoT and IIoT systems in order to help users to explore their data by means of tailorable information visualizations and analysis. In particular, this thesis investigates how end-users can be placed at the center of IoT and IIoT systems so that they can make sense and use of digital data for end-user digital data work, combining the areas of IoT system design, EUD, and information visualization (see Figure 1). The main goals of the thesis are:

- To gain a deeper understanding of the use and appropriation of IoT and IIoT technology in different contexts,
- To gain insights about the use of digital data for daily routines, habits and work practices; and
- To evaluate possibilities for the development of a system design for end-user data work.

This work is based on empirical field studies that investigate different settings within the IoT and IIoT context. Seen through the lens of appropriation [37, 99, 102, 291, 337], relevant practices in deploying and using IoT and IIoT technology, especially digital data, for routines, habits, and processes are identified and discussed in different areas of application. Based on the collected findings, this paper proposes a concept and implementation for digital data work for end-users in the domains of IoT and IIoT.

1.3. Structure of the Thesis

This thesis consists of three parts. Chapters 5, 6, 7, 8, and 9 from Part II, which constitute the core of this work, have already been published in peer-reviewed publications. Chapter 4 is a revised version that was submitted and is currently under review. In this thesis the camera-ready versions of the studies have been used and have been adapted to the format of this thesis with minor modifications (mainly by harmonizing the labelling of images, tables and references).

- **Part I** frames this work and places it in the context of the current literature and existing work. Additionally, it defines the necessary terminology in the fields of IoT/IIoT, EUD, and information visualization. Furthermore, it presents the research perspective and methodology of this work.
- **Part II** presents the (use-case) studies on the appropriation and use of digital data that informed the design of the framework. These are presented as a collection of peer-reviewed articles.
- **Part III** summarizes the results and discusses the overall contribution in relation to the current literature. Furthermore, it discusses further questions and links to future research.

I. Overview

2. Related Work

This chapter introduces relevant research topics and directions in the field of IoT and IIoT (Section 2.1), information visualization (Section 2.2) and EUD (Section 2.3) that form the basis of this thesis. Relevant parts of these disciplines are embedded in an “End-User Data Work for IoT and IIoT” outline at the end of the chapter (Section 2.4). These research areas are considered from the perspective of different scientific disciplines. This work focuses on CSCW and HCI, which first introduced the user’s perspective in design and development and began to explore the appropriation of software systems and how people make use of information technology (IT) artifacts, which are central aspects of this work.

2.1. Internet of Things and Industrial Internet of Things Application Areas

Internet of Things and IIoT technology constitute a socio-technical infrastructure that can be used in almost all areas of daily life. This includes smart cities, smart grids, smart agriculture, smart retail, smart supply chains, and smart health. It thus increasingly spans boundaries and contexts in multiple areas, such as work and home. It is shaped by business processes, user preferences, and task requirements.

Typically, IoT and IIoT systems combine hard- and software. This entails sensors capturing various data digitally, networks to transfer these data across different networking infrastructures, middleware, and databases to collect, consolidate, retain, combine, and analyze these data in an IoT/IIoT gateway, which then exposes the data to other devices, services, systems, and actors [9, 219]. In terms of the current state of research, this thesis focuses on areas that have a particularly strong influence on end-users in everyday life and that are part of this research. This involves the areas of smart homes and smart energy (domestic context) as well as smart industry and digital energy management (industrial context).

2.1.1. Smart homes and smart energy

The first smart home and smart home energy management systems were developed in the 1980s when the first personal computers became available and hobbyists created do-it-yourself solutions to collect digital data from the home and to automate specific parts for their daily life [160]. Today, there are an increasing number of commercial smart home solutions readily available on the market. Starting with systems that provide solutions for single use-cases (e.g. smart thermostat, smart sockets, smart lights, etc.) to current solutions that allow the integration of more complex use-cases by combining different sensors and actuators [44]. Smart home energy management systems are home automation systems that focus on saving energy, using a variety of sensors and actuators to achieve this goal. In contrast, smart home systems primarily focus on increasing the comfort of the residents, meaning that they have a large overlap with the home energy management area.

In recent years, research on smart homes or home energy management systems has mostly focused on technology, such as enabling technology, including hardware and (network) infrastructures [6]. New, affordable, and efficient IoT technology has given particular priority to the areas of digital retrofitting, digital network communication, sensors, and actors. Due to new possibilities for setting up digital technology in the home, the complexity involved in installing such systems and operating and maintaining them has also increased. Several studies that deal with topics such as “digital plumbing” and “end-user installation” [148, 355, 356] describe the complexity of running such systems. The studies of Grinter et al. [148] and Tolmie et al. [355, 357] in particular have examined the work that has to be done to manage and run a home network. These studies detail a number of challenges, such as the necessity of a holistic view of network interdependencies and consideration of environments that change over time. Tolmie et al. [355, 357] were able to recognize the strong connection between everyday activities and the set-up process and uncovered the following insights: (1) the work of installing the network is partly integrated into that of physical housekeeping, (2) the maintenance of the technology is based on certain routines and events, and (3) extending the network involves the integration of new technologies on the basis of existing and established practices.

In addition to the installation and maintenance of such digital smart systems in the home, there are many other works focusing on the user-driven configuration of automation rules [240]. These studies distinguish between two areas of home automation configuration that differ in their complexity and their condition of triggering [44]. First, there is the configuration of "multiple-actions", where a command is executed by the user and triggers several events. A prominent example of this is the "all-off switch," where an action of the user (activating a button or clicking a switch) turns off different devices, such as lamps and multimedia devices. Second, there is the configuration of event-based functions, so-called trigger-action rules. Here a (digital) event triggers a certain action, so the user is only passively involved in the execution (e.g. a motion detector reports a detected motion). The configuration of trigger-action rules or task automation [71] forms the content of several available studies (e.g. [90, 93, 177]).

In this vein, research has been interested in how end-users can be enabled to easily create their own rules without the need for explicit technical knowledge. The available tools and research approaches can be divided into two main categories. The first approach is a wizard procedure that guides the end-user step by step through the rule-creation process. The most prominent example of systems on the market is if-this-then-that [180], where users select a trigger event (from a list of available services) and an action that should be executed (from a list of available services) when the trigger event occurs. The second type of approach is so-called wired-programming environments, such as Node-Red [265]. Here, the user has a visual programming interface where more complex rules can be created. The wired-programming environments offer more freedom for creating rules but also require more skill from the user [91]. Such systems take it for granted that users already have full knowledge of the data that, for example, triggered the event. In the literature, however, it is evident that, without visual representation of the data, users find it difficult to interpret or classify them [356]. Existing EUD approaches are promising candidates for solving the problem, but they need to be extended by including aspects of data analysis and information visualization.

Another component of the research in the area of HCI deals with the design of interfaces to raise awareness or to provide transparency. In relation to smart homes, there is relatively little research on the overall design of systems that deal with smart home data or make the combining of digital home data usable for end-users [35]. Available systems mostly provide raw data to the users in form of numbers, text, tables, or basic charts [241] and do not provide a link between the different data, rather treating the individual sensors or data sources in isolation from one another [356]. The study of Mennicken et al. [241] is one of the few studies dealing with the design of a data-based smart home information system. The authors integrate digital home data into a digital calendar to illustrate the logical link between daily routines and the digital system.

With regard to the visualization of smart home data, there is a number of studies concerning eco-feedback to support energy-efficient behavior by raising awareness of energy consumption (e.g. [29, 87, 135, 320, 321]). Assuming that wasteful behavior results from a lack of information, such systems try to make consumer behavior and its consequences visible. The concept is based on rational behavior theories such as rational choice or the theory of reasoned action [122] as well as comparable theories in HCI, such as persuasion theory [125]. The studies examine a variety of approaches, ranging from simple systems that represent raw data of total household consumption [190] to more advanced systems that use different design and motivational approaches to fine-grained energy consumption data [315]. This has resulted in a series of design guidelines [165, 232] and frameworks [29, 123, 308] for the visualization of consumption data in the home. Time, place, and the type of feedback play a crucial role in relation to the impacts of eco-feedback design [123]. Increasingly, other individual and user-specific aspects, such as age [308], gender [5], experience [75, 286], are taken into account as these also influence the effectiveness of eco-feedback.

2.1.2. Smart industries and digital energy management

Industry has always been influenced by (technological) advances. After the advances in the fields of water and steam power (the 1st Industrial Revolution), electricity and assembly lines (the 2nd Industrial Revolution), and automation technology (the 3rd Industrial Revolution), we are now assumed to be in the 4th Industrial Revolution in which the digitization of work processes optimizes their efficiency [55, 192, 248, 295].

Increasingly, IoT and IIoT technology in the form of new hardware or software is being incorporated in companies to better monitor processes and to make visible the scope for optimization. New machines are already equipped with digital equipment, and digital retrofitting is also becoming increasingly common. For example, analog control signals from machines are converted and stored digitally, radio-frequency identification (RFID) tags are used to track parts on the production line, and new input masks are being developed to manually capture data and store them digitally to make them digitally usable [9, 219].

The IIoT is particularly data-driven and could be used for automation and decision support. The literature currently distinguishes between three levels of data types: (1) data about production machines, which contain information about the condition and the work performed (e.g. manufactured parts, speed, etc.) [220]; (2) data about the human workers, such as their working hours or noise pollution [352], and (3) data about the environment and the context, for example, about the temperature in the production hall or the air pressure, that is, data that could affect the quality of the products and the efficiency of the production process [369].

A specific variant of IIoT systems today in companies are energy management systems (EMS), which are currently acute due to climate change and the actuality of the “Energiewende”. Energy management systems are also data-driven systems that attempt to optimize the energy efficiency and resource consumption of companies. Small and medium-sized enterprises in Germany often make use of EMS as first step to IoT and IIoT technology, since, one the one hand, they are partly compelled by law to use energy more efficiently and, on the other, they can reduce their tax burden or receive tax relief by efficiently handling resources [187].

In the literature, the topic of improve energy efficiency within the work context is studied from different angles in order to support companies by using digital technologies. In the information systems community, for instance, studies deal with environmental management information systems [108], with a clear focus on the technical and management aspects. For example, Gahm et al. [136] have examined current approaches to the energy-based scheduling of production processes. Muromtsev et al. [257] and Kong et al. [212] have investigated the possibility of automating sustainable process controls. Load-shifting and demand-response programs that try to adapt processes dynamically to avoid peak loads have also been well investigated (e.g. Hopper et al. [174] and O'Connell et al. [269]).

In HCI, studies dealing with sustainability or energy efficiency in the work context are rather rare. In particular, in HCI, the shop floor and the production sector have been neglected so far. Instead, most work-oriented studies focus on human factors relating to energy consumption in office environments [187, 385]. Nevertheless, such studies offer valuable insights into the increasing complexity of workplace environments. In the two studies by Yun et al. [384, 385], the authors reveal that the motivation of users is a challenge as they are not directly affected by inefficient behavior. This was confirmed by Schwartz et al. [319], who installed smart metering technology in an office environment. Initially, they could see that workers were consciously deal with this topic; however, this effect could not be maintained over a longer period of time and workers reverted to their old patterns. Studies by Carrico and Riemer [53] and by Murtagh et al. [258], which also examined the influence of eco-feedback in the office context, confirm these results, which are explained by the highly complex interweaving of feedback and behavior that lead to the injunction "not to turn things off."

However, Yun et al. [384, 385] assert that the more active support employees received from the system, the more energy was saved. According to the authors, it is crucial that the information that is made available to users be well embedded in their everyday work. This was also recognized by Foster et al. [128] and Abrahamse et al. [1], who investigated various approaches in their work, including environmental psychology (such as social comparison, goal setting, etc.), to derive design guidelines for eco-feedback systems.

The findings discussed above only partly overlap with those pertaining to private households. Accordingly, a “one size fits all” solution is rarely appropriate. Feedback should be application-oriented and action-oriented so that users can make sense of the data [319]. This is consistent with the statements of He et al. [165], who do not consider standardized eco-feedback to be realistic. The main argument concerns the individual phases of a behavioral change process [297]. Constanza et al. [74] support the consideration of individual aspects, especially individual expertise (e.g. technical knowledge), when designing eco-feedback systems in an organizational context. However, Hazas et al. [164] note that it is not enough to consider only the individual.

For this, Bedwell et al. [21] provide another important finding in their study on energy consumption in office environments. They recognize that organizational structures (roles, responsibilities, and hierarchies) must be taken into account when designing systems. Therefore, behavior at the workplace is influenced by both individual changes and organizational changes (and vice versa). This represents a major challenge for the design of organizational eco-feedback.

2.2. Information Visualization

The issues outlined in the previous section have a direct impact on the presentation and integration of digital data in such systems. Information visualization deals with the question of how information can be obtained through the effective visualization of data in order to help people carry out their tasks more effectively [305]. The discipline has a long tradition within the HCI community (e.g. [69, 167]); it tries to involve users in the process of data exploration so that their knowledge and experience can be integrated into the data analysis [200].

2.2.1. Ways of doing information visualization

There are many ways to create suitable visualizations to achieve a certain goal or to solve a certain problem (e.g. [3, 67, 199]). In his survey, Keim [199] distinguishes the different approaches on the basis of three criteria. The first criterion is the type of data to be visualized. These can have different characteristics, which influences the necessary visualization. Keim [199] distinguishes between one-dimensional data, two-dimensional (2D) data, multidimensional data, text and hypertext, hierarchies and graphs, as well as between algorithms and software. The focus is on the dimensionality of the data, that is, the number of attributes of a measurement. However, not only the dimensionality but also the relationships and the flow between the data points are of importance. Suitable visualizations can already be identified based on the data type, for example, a line chart for stock price data (one-dimensional) or a map for global positioning system (GPS) data (two-dimensional).

The second criterion is the visualization technology. Keim [199] distinguishes between standard 2D/three-dimensional (3D) representations, geometric displays, icon-based visualizations, dense pixel displays, and stacked representations. The visualization technique indicates the possibilities for mapping data points to visual elements, which are better or worse suited to the task depending on the data set. For example, dense pixel displays are particularly well suited to visualizing dependencies on many data points since they display each data point using one pixel and thus make cluster points visible.

Keim’s [199] third criterion distinguishes between the classification of interaction and distortion techniques. Here, he names interactive projection, interactive filtering, interactive distortion, and interactive linking and brushing. Here, the user's interaction is in the foreground so that the exploration goals can be achieved step by step. The user can thus interact directly with the data to extract the targeted information. As an example, Keim [199] mentions the linking of different visualization forms so that the disadvantages of individual forms neutralize one another.

The approach of Chittaro [67] is divided into six steps: mapping, selection, presentation, interactivity, usability, and evaluation. In the first step, information is "mapped" to visual variables, therefore, an accurate visual representation of the data points is created. The selection step (Step 2) involves the selection of a (sub)section of the data that are relevant for the solution of the task. Presentation (Step 3) involves placing the information in the available space (e.g. limited by screen size, etc.). Step 4 (interactivity) describes the selection provided to the user for interacting with the visualization. Usability (Step 5) focuses on the human factor so that the visualization can be kept simple, accessible, and can be used. The last step (Step 6) is to evaluate the designed visualization and to check its suitability for achieving the goals.

A more systematic approach to creating suitable visualizations, especially for time-based data, is offered by Aigner et al. [3]. In their approach, they distinguish between three levels, each of which should answer a question: time and data (What has to be presented?), task-level (Why should it be presented?) and visual representation (How should it be presented?).

At the first level (time and data), a distinction is made between the modeling of time and the characteristics of the data. When modeling time, it is first necessary to identify the scale involved: Are time specifications given only relatively (ordinal), are they "rounded" to fixed time specifications (discrete), or are they real time specifications with a further time unit between each specified point in time (continuous)?

Furthermore, Aigner et al. [3] distinguish between data point-based (no information between two points) and data interval-based (where the subsections are known) time-series. The third aspect of time is arrangement. A distinction is made between linear time (continuous) and cyclic time (recurring). Aigner et al. [3] also differentiate between viewpoint, granularity and time primitives. When characterizing data, both Aigner et al. [3] and Keim [199] distinguish between the dimensionalities of the data (univariate - one-dimensional vs. multivariate - multi-dimensional). In addition, the scale of the data is also differentiated, that is, whether the data are quantifiable or not (numbers vs. words/terms). Aigner et al. [3] differentiates between event-based data and states as data types. States can be understood as values between events. Finally, the assignment or relation of the data is considered (abstract vs. spatial).

Task models are widely used within the HCI to ensure that the specification of the task is fulfilled by the visualization [70]. Andrienko and Andrienko [7], among others, offer a basic task model, which consists of three levels. First, a distinction is made between the two main tasks: elementary tasks and synoptic tasks. For elementary tasks, not all existing data points are considered in their entirety, but only individual points. Conversely, synoptic tasks concern a general view of all the data points. Elementary tasks can then be divided into lookup tasks (searching for a specific data value), relation-seeking (searching for relations between data references), and comparison (of values). In the task model, synoptic tasks are further divided into descriptive tasks (to find a pattern that describes a set of data) and connected tasks (finding influences between variables).

The third level that Aigner et al. [3] introduce is that of visual representation. Here, the authors first distinguish between static visualizations, which do not change their data base (but can be interactive), and dynamic visualizations (which adapt their data base). As a second step, the dimensions to which the data should be mapped are determined, that is, either 2D or 3D.

Using the information visualization pipeline [52] to compare the three approaches reveals similarities as well as some differences: Keim [199] and Aigner et al. [3] first mention the characterization of data as a starting point for the first selection of potential visualizations. While Keim [199] and Chittaro [67] move directly to the mapping of the data to visual variables and visual representations, respectively, Aigner et al. [3] separates this step. They explicitly set the level of identification before this step, while Keim [199] and Chittaro [67] undertake this step directly with the mapping of the data. Keim [199] and Chittaro [67] introduce a final step, which explicitly takes care of the interaction and the evaluation of the created visualization in order to create more suitable visualizations. Aigner et al. [3] place more emphasis on explicit support for the tasks through the use of gestalt laws (e.g. color coding). Nevertheless, what is common in all approaches is that the user is at the center, as he defines the problem, selects data sections, and does the exploratory work.

2.2.2. Frameworks and tools

There are only a few research prototypes, commercial tools, and frameworks available (e.g. [19, 114, 167, 350]) that support users in this process of creating own suitable visualizations.

These tools support users in choosing and importing the “right” data sets as well as with visualizing them in different ways. This includes, for example, the query of interfaces for data import, the consolidation of data into formats suitable for visualization, the volatile storage of data, and the combination of different data sources. The user should undertake the visualization of the data in a simple and intuitive way.

These tools and frameworks predominantly originate in the information visualization community [167]. One of the first prominent examples is the InfoVis Toolkit by Fekete [114]. The InfoVis Toolkit is a Java library for Java Swing applications that allows the creation of advanced 2D visualization components based on dynamic queries. The InfoVis Toolkit uses tables as its data structure, and it already contains a large number of interaction components (range sliders, fisheye view, etc.) and five supported visualizations (scatter plots, time series, treemaps, node-link diagrams, and adjacency matrices). A focus of the work of Fekete [114] is how data points can be easily mapped visual forms.

Another example is the XML Toolkit by Baumgartner et al. [19]. First developed in 2000, this was initially a toolkit for teaching and research purposes that was then opened for further information visualization use-cases. The goal was to automate the skill needed (selecting algorithms, interaction forms, etc.) to find suitable visualizations that best fit groups of users, their tasks, and their data. The authors developed an XML-based interchange format for including different kinds of data in the toolkit. Based on this unified format, multiple algorithms are included to visualize the data (e.g. BubbleMap, GRIDL, Hyperbolic Tree, Treemap, etc.). However, users need a basic understanding of the algorithms that are included to create own visualizations.

Prefuse by Heer et al. [167] is another toolkit for interactive visualization that has the goal of creating very specific data representations. Prefuse offers several interfaces for integrating data. From this data, visual forms are generated, which are then rendered and displayed on the screen. In addition, the Prefuse toolkit offers various interactive controls with which the user can interact with the visualization. Prefuse is primarily aimed at programmers who can integrate the toolkit into their application as a library in order to use it as a basis for domain-specific tools.

A popular commercial software application for creating visualizations of business intelligence data is Tableau [350]. Tableau is professional analytics software for the analysis of primarily static business data, such as sales or customer data. It offers a variety of functions and visualization options and is primarily aimed at specific areas in companies that deal with the evaluation of company data (e.g. the finance department or marketing department). Tableau focuses on analysis rather than on monitoring digital data.

Another current example that has received much attention due to developments in IoT and IIoT technology and digital data, is the visualization tool, Grafana [353]. It is developed as an addon to influxDB, a specialized time-series database that can store time-related data highly efficiently and that has integrated time-based operations (such as aggregation). The data is already available in a uniform structure. The user can then write his or her own queries (in a manner similar to structured query language) and display the data on a timeline.

These tools have in common that they try to relieve the user of work. However, explicit or expert knowledge is often needed to use the tools, and the user has to have experience of database queries, programming, and visualization basics (e.g. how to best map values to a different axis). In addition, these tools focus on either monitoring or creating analyses. Furthermore, it is often not possible to take the specific context into account and thus allow different users easy access to interpretable data. This excludes a large proportion of users who come into contact with the data through new (IoT and IIoT) technology.

2.3. End-User Development

An approach that could close this gap is EUD. End-user development is an established field of research that aims to make systems that are easy to adapt [223]. End-user development is part of HCI and has evolved from the idea of making systems easy to use up to the idea of enabling users to extend systems to evolving and changing needs themselves. This can be achieved through the integration of simple environments that allow users to develop new content independently without the need for programming skills, or as Lieberman et al. define EUD:

> *End-User Development can be defined as a set of methods, techniques, and tools that allow users of software systems, who are acting as non-professional software developers, at some point to create, modify or extend a software artefact.* [223]

One of the most prominent examples of EUD are spreadsheet applications. Users can enter their own forms, formulas, and dependencies in such applications, which can automate or support various working steps. It is always of interest to see how people use such applications for other purposes other than those for which they were originally intended [223].

2.3.1. Concepts

End-user development includes a wide range of different concepts, the most prominent ones are parameterization/tailoring, scripting, wizards, programming by example/programming by demonstration, model-based development and visual programming [223]. These concepts or activities can be classified into two types [223] or classes [73]. The first allows the user to customize the software using content that is already included in the application. The user is not able to create new content, but has pre-defined options to choose from. The second type of concept provides users with an environment that lets them modify content or create new content. Parametrization, tailoring or annotations typically belong to the first type of concept, while the others belong to the second.

In most cases, parametrization [361] or tailoring is the simplest concept of EUD. Software is built in a flexible and configurable way so that the user has numerous options for configuring the software based on predefined choices. Scripting [361] refers to the possibility of developing one's own small programs, often in an program-specific scripting language, within the software in order to simplify desired functions or processes. The most prominent examples are shell scripts in Windows and Linux. Wizard-type approaches [307] guide users step-by-step through the creation process and ensure that nothing is omitted.

Model-based development [223] is an abstraction technique by means of which the user creates the conceptual description of a method or function and the system translates this model into program code that can be executed. Programming by demonstration is a technique that provides users with examples of automated flows or algorithms that they can adapt and reprogram to use for other contexts or with other data [30] (e.g. Apple's Automator). Visual programming operates according to a modular principle by means of which the user can use visual function modules and combine them in a simple manner [49]. It requires more logical thinking than programming skills; however, due to the various possible combinations of different modules, many possibilities for the development of one's own functions arise.

Morch [249] attempts to define these approaches even more finely and names three levels of tailoring activities. Customization (Level 1) refers to the modification of the appearance of presentation objects by selecting parameters from predefined configuration options or, for example, by hiding fields in the user interface that are not needed by the user. Integration (Level 2) allows users to extend the application by enabling them to add new functionalities. At this level, adding new functionality is not a matter of programming new parts but rather concerns the combination or linking of predefined components to create new functions. Extension (Level 3) allows "radical changes" [249] to the application itself that cannot be anticipated by the developer. These changes may be archived by changing or reworking the program code itself (by end-users, developers, or by the application itself).

Within research on EUD, an early attempt was made to enable domain-expert users to adjust the program for their workflows and their context. In light of this, the process of the EUD itself should be integrated "into users' existing workflows" [210] to keep "the cognitive load of switching from using to adapting ... as low as possible" [223]. Additionally, Haines et al. [155] suggest four recommended technologies for EUD to improve usability:

- Consider the context of the user to automate the user's workflow;
- Provide defaults and help the user to make the right decisions;
- Help with examples and show fixes for error handling; and
- Help users identify reusable components.

2.3.2. End-user development in IoT and IIoT

Especially in the context of IoT and IIoT, where personal activities and everyday habits and tasks are increasingly digitalized, EUD is a promising approach to let systems better fit the needs at hand.

Barricelli and Valtolina [17] note that EUD can play a role not only in the interface or interaction but also a much greater role in the entire IoT and IIoT ecosystem. Therefore, they argue for the distinction between hardware, software, and data. End-user activities at the hardware level mainly include the configuration or parameterization of devices (e.g. polling intervals, alarm noises, etc.). This also includes the installation of the sensors, for example, in the smart home area, where set-up can be undertaken by the end-user [36].

At the software level, Barricelli and Valtolina [17] define EUD as activities that combine more than one sensor/device and create new functionalities. Especially in the domestic context, there are already a number of studies within the literature that deals with this topic. As mentioned above, in the context of smart homes, there are already many available approaches that put users at the center of configuring their smart home system. Mostly focusing on rule creation for task automation or alerting, tools such as if-this-then-that [180] allow users to create their own new functionality by combining multiple services. Additionally, in the context of ambient-assisted living, Burnett and Kulesza [50] developed an approach called explanatory debugging [215], which allows end-users to influence the predictions of machine learning systems to better consider their personal habits and the personal context. With this approach, the system should clearly communicate how it works, and the user has the option to define scenarios that are “OK” or “not OK” for his or her context; the system then considers these in further executions. All these activities can be classified as relatively low-level EUD tasks. More complex activities include the use of visual programming or wired-programming environments to customize IoT and IIoT systems behavior. In terms of data, EUD activities involve data aggregation, filtering, and porting. These could also be realized in the more complex environments, such as Node-Red [265] and Yahoo Pipes [397], which are often too complex for end-users [91].

The literature is primarily constituted by works on the domestic context and in the field of trigger-action rules. Currently, there is a lack of studies dealing with EUD in the industrial context, especially those explicitly dealing with the use of IoT or IIoT data (in the sense of analysis and visualization) by end-users.

2.4. Research Framing and Discussion

The literature on the IoT and on the IIoT concerns the acquisition, transmission, and use of large quantities of digital data; however, the IoT and IIoT are mostly discussed from a technical point of view, focusing on network technologies or hardware issues and neglecting the role and involvement of the user [65, 213, 314]. Even when users are involved, this usually occurs at a more technical level, focusing on the automation of tasks and activities, where mainly data-centric approaches (statistical models and artificial intelligence-based approaches) that automatically identify and find patterns to trigger some sort of action (e.g. via actuators) are investigated (see [9, 219, 220]).

In contrast, the literature within the HCI and CSCW communities strongly argues for involving users [80, 253] in making sense of data [213] as a prerequisite for their integration into everyday activities [306] by means of articulation (i.e. work that is necessary in order to be able to work) [341]. Understanding of such systems has an immense influence of their usefulness, otherwise users may lose confidence and did not trust such systems, which may result in them being used less or in users even searching for ways to bypass them completely [334, 343]. Furthermore, the full potential of this new technology cannot be fully exploited, since users are experts in their own domain and therefore play a crucial role in shaping the problem, interpreting the data, and finding the right conclusion. In this regard, they are even better than machines, but who in return are able to process great amount of digital data in a short time [64, 254, 267, 381]. These data-interpreting skills of humans should consequently be combined with the capabilities of machines to process large amounts of data [381]. It should be noted, however, that a selective presentation of data alone is dangerous [105]; users must be enabled to take control and to consider their context to make sense of data [75]. Therefore, systems have to be designed as toolsets - and not as solutions - that give users the option of working with this new technology in a user-centered and task-oriented manner.

As a result, one-size-fits-all solutions are no longer suitable; users need systems that they can integrate into their everyday lives and that can be adapted to changing environments, circumstances, and needs. A promising concept to achieve this individuality of systems is EUD. The concept aims at the individualization, customization, and tailoring of applications by users themselves [50, 223]. Especially in the area of the IoT and the IIoT, this approach is considered promising; however, there are currently only a few studies that have investigated the use of EUD in relation to IoT and especially in relation to the IIoT. Additionally, considering the data-centric focus of the IoT and IIoT, EUD approaches currently do not completely cover all aspects of working with digital data.

Putting users at the center of the new era of digital systems and technology and enabling them to make digital data accountable and usable in this context therefore remains a challenge. This is mainly because the technological world of the new IoT and IIoT systems is often separated from the domains (e.g. from private or working context). Information technology specialists, mathematicians, and data scientists use advanced methods to analyze data, but without having specific context or domain knowledge. However, as pinpointed e.g. in science and technology studies [18], data cannot be viewed objectively; contextual knowledge is required for interpreting raw data and integrating them in daily practice. Conversely, users who possess this explicit knowledge typically lack the know-how to work with digital data and therefore make them usable and accountable.

In summary, it can be concluded that a human-centered IoT and IIoT is still in its infancy. It is differentiated according to individual areas of application and adaptations and links between different contexts (e.g. domestic and industrial) have not yet been sufficiently investigated and explored. Efforts in the areas of the IoT and the IIoT currently neglect the user-centric view. Here, EUD can be used in particular for individualization, tailoring, and adaptation to tasks at hand; however, there is still a lack of data-centric approaches that make digital data usable by nonexperts. Within information visualization, there are already sufficient approaches that deal with the process of systematically processing raw data, though these have not yet been made usable for end-users. Tools have to be designed that enable users to explore their data by means of tailorable information visualization and data analysis.

3. Study Outline

Based on the state of research outlined in Chapter 2, this chapter present the research perspective and the research questions guiding this work. Thereafter, the research methodology of this study is introduced.

3.1. Research Perspective and Questions

Based on the body of literature and the challenges identified, it can be concluded that there is lack of research investigating how users can become more integrated with the new technology, especially with regard to making sense of digital IoT and IIoT data.

It has been shown that the user-centered approaches from HCI and CSCW can be successful in this regard [38, 135, 166, 301, 379]; however, these disciplines are still in their infancy in relation to technology that consolidates, analyzes, and visualizes large amounts of data from different contexts, systems, and connected objects [89, 213]. However, there is an increasing focus in this direction, and there are different research approaches that focus on the interaction of users with digital data. Human-data interaction, for example, raises the issue of how people should interact with data [80, 253]. Hall et al. [156] for example argue for the need to improve human interaction with data fusion systems. In addition, there are increasing numbers of studies that argue that approaches from science and technology studies should be taken into account [254, 281, 290, 293]. The new technology has an influence on the way people live and work; conversely, people’s habits, activities, and processes also have an influence on the design of such new technology, especially in relation to how the new technology could be used and integrated into everyday activities.

A related concept that combines all aspects of working with data to derive meaningful information is referred to as “data work” [119]. Data work includes all activities that are associated with the process of making sense of data, such as data consolidation, data processing, data refinement, data analysis, and data visualization. With data work as the framing concept for this thesis, the social, technical, and socio-technical aspects of users engaging with data can be studied in detail.

In this respect, this thesis focuses on IoT and IIoT systems in both domestic and working contexts and uses practical design case studies to provide a detailed perspective on the use of this new technology for everyday routines, habits, and processes in order to create new insights into the design of such systems. The case studies aim to extend the current understanding of how to design for end-user data work in the context of IoT and IIoT systems. Consequently, the research questions of this study are the following:

Q1) IoT and IIoT in the wild: How do users set up, use, and appropriate current IoT and IIoT systems in different contexts and what are their data-driven needs?

Q2) Using digital data: What are the requirements for a data work environment and how can digital data be made accountable for end-users?

Q3) Designing for end-user data work for the IoT and IIoT: How may an end-user centered tool that enables end-user data work be conceived and designed?

3.2. Methodology

The overall approach of this thesis follows the design case study framework of Wulf et al. [377, 379], which includes three phases: pre-study, development, and evaluation. This framework is well suited to investigate how end-users use IoT and IIoT technology in different contexts, how they undertake data work processes, and, from this stance, how data work tools for end-users can be designed and evaluated.

In what follows, the basic idea of the design case study and the empirical methods used in the included study are presented in greater detail.

3.2.1. Design case study

Design case studies follow a multi-stage action research paradigm [379] in which ethnographically oriented methods are combined with those from design research [163, 379]. The basic idea of design case studies is to gain an in-depth understanding of existing practices and then iteratively and participatively design application-oriented IT interventions and jointly evaluate them with the user. Design is therefore understood as an open process that is informed by the social practices of a particular application context. Wulf et al. [377] divide design case studies into three phases: the empirical pre-study, the technology design phase, and the evaluation phase. The phases are not to be understood as a strict procedure but as an iterative process that can lead to new insights and requirements even if the IT artifacts are already in practice.

The empirical pre-study should occur before any interventions are performed and thus serves as the basis for further action [377]. In this phase, the researcher should gain a deep understanding of social practices, including existing media and tools and their formal and informal use in practice. This understanding of social practices leads the formulation of a “certain problem” or “need statement” on which the later intervention should be based [377].

In the technology design phase, the design space is mapped to technological artefacts or interventions by addressing the identified practices and problems. The design case study should describe “the specific design process, the involved stakeholders, the applied design methods, and the emerging design concepts” [377].

In the evaluation phase, the IT artifact or intervention should be rolled out for practical application to evaluate the appropriation in its domain of practice [377]. Thereby, new requirements for redesign should be obtained.

Design case studies are therefore particularly suitable for dealing intensively with a context in order to ascertain the requirements for IT artifacts and to investigate the effects of their use on social practices.

3.2.2. Participatory Design

The aim of participatory design (PD) is to involve all stakeholders and potential end-users (e.g. employees, partners, customers, and citizens) in the process of designing and developing software systems to ensure that the solution meets the requirements of users and fits with their practices [28]. The idea informing PD is that developers, designers and end-users create more innovative ideas together than they could in isolation [246].

Participatory design can be understood as a set of methods and techniques that enable designers and users to develop a common understanding of practices, challenges and needs, and possible solutions [33]. It is an interaction in which the user assumes an active role and serves as inspiration and can also participate actively in all design processes in the course of decision-making. The designer or developer is always aware of the context of use and therefore understands it better so that he or she can contribute his or her knowledge of technical and design-specific possibilities.

Participatory design began in the workplace context [33], though, due to the growing distribution of new technology, PD has increasingly focused on the domestic context [81], and several concepts have been successfully transferred from the workplace context to the domestic one [79]. The tools and technique used in a PD process are very versatile, for example, document analysis, interviews, observations, future workshops, thinking aloud, storyboards, and others.

3.2.3. Methods

In each of the phases of the design case studies within this thesis, diverse qualitative empirical methods, such as semi-structured interviews, focus group, cultural probes, field observations, and participatory design workshops are employed. The aim is to understand the individual contexts, to record current practices, develop requirements and concepts, and to test and evaluate prototypes. The methods used in this thesis are briefly described below. In the individual studies, additional details of the concrete application of the particular methods are described.

(i) (Semi-structured) interviews

In the design case studies, semi-structured interviews are used as a means of user/context research and as part of the evaluation of the prototypes designed.

Interviews are a popular research method that can be used to understand contexts, to collect requirements, and for evaluation purposes. Above all, narrative or semi-structured interviews attempt to create an open conversational atmosphere that resembles a normal conversation between two people [173]. Semi-structured interviews can be used as stand-alone methods or in conjunction with other (qualitative) methods [230]. One of the biggest challenges is the design of the questions. These should be open, so that more than “yes” or “no” is possible as an answer, and so that a conversation is established. It should also be possible to alter the order of the leading questions so that the flow of the interview is not fixed. In the selection of the interview partners, this thesis distinguishes between experts and users (users are experts about their context; experts here refer to technology experts in a certain field of application). The aim of an interview is not for its output to be universally valid (it is the same with most other qualitative methods). In this study, it is much more about understanding how individuals perceive, experience [230], or deal with situations or technology.

(ii) Focus groups

In the design case studies, focus groups are used to obtain feedback from the users about the prototypes designed in order to initiate an internal discussion and exchange of ideas.

A focus groups is a special form of semi-structured interview that takes place in a group in order to obtain as many different insights as possible, and so that the participants inspire one another [12, 41, 230, 239]. Additionally, the focus is on the interaction between the participants within the group [250]. The entire discussion is mediated by a moderator who must ensure that there is a consistently open atmosphere in which the participants can freely express their opinions. A certain homogeneity should be taken into account when selecting participants as otherwise too many controversial opinions may arise and a negatively charged discussion ensue [251]. Focus groups are often used as a supplement to other data collection methods within qualitative social research (e.g. in a multi-method approach) to provide researchers with further insights [250].

(iii) Design probes

Within this thesis, design probes are used in the domestic context to uncover how people perceive their home and to discover their (latent) desires and needs to make it smart.

A design probe is a means of involving the user in gathering research data. It is not an evaluative task; rather, it is a technique that is used to understand the contexts of potential end-users in order to inspire design ideas for everyday life [140]. Graver et al. [139] for example use maps, postcards, a camera, a photo album, and a media gallery as their information gathering package, which they gave to elderly people. These probes included challenges or questions for the participants (e.g. they may be asked to take a photograph of their home or to answer the question, “Where have you travelled in the world?”). These probes served as inspiration, which later (among other things) influenced the concepts [139]. Design probes should therefore not be seen as a mere source of information but rather as inspiration for the views and in relation to the environments of users.

(iv) Co-design workshops

In the design case studies, co-design workshops are used to involve participants in sketching and envisioning future systems and to gain better insight into their vision for data-based system.

Co-design workshops are a popular method within participatory design. Various stakeholders, especially potential end-users, are encouraged to actively participate in the development and design process in order to communicate their ideas and needs to the developers and designers. Normally, creative techniques, in which the users themselves actively create designs and discuss the resulting ideas, are used. In the literature, one finds a variety of different approaches to conducting co-design workshops, such as future workshops [191] (critiquing the present, envisioning the future, and implementing IT artifacts for progressing from the present to the future), card workshops [157] (which involve technology cards, inspiration cards, and participatory designing through combination) and fictional inquiries [97] (which use narrative means and create fictional situations to overcome restraints). Vines et al. [365] note that the workshops should be conducted mainly in the context of the later applications, that is, by the users, since there users can adapt themselves to concrete conditions and tend to adopt a more general attitude.

(v) Field observations

Within this thesis, field observations are used to better understand the real practices of employees and to get to know the processes and procedures in companies better.

In the ethnographic tradition, field observation is a well-known method in field studies. In general, field observations represent an activity in which a researcher observes other people in the course of their everyday activities or routine work and records these in field notes [372]. This method is especially useful for identifying deviations from given and lived processes and for activities that are not well articulated by means of other communication methods or which are taken for granted. A distinction can be made between direct and indirect observation. With direct observation, the researcher is directly present in the field; with indirect observation, the researcher observes a human being, for example, via video. In addition, the researcher is able to obtain good insight into the future field of application, which can then be taken into account in the design and development process [372].

3.3. Context of the Research Projects

The design case study approach was applied in this thesis over three research projects in two contrasting settings (the IIoT in the industrial context and the

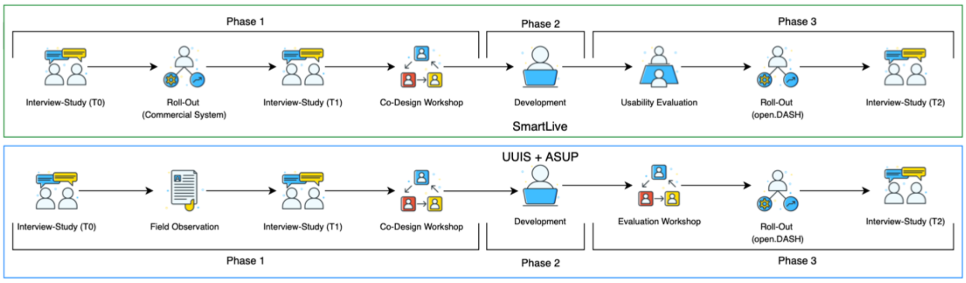

Figure 2. Methodical Procedure

IoT in the home context). The phases and investigations undertaken within these two design case studies are shown in Figure 2.

The first Project was “Ubiquitäre Umweltinformationssysteme / Ubiquitous environmental information systems (UUIS)” (2013–2017), which was funded by the Ministry for Environment, Agriculture, Conservation and Consumer Protection of the German state of North Rhine-Westphalia. The project focused on the development of user-friendly energy management systems that allow users in companies and in the private environments to make energy data visible. The aim was to raise awareness of energy consumption in relation to activities and processes and to test new technologies in a user-centered manner.

The second project was “SmartLive” (2014-2017), which was funded by the German Federal Ministry for Economic Affairs and Energy. The aim of this project was to investigate the usability and user experience of smart home systems and, subsequently, to develop concepts and implications with regard to how to better integrate smart home systems into the everyday lives of users.

The third project was “Anwenderorientierte Smarte Umweltinformationssysteme in Praxis / User-oriented Smart Environmental Information Systems in Practice (ASUP)” (2018–2019), which was also funded by the Ministry for Environment, Agriculture, Conservation and Consumer Protection of the state of North Rhine-Westphalia. Building on the first project, this project examined how new approaches, especially in the area of machine learning, can be used in companies to actively support end-users to identify potential energy savings.

These research projects followed a participatory design paradigm and were oriented according to a praxeological approach, and investigated the appropriation of IT artifacts over a longer time period [302, 379].

Following the phases of a design case study, a pre-study was initiated in the industrial as well as in the domestic context (Phase 1 - Figure 2). In each case, two interviews (Subsection 3.2.3.i) were conducted, supplemented by co-design workshops (Subsection 3.2.3.ii). Furthermore, field observations (Subsection 3.2.3.iii) in the industrial context and design probes (Subsection 3.2.3.v) were used to obtain a first-hand understanding of current practices (see Chapters 5 and 7). Thereafter, in both contexts, the technology design phase (Phase 2 - Figure 2) included the technological development. The findings in relation to the practices and the requirements and design ideas collected were transformed into an executable prototype (see Chapters 6, 8 and 9).

In the evaluation phase (Phase 3 - Figure 2), various methods were used to examine the suitability and to investigate the appropriation of the prototypes developed. In the domestic context, a usability test was conducted and, following the use of the application in the field, a further interview study (Subsection 3.2.3.i) was conducted (see Chapter 8). In the industrial context, a focus group (Subsection 3.2.3.iv) was conducted as the first instrument of evaluation followed by further interviews (Subsection 3.2.3.i) after a period of use in practice (see Chapter 6). These processes ran almost in parallel, beginning in 2014 and with development being undertaken from 2016. Detailed descriptions of the application of the methods are provided in the individual chapters of the studies.

3.4. Mapping of Chapters and Research Questions

Part II constitutes the main component of this thesis. The chapters in II.I deal with studies that examine the industrial context, while the chapters in II.II focus on the domestic context. Part III concludes the thesis and summarizes the results of the individual studies. In addition, the results are discussed in relation to the literature presented; open questions that arose during the work are shown.

II.I

- Chapter 4 describes a long-term study on the introduction of IIoT technology in a company and provides an overview of the organizational and individual aspects that had to be considered, when setting up IIoT technology.
- Chapter 5 shows the requirements for a digital energy management system and proposes a concept for how individual needs and organizational structures can be taken into account in the design of IIoT systems.
- Chapter 6 demonstrates the implementation of a collaborative IIoT tool, which covers various data-related requirements in everyday work and enables flexible data work by end-users.

II.II

- Chapter 7 provides an overview of current studies in the area of the visualization of smart energy data in the domestic context, summarizes current concepts, and shows future research directions in this area.
- Chapter 8 shows how users use smart home systems, what data-related questions arise, and it provides insights into the use and appropriation of a flexible visualization tool.
- Chapter 9 shows the implementation of a context-sensitive system for smart energy data in the domestic context and presents new possibilities for visualization, control, and assistance using context data.

3.5. Limitations and Methodological Challenges

The goal of this thesis is not to verify hypotheses but to gain a deep understanding of the nature of current practices and how they are transformed by the introduction of new technology. This should deepen the researchers' understanding of the practices themselves, for example, in order to identify requirements for new IT artifacts [311].

The investigation of two different contexts (domestic and industrial) posed different challenges, particularly with regard to the conducting of the studies. On the one hand, the industrial context, with its multitude of involved stakeholders and special processes, is much more complex; on the other hand, the structures in the industrial context allow less free space, especially when testing new concepts and systems that are not fully developed for productive use. Although this complicates the third phase of design case studies, it strengthens the first two phases, since they explicitly examine this complexity and also address individuality. In this manner, the design of "practices" mentioned in the literature, which can only be understood or examined by referring to the environment and context, are taken into account [217]. The research approach, therefore, requires a trusting relationship with the stakeholders involved and the addressing of various questions that are not always of a scientific nature, which, in turn, leads to an intensive and risky research approach [379]. In addition, the understanding developed stands in contrast to many social science approaches that try to model human behavior and generalize it on the basis of isolated characteristics [217, 335].

Furthermore, the approach of this thesis and the methods used in the studies follow a qualitative research paradigm, which does not make any statements about general validity. This lack of general validity is also justified particularly by the number of examined users and case examples, as well as their special context. The same applies to completeness, which is difficult to achieve with such an approach. However, the studies in this thesis provide an excerpt from practice to raise awareness of digital data issues and the working with data in order to provide insights that can provide an initial basis for understanding these factors and influence the development of IoT and IIoT technologies and their integration into everyday life.

II. Data Analytics and Visualization

II.I Enterprise Context

4. On Technology-Assisted Energy Saving: Challenges of Digital Plumbing in Industrial Settings

The desire to encourage companies to invest in energy efficiency has prompted various incentives, including taxation benefits. Many companies have invested in digital infrastructures to help them save energy but, as we show below, there are significant challenges in running a digital infrastructure in companies. Some of the projects in question involve acquiring and installing off-the-shelf sensors and implementing them as part of an Internet of Things (IoT) with machines, servers, middleware and other technologies. This paper addresses issues of digital plumbing – the actual work of installing digital technologies – in industrial settings, to date relatively underexplored in the Human-Computer Interaction (HCI) literature. By presenting the findings of ethnographic research conducted during the installation of a digital infrastructure for energy saving in a German company, we help to fill this research gap. In particular, we present a cautionary tale about the practical challenges that can emerge during such initiatives, demonstrating that success and failure in industrial IoT initiatives depends on more than the resolution of technical issues. Furthermore, we uncover ways in which digital plumbing in industrial settings is confronted with certain unique challenges that require different orders of solution to those that might be adopted for domestic IoT.

4.1. Introduction

Recent technical developments, notably surrounding concepts such as the IoT, have opened up a range of possibilities for both consumers and organizations to make use of improved levels of information to increase efficiency and reduce costs. It is therefore scarcely surprising that companies have responded positively to such opportunities. Thus, significant effort has gone into innovative strategies around digitalization projects to establish complex data-based manufacturing procedures. A frequent first step in companies in Germany has been to digitalize energy management processes. This is because, since December 2015, large companies have been obliged to carry out an energy audit to avoid tax disadvantages. Moreover, the introduction of environmental management systems (EMS) has been subsidized by the state, with it being possible for companies to obtain further tax savings by demonstrating that they are continuously using energy more efficiently. Thus, many companies have introduced a digital EMS as their first IoT technology to offset financial losses and potentially receive added tax advantages [58].

The IoT can be understood as a network of physical objects containing embedded technologies to communicate and sense or interact with their internal states or external environment. It refers specifically to the use of intelligently connected devices and systems to leverage data gathered by embedded sensors and actuators in machines and other physical objects [9]. Although the vision of the IoT is becoming more and more influential in modern manufacturing companies, its practical implementation is not well formulated. We know already from extensive research in domestic environments that the implementation of IoT infrastructures is not straightforward [355]. As IoT technology becomes more sophisticated and the number of IoT devices and protocols – including RFID (Radio Frequency Identification), sensors and actuators, UIDs (User Identifiers) and NFC (Near Field Communication) objects – increases, IoT networks become more and more complex [9, 357]. In addition, there remain a number of concerns, e.g. about trust and privacy and rights over data [328].

In current HCI research, there is a growing body of literature that identifies difficulties and challenges in setting up digital infrastructures in the domestic context [148, 355, 357] and a number of papers have explored the possible consequences of establishing digital infrastructures for practical work in commercial settings (see e.g. [51]). To the best of our knowledge, however, there is little research that deals with the installation of a digital infrastructure in a production company – or in other words: 'the work to make an [IoT] infrastructure work' in manufacturing contexts. A possible exception is the work of I. Lee and Lee [219], which surveys the IoT technologies available to companies and the challenges associated with their integration. This study, however, does not look at the actual practical work involved in its installation and maintenance. Therefore, it remains to be seen what the equivalent challenges might be for building digital infrastructures in an industrial context, where the framing conditions might be expected to differ significantly. Specifically, we know little about the problems of practical implementation – what has been called 'digital plumbing' – and its possible consequences outside of a domestic context [355][1]. Hence, the research questions that we attempt to address in this paper concerns: (i) the extent to which digital plumbing issues observed in domestic contexts are also manifest in industrial contexts; (ii) what additional challenges arise in such a setting; and (iii) what their possible implications are.

To answer these questions, we report on a long-term ethnographic study, conducted in a regional German company herein called Alpha, of the design and deployment of a digital infrastructure for an EMS. The initiative emerged from a previous study carried out in the same company that aimed to investigate design opportunities for digitalizing specific processes within it

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[1] Digital plumbing refers to the actual work of installing digital technologies in a particular setting by drawing attention to the collaborative effort of co-situating prototypical technologies, the competencies associated therewith and the practical troubles encountered [355].

(anonymized). The main goal established by the company was to demonstrate to the relevant German authorities that they were engaged in initiatives to save energy and increase energy efficiency, so that they could benefit from tax deductions. We present a detailed description of the difficulties and challenges involved in making innovative technologies work in a context that is not well-prepared for them. In our case, the company engaging in the digitalization of its energy management process did not fully appreciate the 'plumbing' work that would be necessary, nor were they aware of the implications that this would have for other company processes. Our study reveals how planning, set up and running a digital infrastructure in real production settings presents significant challenges.

The paper therefore extends the literature on digital plumbing by showing how the practical procedures entailed in 'getting things to work' are as much exigencies in an organizational setting as they are elsewhere. We specifically draw attention to the fact that it takes much more than getting off-the-shelf sensors and installing them to effectively manage the implementation of an EMS. We highlight the existing socio-technical factors that need to be understood to make such an infrastructure to work within an organizational setting, illustrating some of the many (and unexpected) issues that can arise from such initiatives – e.g. the generation of datasets that cannot be transported, processed and/or stored at the same rate as they are generated or the fact that information mined from data will not necessarily just 'fit' a company's established cost center procedures. We argue here that these kinds of consequences are not just isolated war stories but rather indicative of the kinds of routine challenges constructing such infrastructures will encounter because of the way in which manufacturing processes are organized and the ways they differ foundationally from the kinds of processes one encounters in people's homes. This makes these concerns core issues for HCI research, because they directly speak to how users make sense of, use and appropriate computing technologies [266, 310] in an important domain of human activity.

4.2. Research background and related work

Although it would be impossible to cover the whole literature on IoT and associated issues here due to its size, we deem it important to provide at least an overview of the main challenges concerning such technologies, especially with regard to industrial contexts. In the following we therefore review the most relevant literature, before introducing and contextualizing our own research context.

4.2.1. Energy Management in Organizations: Drivers, Benefits and Research Directions

According to the German Federal Environment Agency, energy consumption in industry, trade and commerce in Germany totaled 375 terawatt hours (TWh) in 2016. Despite the expansion of renewable energies and the introduction of savings and energy efficiency measures – e.g. through the use of energy-efficient lighting, ventilation and compressed air systems – there is a growing trend towards greater energy consumption in the industrial and commercial sectors [344]. The reasons cited for this include a lack of awareness of the reasons for the level of energy consumption, a focus on subsystems, the overhead involved in the structured recording of energy-relevant data and, above all, the inadequate creation of economic incentives and [202].

In response to this trend, the member states of the European Union issued the Energy Efficiency Directive 2012/27/EU, which came into force in December 2012. This directive resulted in large companies being obliged to carry out an energy audit for the first time by December 2015. This was intended to motivate companies to systematically analyze their energy flows and identify potential savings. DIN EN 16247-1 describes the detailed requirements for the performance and quality of an energy audit. According to this standard, an energy audit is a systematic inspection and analysis of the energy input and energy consumption of a plant, building, system or organization with the aim of identifying and reporting on energy flows and the potential for energy efficiency improvements [47]. The standard generally requires an energy audit process that meets the criteria of appropriateness, completeness, representativeness, traceability and verifiability. In addition to possible energy savings, there are also non-energy-based advantages that make systematic consideration of energy consumption sensible for companies and that can serve as a further incentive. These can be, for example, a reduced amount of waste, improved maintainability of machines and optimized product quality as well as advantages in the context of public tender requirements – such as, for example, proof of an ecological CO_2 footprint [299]. In Germany, the government also allows the possibility of reimbursement of electricity and energy tax (top-level tax equalization) by up to 90 % where there is systematic energy management in accordance with ISO 50001, as in other countries of the European union [131], tax incentives for the efficient use of energy is a great motivator for companies.

Currently, there are *three strands* of work within research on increasing the energy efficiency in companies: the first one includes using traditional *media to raise awareness* about energy consumption – e.g. [238] and [196]; the second is situated within HCI and spans research into *the design, deployment and use of interactive systems* for supporting energy saving in different contexts – e.g. [258] and [319]; the third mostly relates to studies in Information Systems (IS) that focus on how Environmental Management Information Systems (EMIS) can decrease the energy usage in production processes [108].

Matthies and colleagues [196, 238] conducted one of the first studies examining how ecological information works in the office hallway, by developing checklists and sample templates for eco-campaigns in buildings. In addition to focusing on traditional media, Azar and Menassa [11] have investigated the motivational factors concerning eco-feedback in organizations. In their work, they present a comprehensive sensitivity analysis regarding the behavioral parameters in typical office buildings. They developed a framework that supports the implementation of energy-saving measures in commercial buildings. Their findings show that occupants' energy behaviors significantly influence energy use and that understanding the sensitivity of building energy models to different inputs is essential to improving energy predictions and building design. An attempt to provide general design guidelines for organizational eco-feedback was made by Foster et al. [128], who took notions from environmental psychology, such as social comparison and goal setting, into account. They produced a framework of key themes describing in detail user perceptions and considerations for the design of energy interventions to drive forward reflections on this issue. In addition, Carrico and Riemer [53] have shown that providing monthly feedback with motivating messages can result in a significant reduction of university employees' energy consumption.

In an HCI context, Schwartz et al. [319] installed smart metering technology in a research institute and observed that workers take the responsibility for sustainable energy practices if their consumption is made visible and they are supported, for example through feedback. This led to significant short-term positive effects, but the effort was not sustained in the longer term. Nonetheless, organizational eco-feedback seems to be a promising candidate for supporting energy saving at work. Yun et al. [385] implemented the first functional prototype of an energy-dashboard. In addition to that, some empirical studies evaluating organizational eco-feedback have been conducted over the past few years with different and insightful results. Murtagh et al. [258], for instance, obtained similar results to those of Carrico and Riemer [53] when focusing on changes in practice after the installation of eco-feedback applications in office settings. One of the main conclusions to be drawn from these two studies is that feedback and behavior are complexly intertwined and that there are many reasons to 'not turn things off'. In another study by Yun et al. [384] the authors conducted a long-term study to compare manual, online and automated controls. They found that the more support users receive, the more energy there is saved. However, they also found that the lack of integration of the topic into people's daily work life created some barriers to its use.

In most cases, it is prototype household technology that is used to investigate the effects of eco-feedback. This, arguably, does not predict productive use in companies. Nonetheless, these studies give valuable information about the increasing complexity of workplace settings in comparison to the domestic context. Bedwell et al., for instance, examine energy consumption and management in an office building [21]. Among other things, they recognize that the multitude of different roles and responsibilities in companies will increase the level of complexity and therefore argue that communication and organizational structures must be considered. A study by Constanza et al. [74] supports this view and shows that a broad understanding and awareness, especially for non-technical users, is important for sustainable action in companies. Both studies argue for making "errors", in terms of unsustainable behavior or unnecessary consumption, visible and suggest the possibility of preventing such errors through good design and transparency [21, 74].

There is also a growing body of literature in the IS Community that deals with increasing energy efficiency in organizations [108]. As with many HCI approaches, those of the IS community are based on collected environmental data. However, the IS community often focuses on the optimization of processes and workflows. Hopper et al. [174] and O'Connell et al. [269], for example, examine demand-response programs by adjusting machines as well as changing parts of processes for load-shifting. Gahm et al. [136] have conducted a review of energy efficient scheduling within the production and other studies, e.g. by Muromtsev et al. [257] and Kong et al. [212], have looked at the development of automated tools for sustainable process control. The focus of such studies is on reducing energy costs and increasing productivity by adopting a clear technical and management focus.

4.2.2. The work to make digital networks work

A significant body of HCI and CSCW research has dealt with the work to make a digital network work. Bowers' paper "The Work to Make A Network Work" [38] has proven influential in this context, dealing with the set-up process and running of a technical infrastructure in an organization. In contrast to former studies, e.g. Orlikowski [274] or Harper [161], Bowers [38] paper highlights the difficulty of managing a network and the need for CSCW tools for people in an organization. Bowers describes the challenges as socio-technical, with there being both technical challenges, which require technical knowledge regarding the configuration and maintenance of a software architecture for the most basic services to work reliably (e.g. e-mail), and social challenges, like acceptance and organizational change. He also points to additional work, such as setting up everything to fit specific needs or identifying workarounds if something does not work, that had previously been neglected in CSCW research.

Other studies have addressed issues of this kind in domestic contexts. Grinter et al. [148], for example, look at the work done to establish network technologies in the home. The authors identify various challenges in set-up, troubleshooting and maintaining a home network, e.g. the necessity for a holistic view of network interdependencies. Maintaining such a view becomes even more difficult if the home network evolves over time. Another finding of Grinter et al. [148] relates to the existing characteristics of houses, where old electrical circuitry is not necessarily designed to handle the amount of new computer and infrastructure technology. They also identify the work required to set up and maintain a network infrastructure, including involving parties outside the home, such as telecommunications providers. Even in a domestic context, it seems, there is a degree of ‘interorganizational’ work to be done.

Tolmie et al. [357] build and elaborate on Grinter et al.’s [148] study by examining ways in which the management of the home network is becoming an integral part of the larger management of the household and is thus connected to daily routines and activities. The authors describe an ethnographic study that set out to examine the particular demands of so-called “digital housekeeping” from household members’ perspectives. The link between everyday activities and the set-up of technology can be seen to have three characteristics. Thus, the installation of digital resources can intersect with and become part of other physical housekeeping issues, such as the need for the location and construction of a technology to be childproof. The maintenance of technology in the home is also built around other routines and events. In addition, there is a need to plan and prepare for change, where the challenge is to fit new technology within a body of practices that are already established. The authors also discuss how digital resources require different kinds of housekeeping: they differentiate between necessary and recurrent tasks that come in handy when dealing with digital resources; and occasional tasks that arise irregularly, e.g. when things break down. To counteract these challenges, the authors provide implications for design to make the home network work, mainly concerning the development of the home network with legacy in mind and the need to provide transparency. The authors especially emphasize the need to ensure that new technology is not only available for installation, but also compatible with existing infrastructures and that the transparency of the home network allows for the ready accountability of its parts and infrastructure among ordinary householders.

In a follow-up paper, Tolmie et al. [355] elaborated upon these ideas with the notion of digital plumbing, which relates to the “mundane work involved in installing ubiquitous computing in real homes”. They understand digital plumbing to be a critical part of integrating technology in everyday life and the critical need for it to be adaptable to everyday practices. In their study, they examine the installation of UbiComp technology in a home with an existing network. This work was realized by two “digital plumbers” in a real home. It became apparent, first, that the necessary tools for the installation of UbiComp technology are not self-evident at the outset and that different software versions, for example, bring different requirements. Secondly, what additional tools and hardware might be needed depends on the specific nature of the existing network. These factors, of course, implicate specific competencies such as network skills, knowledge about operating systems and how specific applications work.

Often such knowledge and skill are deployed cooperatively, using prior experience. The authors propose four areas for improvement and support: (1)

supporting preparatory work; (2) supporting the assembly of tools and parts; (3) supporting the management of contingency; and (4) supporting coordination and awareness. At this point it is interesting to point out that the other part of this cooperative work towards resolving issues is the work that takes place between the digital plumbers themselves. Service personnel in other professions frequently share amongst one another stories about past problems and their solutions, which helps build a common understanding of how to address specific issues. Ethnographic studies on precisely this kind of work have already been undertaken and serve as a point of reference to which we can relate an evolving understanding of how the cooperative work of digital plumbing is organized. The work of Orr [275] in relation to the activities of printer service engineers is exemplary in this respect.

Additionally, in the context of the IoT, more advanced sensors and network systems need to be developed for the domestic context (e.g. Smart Home systems). For example, most recent systems rely on low power wireless communication protocols and therefore do not require the use of cables, so the placement of the sensor no longer has to be carried out by experts [20, 185]. However, Jakobi et al. [185] point out on the basis of a living lab based study conducted in 12 households, that this doesn't actually make installation any easier. Due to a lack of knowledge about the peculiarities of wireless communication technology, not everything can necessarily be connected intuitively. The technology develops rapidly, but understanding and know-how do not grow at the same speed [343]. Beckmann et al. [20] therefore argue for the support of end-user installation. Due to the diversity of home configurations, maintenance and servicing are typically better carried out by the users if they installed the sensors themselves [20]. There is already some existing work in this regard. Jewell et al., for example, indicate new approaches to easily and efficiently connect things to the internet to overcome specific technical challenges [189].

4.2.3. Challenges Associated with the Integration and Use of the IoT in Industrial Settings

Technological advances, unsurprisingly, have always influenced industrial development, starting with the introduction of mechanical systems to support production processes, through to new software systems to create highly complex decision support, up to automation in order to increase efficiency in the production process [248]. Indeed, the radical influence of new technology has led to such developments being characterized as, in turn: (in respect of water and steam power) the 1st Industrial Revolution; (with electricity and assembly lines) the 2nd Industrial Revolution; and (with the introduction of programmable controllers and automation) the 3rd Industrial Revolution. Currently, cyber-physical (production) systems (CPPS) are supporting the digitalization of work processes, signaling a 4th Industrial Revolution based on concepts such as smart factories and the Industrial Internet of Things (IIoT) [55, 192, 248, 295].

The recent development of IoT technology and the emergence of sensing technology has led to new ways of integrating hardware and software into an organization. Sensors can capture various data digitally. In principle, nearly every electronic device can gather data from various sensors and communicate this to other devices or applications. Products can be identified in a processing chain by putting RFID tags onto them or sensors can be integrated into buildings to measure temperature, forming part of a large network of devices including smartphones, laptops and other monitoring technologies [9, 219].

In the literature, three types of data have been distinguished in connection with production. First, so-called machine data can be recorded, which collects detailed states and values about machines, such as the number of strokes, details of energy consumption and various other parameters [220]. In addition, sensors allow the recording of data about the workers of a company, such as working hours, the distance covered, or the current work step [352]. The third category is so-called context data, which can be influenced or triggered by machines and employees, but can still have an influence on other aspects of the production or the production process [369]. This includes, for example, temperature data, vibration data and air pressure. This has led to the availability of a huge amount of data (Big Data) that contains a wealth of information for supporting and optimizing processes. To extract this information from the data, however, a great deal of effort is required. Data is now of a scale that it can no longer be analyzed by humans and requires special IT systems to support people in the data mining process [219]. Beyond this, there is a need for new systems that can make use of this sort of data to optimize things like production processes.

Current and past studies have identified a series of challenges associated with IoT technologies that are still some distance from being solved. This is largely because IoT technology can be used in so many different situations and service such a wide range of interests. Atzori et al. [9], for instance, discuss a number of possible application fields for IoT technology, such as in provision of information to a person using a smartphone near an NFC-chip, authentication of a patient in a hospital or trackability of different objects in daily life or in a big factory.

I. Lee and Lee [219] have drawn attention to *five major challenges* associated with the integration of the IoT in industrial settings: 1) *data management*, i.e. dealing with the data produced; 2) *data mining*, which refers to extracting valuable information from the available data; 3) *privacy*, regarding the control over personal data; 4) *security*, in terms of encryption and access rights; and 5) *chaos*, resulting from unpredictable and random system behavior due to the disruptions a faulty device or signal may cause in one small area of a highly interconnected world. These challenges, as well as the many uncertainties in IT projects, such as new technologies, changing requirements and team building between different developers, must be addressed if organizations are to arrive at successful outcomes. Many of these challenges have been manifest in the plumbing work carried out during our study, as will be discussed in our empirical sections.

With regard to *data management,* Gubbi, Buyya, Marusic and Palaniswami [149] argue that the decentralized processing by algorithms and neural networks in the IoT is key for future development, with cloud-centric architectures being the best solution for cost-based services. This implicates new challenges for the IoT, such as security standards or communication between the centers. However, existing opportunities and challenges rely on current IoT architectures, as I. Lee and Lee [219], Atzori et al. [9] and many others have pointed out.

In terms of *data mining*, Gubbi and colleagues [149] discuss how current data mining uses "supervised and unsupervised learning" to pre-process data, to make it usable and to make devices smarter. However, the next generation of data mining algorithms will use ontology and semantic web technologies to enable sensors to make decisions by themselves [360]. In the IoT and in general in sensor networks, novel challenges emerge through overall resource constraints like limited battery capacity or limited processing power.

In relation to *privacy* and *security*, I. Lee and Lee [219] stress that the problem of privacy predicates a need for knowledge about possible data usage by third parties. Indeed, privacy and trust, alongside other aspects of IT-security like vulnerability and backdoor analysis or the development of adequate security protocols, are ongoing challenges and research opportunities [393]. As Zheng, Apthorpe, Chetty and Feamster [394] have shown, users do care about the security of components in the context of Smart Home and will trust well-established companies like Google or Amazon more often for the implementation of state-of-the-art encryption and protection of their data from a technical viewpoint. Yet, owners of smart home systems do exhibit concern regarding privacy and data protection of the systems and their associated devices and are sometimes nervous about unauthorized third-party access. In the industrial context, interests in data protection are magnified because of the heterogeneous nature of the data, its origins and the range of interests and knowledges being deployed around it. The ramifications of data breaches are, arguably, a great deal more serious in this situation.

Turning now to the notion of *chaos*, the interconnected world of sensors and actuators, software and intelligent systems, is changing more dynamically than the consumer product cycle. As I. Lee and Lee [219] point out, this can lead to a significant amount of damage if a failure occurs within a system. Examples of such incidents have been given by Khurana, Hadly, Lu and Frincke [203], ranging from minor effects inside a Smart Home to power system blackouts and chaos in the energy market. The authors therefore list effective cybersecurity provision as a key-challenge and a requirement for upcoming interconnected infrastructures. Komninos, Philippou and Pitsillides [211] have also suggested that common IT-security protection objectives are a major challenge in the connected smart grid environment, presenting a possible target even for terrorists or hackers in general. Several countermeasures exist to face such challenges and provide a reliable and secure environment for the data, underscoring the importance of such systems and their reliability. Thus, committees and working groups have now been set up on a national and international level to prepare standards and frameworks for smart grid implementation.

In the industrial context, it is evident that sensor technology can significantly contribute to the manufacturing process and can be an integral component of the value chain [132]. However, each of the issues rehearsed above pose very significant challenges in the commercial and industrial environment. For the Industrial Internet of Things (IIoT or Industry 4.0), these challenges are substantial. As we will see, *data management*, *data mining* and *chaos* all played an important role in our empirical material and the effectiveness of digital plumbing in this context.

4.3. Methodology

The study we present was part of a Participatory Design (PD) and Action Research process [378, 379] in collaboration with Alpha, a production company in South Westphalia, Germany. Alpha has more than 2500 employees in 30 subsidiaries in Europe, North America and Asia. All subsidiaries are part of a holding company that is based in Germany. The company's customers are from the automotive and supplies, telecommunications, consumer electronics and construction industries. In its design and structure, the research process followed the methodological approach of Grounded Design (GD) [311, 380] and was therefore evolutionary and multi-cyclical. The heuristic approach of GD is based on established investigation methods and thus makes use of the methodological tools of ethnographic field research, PD and Action Research. By means of various ethnographic methods – such as (participant) observation, (expert) semi-structured interviews [10, 101] and design workshops – in addition to formal, easily externalizable requirements – implicit and poorly specified requirements were made observable and used for the construction of a deep understanding of the user contexts and their needs, so as to inform the design and deployment of socio-technical systems and to assess their appropriation [380].

4.3.1. Research Context and Data Collection Activities

Our approach, visually summarized in Figure 3, involved an initial pre-study at Alpha in 2012 before the project described in this paper began. Semi-structured expert interviews were conducted as part of the initiative to highlight and understand the company's requirements and objectives. The goal of the pre-study was to define a standard format for energy management that could be used throughout the company to meet the legal requirements of an energy audit and achieve tax savings. During this study, a concept for the storage, analysis and visualization of energy data was developed based on the current (predominantly manual) collection of energy data.

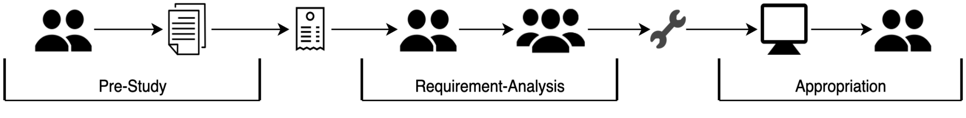


Figure 3. Timeline for Research Activities

Following the conclusion of the pre-study, Alpha's management decided to go ahead with implementing the concept we had developed. For that they acquired more than 140 high-end off-the-shelf sensors, which were to be installed by electricians from a third-party company, sub-contracted for this specific initiative. We were able to observe the work of electricians from the company, herein called Gamma, mounting energy sensors at Alpha and the partners who installed the middleware and were responsible for managing the data storage by a company we will call Beta. The observations took place over a period of 36 months and were accompanied by interviews with various actors. Overall, we conducted 24 semi-structured interviews and two design workshops with employees of Alpha to understand what potential benefits, obstacles, needs and opportunities for eco-feedback existed [301]. In this paper we focus on the results of our observational study, enriching them with quotes from the interview study, as this allows us to convey the issues we observed during our fieldwork from our participants' perspective. In total, 18 employees from companies Alpha and Beta were involved in the research, as specified in Table 1. Interviews lasted between 30 and 60 minutes. The interviews were audio recorded and transcribed for posterior analysis using the *intelligent verbatim* method, in which everything is transcribed word for word, except for mumbling expressions (e.g. 'ums' and 'ers'), filler phrases (e.g. 'you know') and stumbles [364].

Table 1. Data collection phases and their participants

Phase	# Interview	# Participant	Role	Partner
Pre-Study	I1	P1	Innovation Management	ALPHA
	I2	P2	Maintenance	ALPHA
	I3	P3	Energy Controlling	ALPHA
	I4	P4	Maintenance	ALPHA
	I5	P5	Controlling	ALPHA
	I6	P6	Vocational Trainer	ALPHA
	I7	P7	CEO	ALPHA
	I8	P8	IT-Department	ALPHA
	I9	P9	Business Division Manager	ALPHA
	I10	P10	Purchasing	ALPHA
Requirement-Analysis	I11	P11	Environmental Manager	ALPHA
	I12	P1	Innovation Management	ALPHA
	I13	P12	Project-Manager / Production-Manager	ALPHA
	I14	P11	Environmental Manager	ALPHA
	I15	P3	Energy Controlling	ALPHA

	I16	P13	Energy Manager	ALPHA
	I17	P14	Business Division Manager	ALPHA
	I18	P15	Business Division Manager	ALPHA
	I19	P16	Business Division Manager	ALPHA
	I20	P17	Controlling	ALPHA
	I21	P18	Controlling	ALPHA
	I22	P13	Energy Manager	ALPHA
Appropriation	I23	P18	Project-Manager / Main Developer	BETA
	I24	P12	Project-Manager / Production-Manager	ALPHA

4.3.2. Data Analysis

The data was analyzed under the auspices of a Thematic Analysis (TA) approach [40]. This approach entails a set of well-established steps involving open coding of the data material, systematic revision of the coded segments, and identification of code-families and their relationships in search of themes that enable elaboration of a deep understanding of the explored contexts [40, 141]. After transcribing the interviews, we reviewed and coded the transcripts in an iterative process, leading to the compilation of the data categories present in the collected data and the elaboration of relationships between these categories. We used a combined bottom-up and top-down approach to coding, which is very characteristic of TA. We started with the top-down approach, by looking for excerpts that would fit *apriori codes* [141] based on the interview guides used for the semi-structured interviews. We simultaneously identified a series of *empirical codes* (ibid.), which were used in turn for coding relevant data excerpts across the body of the empirical data. Once the coding was finished, we looked for the relationships between codes in order to identify and develop our themes, as is typical of the TA approach [40]. Overall, 3 higher-level thematic fields emerged, which comprise specific characteristics and details in terms of content and to which we orient ourselves in the analysis and presentation of the results (see Table 2).

Table 2. Themes, Codes and Code Descriptions

Theme	Code	Description
Integration	Selection of sensors	Details that played a role in the selection of the sensors, as well as the determination of the installation location and destination
	Installation and mounting of sensors	Work relating to the installation or technical and electrical assembly of the sensors, including the persons and departments involved
	Competencies for installation	Knowledge and competencies required for the installation of the sensors
	Optimal process	Best practices concerning the introduction of digital EMSs in companies
Data handling	Data query of the target status	Required status for successful data queries as well as the target status
	Data connection and data retrieval	Process of data retrieval including **challenges**
	Data storage	Data storage considerations including **challenges** and procedures
	Data supply	Issues of making data available to third-party vendors
	Best practice data query	Lessons learned when consolidating data
	Data usage	Issues regarding data use and the processes that must be supported by such data
Adoption issues	Personnel problems	Problems and **challenges** caused by personnel misunderstandings of the technologies introduced
	Technical problems	Problems and **challenges** caused by technical factors

4.3.3. Limitations

The study was carried out under a qualitative research paradigm and as such it does not allow for quantitatively oriented forms of generalization because of the sample size and specific characteristics of the study context. However, we are confident that our findings provide a perspicuous example that points to the kinds of problem other installations might experience.

There is also an issue of completeness. We are attempting in this contribution to raise awareness regarding some of the issues surrounding digital plumbing in organizational contexts and to present findings that can provide some initial basis for understanding the critical factors that can influence the development of IoT technologies and their integration in the everyday processes of companies. We do not claim that our case reveals every potential pitfall relating to this. Rather, we point to a set of problems that have until now been somewhat overlooked and that are indexical of a broader set of concerns. As we argue in the next section, there are associated challenges in terms of the necessary digital plumbing work and the types of technology involved.

4.4. Challenges to making a digital infrastructure for energy savings work in industrial settings

In analyzing the data to answer our research questions, we uncovered findings that suggest that *integration, data handling* and *adoption issues* form three key themes relating to digital plumbing in manufacturing settings. Each of these poses considerable challenges to establishing a digital infrastructure for an IIoT and to making energy savings work in such settings. In the following sub-sections, we marshal these three themes into analytical categories, drawing on both the empirical data and findings from the literature to articulate our analysis. We start by discussing issues stemming from the digitalization of the energy management process, which was accomplished by the *integration* of off-the-shelf sensors bought by Alpha. In our view, this was the first step towards the elaboration of a cyber-physical infrastructure and, given the right conditions, could eventually have evolved into an IIoT. We then move on to discussing middleware issues directly connected to *data handling*. Finally, we analyze how the use of the data collected by the newly deployed infrastructure posed *adoption challenges* that arose from both technical and organizational issues.

4.4.1. From installation to Integration

When it comes to the collection of digital consumption data in industrial settings, new sensor technology that combines both an electrical component – integrated into the company's physical infrastructure – and a digital component integrated in the IT infrastructure (thus making the sensor data available on the network) are highly indicative of the practical complexity associated with the installation of ubiquitous technologies in real companies. When sensors are installed on a network, significant hurdles can arise that must be addressed both technically and organizationally. On the technological side, one has to deal with growing data traffic and advanced data storage methods, which can lead to greater maintenance effort [219, 395]. Most of these concerns also implicate more efficient and faster protocols for data transmission and more advanced security models [9, 168, 328]. On the organizational side, the literature suggests that IT projects in general face serious problems, including a tendency towards significant delay, failure to provide the required functionality and significant cost overrun. Most such problems, it has been suggested, arise from managerial decision-making regarding tensions between team-members and difficulties in bringing about the necessary coordination and cooperation [259]. There is no reason to believe that the implementation of IoT solutions in such environments will not also encounter similar difficulties. Indeed, there may be even more challenges associated with IoT integration. Our findings corroborate these observations, as will become evident across the following (sub)sections.

(i) The Physical Documentation of Digital and Contextual Information

Our observations suggest that the physical documentation of digital and contextual information when new IT-systems are installed is an important aspect of the work to make an IIoT work. Our reasons for emphasizing this are detailed below.

During our study, we observed electricians (partner company of Alpha) installing, wiring and connecting the sensors acquired for the digitalization process. This was done successfully and no problems with the operation of the sensors were identified. However, the electricians failed to record important information about the connection between the physical and the digital world in appropriate documentation. Every sensor had its own IP address and register, but there was no information about which IP address belonged to which sensor and what exactly the sensor was measuring (units, conversion factors, etc.). This means that it was not possible to map the digital positions of the sensors in the network to their geographical position. Missing this metadata meant that there was no basis for later analysis and documentation. This became even more important, when machines were moved or changed in the way they were connected to the electric meter. Wrong sensors were subsequently connected to the machines and consequently the mapping from sensors to machines was faulty and unusable.

To develop a set of valid metadata, the IT service company (Beta) visited the factory to assess the allocation of sensors to physical places and the corresponding electrical sub-distributions. They went from sensor to sensor and tried to discover the addresses independently. However, this turned out not to be possible for all sensors. Alpha then asked the electricians to create a new electric plan. After a description of the problem by the IT company, the electricians measured all the lines again and documented the addresses. Alpha's employees were also involved, as they were able to supplement the necessary context information about the individual machines, which could not all be covered by the electricians. Here it is particularly evident that this is not just an electrical challenge. In relation to this, a project manager (P18) of the IT service company pointed out that:

"[i]t was difficult to tell the colleagues [the electricians], what we needed on a network or field bus basis to address the sensors", I23.P18

After the assignment of the sensors to the different network sockets had been completely clarified, the sensors could be matched by the IT service company to the internal network of the factory building. This is where the two worlds (physical infrastructure and digital infrastructure) were brought together, which is the basis for the integration of IoT technology into working practices. This shows in particular the need for cooperation between different stakeholders with different expertise.

The second problem was the transfer of the data to the central holding company of Alpha, which was at another location. The IT service company was not able to address the sensors from this other location via the company-wide connection. Normally, the company-wide infrastructure allowed data access between different locations via the Internet. In this case, however, the energy sensors were integrated into a special virtual machine network, which was company-wide but with special IT-security settings. This meant that Alpha's IT-Department could not detect any errors, yet Beta was unable to connect to the sensors from the holding location of Alpha. Beta and the sensor manufacturer then jointly tried to understand the error by using different network analysis tools. In the end, they discovered that the software on the sensors created a special IP flag when the data was sent. The security settings in the company-wide network, however, blocked IP packages with these specific flags, so the data could not pass out of the building's specific network. At the same time, the sensor system had not been set up to inform the plumbers about the actual status of the system. A basic usability heuristic (cf. [263]) had not been followed in the implementation of the system. Consequently, the usability aspect of the sensor system had created noise for the plumbers, which added considerable overhead to the activity. Ultimately this error needed to be corrected through an update of the sensor system by the sensor manufacturer. Regarding this, the project manager from Beta said:

"We didn't notice it, because if we were in the factory itself the connection worked fine. Therefore, it was difficult to find the error. We first had to check what happened with the [digital] packages on the signal path", I23.P18

The troubleshooting was particularly time-consuming because, initially, Alpha's IT-Department was not able to provide support for the process. This led to costly activities by the partners to identify the problems. A local investigation had to be carried out to identify the sources of error. The project manager from Beta summed it up in the following way:

"So originally it was incredibly difficult to tell colleagues how this system works at network- or fieldbus-level, what information we need to completely address the devices. Some of it was already there; had been prepared by Gamma, but we looked for mistakes where we didn't know where they came from and because Alpha couldn't give us any information it was very complicated", I23.P18

After fixing the bugs, a connection between the sensors and the middleware in the central holding company of Alpha was established and Beta was able to address each sensor. In the end, involving Alpha's IT-Department resulted in a better understanding of the company network, the sensors were integrated into the company-wide network and most of the issues described above were solved. The measures taken show that the involvement of all members who will be affected by the integration of a system can reduce the problems and uncertainties that occur in such complex and connected environments. Once implemented, reworking and collecting the necessary information about a system and documenting it involves significant overhead.

The findings presented above demonstrate that the standardized documentation of physical infrastructures and installations contain important information that can help experts to understand an installation. However, we could not find any standard or uniform practice that combined information regarding the physical installation with information about the digital infrastructure. This would have helped the electricians to avoid the problems of addressing the sensors that triggered a series of further problems during the digital plumbing. Note also, that digital plumbing in this context is not a one-off exercise but rather an ongoing process that has to be undertaken every time configurations change.

Another issue revealed by these findings is that contextual data from the organization can also be a valuable resource for digital plumbers, because unfamiliarity with cost centers, machine parameters and labels, and other relevant information disrupts preparation for the installation of IIoT technology.

Last but not least, frequent adaptation of the processes and changes in the physical installation were not continuously documented and these changes were not visible in the IT-systems themselves. Normally, in this kind of context, metadata underpins every business process and are provided as a matter of course when working with customers or vendors [231]. Providing metadata in the context of the IoT is not yet, however, as well-established as it is in the other fields relying on metadata. Access to such data should be of self-evident value because these additional specifications are important to provide a context for the information and therefore a meaning for the otherwise rather useless data generated by the sensors. As has been previously pointed out in the literature, pure, non-contextualized data has no value [219]. Contextualizing the information is a mandatory step when performing some kind of analysis or visualization (ibid).

(ii) The Socio-Technical Aspects of Digital Plumbing

Grinter et al. [148] uncovered a series of issues that are of moment when engaged in digital plumbing [355] and digital housekeeping [357]. One of these concerns the social-technical aspects of digital plumbing. Their study showed that, beyond the utilitarian aspects of new technological infrastructures brought into the home, there were strong moral imperatives that shaped the selection and configuration of services and devices on a home network. In addition to this, Tolmie et al. [355] drew attention to the fact that there are also socio-technical issues regarding the location where new technological elements will be installed. Technically, the choice of where elements will be installed depends on the feasibility of installing them at that particular location; socially, it depends on those who will use those elements and whether they want them in that location.

In our case, the responsible employees at Alpha created a list of the sensors that would be needed and the machines upon which they should be installed. This was done independently on the basis of a preliminary study and analysis of their potential use. The investment to equip all devices individually with energy sensors is very high and, to save money, Alpha only equipped large-scale consumers with their own digital meters, as these were of most interest to the energy managers. Machines that consumed less energy were grouped with other machines of the same type and the energy was measured at a group level via one digital meter (e.g. all presses of the same type). When choosing the vendor of the sensors, Alpha relied on the current market leader for energy sensors in Germany and ordered more than 140 energy sensors of the same type for the project. The installation of the sensors was conducted by Alpha's partner company, which was responsible for electrical maintenance at the facility. The electricians had been one of their service providers for a couple of years and was therefore trusted to install the sensors. They also knew the specific electrical infrastructure of the company. These decisions formed the basis for the entire process and influenced the subsequent steps.

For the integration, the IT service provider Beta was commissioned by Alpha to store the data centrally on a database in another location. From an electrical point of view, the installation was successful, and the sensors were able to measure the energy-related data, but the subsequent integration of the energy sensors into Alpha's digital network was problematic, as seen in the previous section.

Our findings therefore demonstrate how we still know very little about the work required to install IoT technologies in real organizational contexts. Much of the concern regarding the IIoT has been at a theoretical, technical or policy level, as is evident in the literature review provided in Section 4.2 above – see e.g. [9, 132, 219]. Nevertheless, as Tolmie et al. [355, 357] put it, 'digital plumbing is quite indispensable' (p. 191), since digital infrastructures do not come to life spontaneously, but rather as a result of meticulous work, that involves, amongst other things, legacy issues, planning and preparation for installation, finding the right place to locate the technologies and keeping the surroundings in acceptable order (ibid.). Furthermore, as both Grinter et al. [148] and Tolmie et al. [355, 357] are keen to point out, this work is imbued with social and moral reasoning that elaborates upon any technical decisions that are made. In fact, we would argue that these issues are even more critical in organizational contexts, because they involve more actors, more regulated contexts and more complex infrastructures, as is evident in the empirical material we have provided and will discuss further in the next section. The fact that the management of Alpha thought that simply buying the best off-the-shelf sensors for building their IoT and that leaving the installation in the hands of competent electricians would be sufficient, is evidence of that.

4.4.2. Middleware issues in Handing Data

The abovementioned issues also influenced the work on the middleware – and thus the collection, storage and distribution of energy-related data – by Beta. After fixing the problem of the unclear assignment of the incoming data to the physical endpoints, Alpha was responsible for enriching the data with semantic information. This included, for example, the designation of the machine connected to the endpoint, its type, its location and other economically relevant data. Although this was a rather important step, Alpha's energy manager was not able to fill out all this information because no meta data on business level was gathered and maintained in the first place. Alpha therefore lacked basic information about the collected data, such as the units (energy, temperature or pressure), the ID of the sensor that produced the information, the assignment to a cost center or a clear name that was readable and understandable to humans. This confirms that metadata is a necessary requirement for working with IoT technology [94, 219]. It was necessary for Alpha to enlist several people to retrieve the relevant information. In addition to the energy manager, employees of the plant had to be involved on site. Due to the constant adaptation to the production requirements in the plant, where machines are changed over or partly connected to other connections, the documentation of this master data ought to have been a regular, indeed continuous process. In reality, however, this was often neglected, so that the assignment of the data was not up-to-date at any time. This was made even more difficult by the many actors involved in this process and the numerous documents to be synchronized.

We observed that data center architectures at the time of the study were not prepared to effectively handle the heterogeneity and volume of data to be generated by the IoT sensors and other associated technologies, making *data* *management* a challenge, in line with previous findings by I. Lee and Lee [219]. As Zhang et al. [391] note, data centers must undergo a transformation to accommodate the demands stemming from the integration of IoT technologies. Among other things, large investments in data storage must be made so that these centers are able to store and process the massive amounts of data that are generated. The following sub-sections unpack the issues with data management and *data mining* – another challenge for IoT infrastructures in manufacturing settings according to I. Lee and Lee [219] - that emerged during our study.

(i) Querying for Data

As a project manager from Beta stated, in the beginning, they wanted data to be gathered from the sensors with as much granularity as possible. So, in the first implementation the sensors fetched data in time intervals of (partly under) a second. This led to the problem that writing data to the database and querying the data while analyzing it was effectively unmanageable with the current infrastructure, i.e. the type of database and software the company relied on. This echoes I. Lee and Lee's [219] discussion of the problem of mining current data: The algorithms used were not adequate to the data-mining challenges, be it the analysis of existing large bodies of heterogeneous information in data-storage or the way that sensors might otherwise do a pre-analysis of captured data and decide how to handle it. This also goes hand in hand with the need for a more efficient way of transmitting data to the network and better use of constrained resources [360]. To deal with this problem, the company implemented software that aggregated the fine-grained data to longer intervals before putting it into their storage. However, the software was not error-free because of the need to implement it quickly, which in turn led to a lot of data being, in essence, useless. Additionally, in some cases it is not necessary to store data in small time intervals such as a second. Values relevant to billing, for example, can be stored in 15-minute intervals. For many use cases, participants told us that larger summaries would suffice:

"Yes, [monthly] will be enough […] to determine whether there is a trend towards being good or bad in terms of [...] energy use, with this indicator we have to deal, and should it be deteriorating then we need to search for causes", I18.P15

For this reason, coarse-grained data is needed as well, which is usually queried at intervals of at least 15 minutes. On this point, the project manager from Beta argued that

"[a]fterward, we had to say that this might not have been realistic, because the devices were very busy, and you couldn't reach the other consumers at the same time. This may still be a valid wish if you buy the equipment that you can use in parallel. In other words, the granularity was extremely reduced, and it was then said that data every minute would be nice, but only this data every 15 minutes is actually relevant for review or reporting", I23.P18

Another problem arose because the middleware was not able to handle a large number of connections with the installed sensors and the devices where sensors were aggregated. A Modbus-Master device was used to route the data generated by the sensors to an appropriate endpoint. However, this led to faulty data with the middleware rejecting the data bundle pushed from the infrastructure to the company, resulting in a lot of data being "null" and therefore effectively useless. As one interviewee put it:

"It [the system to store the data] was not that flexible that you can configure bundled data because when there was a 'rotten egg' or a problematic register, then this complete bundle is discarded and must be subscribed again and therefore we have not excluded that the data which then remained zero could have been improved with more flexible error handling in the middleware. What we then had was simply implausible data", I23.P18

(ii) Storing the Data

Over the course of the project it became clear that some system requirements could not be met. Time-series-data had not been well-implemented but became important at a later stage. The project manager from Beta (P18) described how he wished to implement a resilient system that would be as flexible as possible and able to handle the amount of data published and to store it, regardless of the amount and type being sent, in an appropriate way. However, Beta had problems with the appropriate storage of the energy-related data. Each sensor was able to collect over 100 different kinds of energy-related data per second. With nearly 150 sensors installed, this amount of data was too large for the database structure. Therefore, the company had to test new approaches to aggregation and to allow the storage of just the important data. The project consortium and Alpha itself gave little thought to what would happen after installing the sensors. Beta had some experience in this area could provide a ready-to-use system to take the data and store it in a database. The system was extended with another adapter receiving and providing the data generated in this project. The data was then stored to a Microsoft SQL-Database. Though Beta was not experienced with time-series data, they tried storing it to this database as well. The project manager from Beta explained that the only way was to do this was once again to aggregate the data:

“If you want to write down the relatively high granularity level and then evaluate it according to all the rules of the art, the queries are unpleasantly slow. So, we then constantly aggregated to certain aggregation levels [...] and immediately delivered back; but also, with a system, which was comparatively ad-hoc, where I would wish in the end if you had a complete time series database or a middleware, which can store this from the beginning, so you have even greater degrees of freedom. So, in the end, aggregation of data was a challenge”, I23.P18

Our data therefore suggests that when it comes to handling data, it is often the case that new areas of responsibility will emerge – as we observed when the IT-Department and Beta were given new responsibilities and started having a central role in the distribution of data to the various divisions of the company and different network structures.

We have also observed that existing IT systems or architectures will have to evolve. They are often unable to cope with the requirements of new digital applications. Storage space, query and transmission speed as well as processing performance can become real bottlenecks, as has already been discussed in the literature [354]. Thus, existing structures, e.g. ‘old’ SQL queries, might be unsuitable for things like time-series data and need to be replaced by appropriate systems that allow for the processing of large amounts of data. Trying to fit the new technology to old data structures in our case occasioned a set of problems that could have been avoided. This also emphasizes that the work of digital plumbing does not stop at the moment installation is complete but rather needs to be an ongoing process as new requirements and the need for new kinds of functionality arise.

Last but not least, there are still open issues concerning privacy and security that might be addressed by future research [219]. Current practice often consists of separating the machines’ network from the public internet to ensure that security can be maintained. However, this can create an extra layer of difficulties that need to be overcome, as was saw in section 4.4.3.3.1. With new intelligent machines or sensors that retrofit older machines, new IT security structures may have to be developed to support the central collection of data.

4.4.3. Adoption Issues: Using the Data for Energy Saving

The original goal of the environmental department was to automatically store meter readings for the statutory audit process to save taxes. At the same time, however, a larger digital basis was required to further identify efficiency measures that could be implemented within a digital EMS. Therefore, the environment department drew up a list of measuring points at Alpha where digital meters should be installed. Consequently, the digital plumbers had to face a series of challenges. As we will see, the Environmentalism, Industrial Safety and Facility Management department developed the measuring point concept on their own without involving other potential stakeholders or exploring use scenarios. This led to problems that could have been avoided – e.g. users not really knowing how they might use the data being collected from the sensors, or for what purpose. Moreover, our findings suggest that to create opportunities for adoption, the technical infrastructure should not be seen as separate from organizational structures but rather complementary to them, though, in some cases, digitalization can require the conversion of organizational structures (e.g. cost centers). All the issues covered across in the following sections reveal specific features of digital plumbing in organizational contexts that shed light on some of its practicalities that are not yet well-understood.

(i) Accommodating Different Demands

During the installation of the sensors, we spoke with the various departments and stakeholders in the company – i.e. Maintenance, Control, IT, Purchasing, Environmentalism, Industrial Safety and Facility Management, Heads of Business Units (Production) and Machine Operators – about the possible use of digital energy data to identify the requirements for an EMS. It became apparent that the requirements and problems for the various interest groups were very different, predicated on heterogeneous working practices that were in turn prompted by varied contexts of use.

Operational level

At an *operational level* the interviewees criticized the lack of information about the actual amount of energy consumed. This made analysis and assessment immensely difficult. To understand their local energy system, employees highlighted the need for an eco-information system that would provide the opportunity to visualize maintenance data at an operational level. A responsible employee needs a good overview of the average consumption behavior (of the company) compared to the current energy consumption to be able to reason effectively about the energy data. In this respect, an interview partner from the Maintenance department stated that

"[…] in terms of predictive maintenance […] if the heating element has not 3.1 kW [power] anymore, but only 1.4 kW [power], then I can ask myself: maybe they are completely filthy that I had to make them clean again or [they] go slowly in wear and I have to replace them", I2.P2

So, energy data might be helpful in identifying reasons for a failure, e.g. a pressure drop in the compressed air lines. The interviewee from the Maintenance department (P2) stated that in the case of machine error:

“[t]he colleagues go to the machine and do not even know what causes the problem, but with such a system [Energy Information System], they can get much more information before being there like: […] is it an electrical fault?”, I2.P2

Collecting information about unusual events was a need identified by other units as well, for instance the management. The head of electroplating was interested in calculating the energy costs that reflected Alpha’s cost center structure and he also wanted to obtain feedback about unusual behavior or levels of consumption – especially on compressed air – so that necessary action could be taken quickly.

In our interviews the employees, it became clear that a large amount of informal knowledge is deployed in dealing with the machines and processes in their daily work. When they discuss their experiences and best practices among themselves, energy is a common topic, but as there is no accurate consumption data, this is usually done at an abstract level, such as discussion of machines that are left on standby consuming energy. However, one of our interviewees mentioned that real energy consumption data would be interesting for him by enabling him to know how much energy individual processes require.

Nonetheless, it was regarded as essential to provide machine workers and Heads of Business units with data on their controllable consumption. In the interviews, some employees (Business Division Manager (P11) and another person (P3)) from the department said that the workers had also mentioned to them

“[…] that they can’t do something, without data”, I14.P11 and

“[n]obody can tell me, what their machine really consumes”, I15.P3

As noted above, the main challenge is to divide energy consumption into various forms of use, such as heat and hydraulics. With a view to a continuous improvement process, an eco-audit is now also being carried out. At present, the survey and evaluation process for the execution of this is being carried out manually, which means a great deal of effort because a large amount of heterogeneous data is needed.

Management level

When we conducted our study, we found that the Controlling department was using information about energy consumption based on informal communication with the Manufacturing and Purchasing departments. The Controlling department collects this information once a year and takes it into account when compiling internal analyses and evaluations. Unfortunately, the collected data was of rather coarse-grained quality. One participant stated, that fine-grained data:

"[…] would improve all of our operational accounting, for example the direct costs per product that are currently calculated by estimation", I20.P17

This goes hand-in-hand with our observation that, to take a closer look at consumption optimization, the interviewees had said that they first needed precise energy data to be able to analyze the current processes within a department.

Each division had a different attitude towards the use of energy data. Some interviewees emphasized that interest in energy data was growing because they were becoming an increasingly important cost-driver in the production process or that cost allocation on a per-product-basis would be much more easily done through the use of an EMS, as noted above. Cost-allocation does not necessarily need to be made on product-basis but also on division-basis as the company also formulated demands around projects so that costs could be assigned to the business unit that produced them. One participant even suggested some real impacts that transparent energy-data would have:

> “We need to know what energy is really needed for a specific product. Not as it is right now […] then I could imagine that maybe one or more products get pushed out of our product portfolio”, I15.P3

Other employees and business units were not that interested in using energy-data. The Business Division Manager (P16) saw the saving potential to be very limited and was, therefore, relatively uninterested in obtaining more detailed eco-feedback. However, he did see the benefits of using the data to support investment decisions through better return-on-investment (ROI) calculations. Other departments, mostly energy-intensive ones, were not interested because they did not see the opportunity to save energy. The production business unit manager explained that he did not need to engage in special energy management because production innovation was mainly driven by productivity improvements. In his opinion, a monthly report should be enough to get an overview of whether something unexpected has happened. As part of the internal reporting process, interviewees found that it was difficult to provide internal reports to the different business divisions because the granularity of the energy data was not fine enough and could not be matched to the organizational structure.

One crucial aspect of management and control is the use of reports and reporting for both internal employees and other institutions and companies. For the Environmentalism, Industrial Safety and Facility Management department, for example, it was especially important to increase efficiency within the organization. However, to be able to develop appropriate measures to improve energy efficiency, the most important energy drivers had first to be identified. A separate key performance indicator (AlphaGreen) is currently used as an internal reporting tool for measuring efficiency. Regarding external reporting and cross-industry benchmarking, interviewees pointed out that standardized reporting, for example key performance indicators by the Global Reporting Initiative (GRI), would need to be used in the near future. Due to the importance of suppliers like Alpha indicating their CO_2 footprint, this kind of calculation now needs to be implemented in their system.

When purchasing energy, it is important to have a good forecasting model of energy consumption to estimate the quantities required as accurately as possible. The employee responsible for purchasing mentioned that their current energy procurement was organized in 10 tranches per year, which are purchased with different timestamps prior to the commencement of delivery. Currently, this data is manually collected at a rather coarse-grained level, which makes an accurate view of historical consumption very difficult. He therefore hoped that eco-feedback systems could help to improve the accuracy of reports on this issue. In addition, the Purchasing department had a strong interest in energy consumption forecasting as this could support price negotiations with energy suppliers. For this task it was essential to divide the energy costs into separate working prices, offshore-apportionment and energy tax. Outside of this, the employees had some other demands on (future) implementations of the EMS, such as the active and reactive guidance of investment decisions based on eco-feedback as well as production-efficiency calculations.

Summing up, we observed that there was a need for energy data to provide more information for certain kinds of management, as well as to support the business at an operational level. Looking at this further accentuated the fact that how energy data is oriented to and used is bound up with specific, socially formulated perspectives and that this needs to be taken into account in terms of what data is collected and how it is presented. This is very much in line with the arguments presented by [21]. We have also seen that the need to communicate energy-related information both internally and externally can have an impact. Thus, energy data could be used to complement current operational key performance indicators, such as energy costs per article produced and company performance in relation to things like CO_2 footprints.

(ii) Matching of Data Requirements and Infrastructure

The various requirements identified in our analysis demand a flexible system at the UI level, but explicit needs can also be identified at the infrastructure level. Overall, the measurement plan was sufficient to enable the energy department to automatically meet legal requirements. However, the intention to create a basis for additional savings through the automatic storage of meter readings for the statutory audit process could not be fully met.

The different needs of the various stakeholders can be divided into the following perspectives upon what kind of data is required. Maintenance and Machine Operators felt that the energy-related data – such as electricity consumption – should be gathered at a fine-grained interval of less than 1 minute to allow near real-time monitoring and analysis and also to capture the status (standby, off, on) of a machine. Environmentalism, Industrial Safety and Facility Management, IT and Purchasing wanted the data to be stored as raw data to allow a historic view on the consumption data as well. In addition, Purchasing argued that it should be possible to aggregate the consumption data so as to be able to read the total consumption of sub- and main distributions. Another requirement was the use of unambiguous metadata to describe the consumption data in detail. A business manager wanted to be able to make a comparison of consumption data across different machines (with the same function) and the consumption of a machine with different parameters/settings. However, comparison between different setting options of a machine can only be carried out if machines have their own measuring device. Even if the total energy consumption can be recorded digitally via the sub-distribution or at the latest the main distribution, in some cases only entire machine groups can be measured together. However, since individual machines from these groups sometimes belong to different business units or are assigned to different cost centers, it is not possible to allocate consumption correctly. As other studies have already mentioned, this mismatch results in limited integration of digital data into the everyday working activities of the users and thus reduces the use of the system [384]. Another category of requirements deals with the exact allocation of consumption, e.g. to business units/divisions, cost centers, location or products.

Table 3 compares the requirements with the current possibilities in Alpha. Here it can be seen that many of the requirements cannot be implemented (-) or only partially (o) given the current infrastructure. This mismatch, on the one hand, is because of the measuring point concepts used, which are designed centrally without taking other business divisions or departments into account. On the other hand, organizational issues, such as the fact that business divisions and cost centers cannot be clearly allocated to machines, also creates difficulties. This was aggravated by the fact that, for cost reasons, not all machines were equipped individually with sensors and some machines were recorded by a single sensor. The selection of the machines to be measured individually was based on assessments undertaken by the Environmentalism, Industrial Safety and Facility Management department, which were based on their own specific interests.

Table 3. Comparison of requirements for energy data and possibilities through existing infrastructure (+ = implementable; - = not feasible to implement; o = only partially implementable)

	Task	Requirements	Available
Maintenance	Ensure that the operational state is maintained (preventive maintenance) or restore after failures.	o Fine-grained energy consumption data for single machines o Machine operating hours based on energy consumption	Fine-grained energy consumption data for some machines Fine-grained energy consumption data for groups of machines
Control	Systematic recording, monitoring and informational compression of data for report and cost allocation.	- Energy consumption per produced output - Energy consumption by cost centers o Energy drivers + peaks	Energy drivers and peaks at sub-distribution level
IT	Oversight of all technology equipment information, configuring network access, setting up and making changes to existing workstations and assigning access rights.	+ Timely gathering of sensor data	Timely gathering of sensor data
Purchasing	Supplying the company with goods and services that are required to carry out the production process as well as the planning and control of material cost development.	+ Total energy consumption of a subsidiary + Monthly-based forecasts of total energy consumption	Total energy consumption of a subsidiary Monthly-based forecasts of total energy consumption

Environment Management	Observance of official environmental concerns and ensuring the sustainable environmental impact of the company's products and processes.	o Fine-grained data at location level, business unit level, organizational unit level and hierarchical level o Consumption by use (mechanical, heating etc.)	Fine-grained data at location level (total and sub-distributions) Consumption for heating
Division Managers	Planning and monitoring of the department to ensure that managerial strategic plans are implemented.	o Energy consumption of the business division o Energy consumption at machine level	Energy consumption data for some machines Energy consumption data for groups of machines
Operators	Responsible for the operation of the production machinery.	o Real-time consumption data for single machines	Energy consumption data for some machines Energy consumption data for groups of machines

4.5. Concluding Discussion

During our study, we were able to observe a number of issues that had to be dealt with when planning the installation of and implementing a new IoT infrastructure for digital energy saving in Alpha. This, we suggest, yields some valuable insights regarding the many digital plumbing problems that can arise during installation, commissioning and integration as well as in the use of digital infrastructures in manufacturing settings.

To conclude, we will examine how this both relates to and extends upon existing work on digital plumbing. The original studies of digital plumbing identified four key aspects of the work that needed to be attended to when undertaking such an exercise of seeking to provide support. These covered: preparatory work; the assembly of tools and parts; the management of contingency; and coordination and awareness. In the following we shall both expand upon and add to these.

4.5.1. Supporting preparatory work

In Tolmie et al.'s [355] original study of digital plumbing in a domestic context a number of elements of preparatory work were seen to be key to realizing such an activity. One of these related to digital plumbers needing to actively coordinate with and collaborate with household members by planning what to install and where, with all the stakeholders, not just a single representative. Doing this required negotiation prior to even entering the site. Thus, digital plumbers needed to identify not just technical constraints in advance (an important aspect in its own right), but also social constraints, by talking to all the household members and ensuring that the proposed installation would meet their requirements and not lead to trouble (such as equipment and cables being left within the reach of small children).

Our study of Alpha also strongly points to this need for preparatory work, with its absence being a key factor in many of the ensuing troubles. The development of an appropriate technical infrastructure, which is not yet available, therefore requires a social interaction between all participants in advance. This, as Tolmie et al. [355] point out, will provide a means of identifying not just the technical constraints, but also the social ones. In a commercial and industrial context this will include the identification of things like very different interests in engaging with the data and its use and then negotiating mutually acceptable solutions. Indeed, when troubles were discovered at Alpha, social interactions regarding the technical aspects played an important part in the resolution of the problems that had emerged.

Another feature uncovered in past research points to is the need to develop tools dedicated to doing the work of digital plumbing, in a domestic context this might involve things like appropriate mapping of the existing infrastructure [148, 355]. In the case of the study we have described here, the installation was undertaking by an external company, Beta, and further work involved the expertise of Gamma. In the situation Tolmie et al. was describing there was an envisaged need for expert digital plumbers for domestic environments to recognize the scope for providing such a service and to establish enterprises accordingly. In the commercial world, companies with the relevant expertise are presumed to already exist and turned to accordingly, with installations of the scale described here rarely being undertaken in-house. Thus, it is assumed that such enterprises will already have the relevant tools and parts in their possession. It was not clear in the installation observed that this was actually the case and, as the work involved mapping out of the relevant devices to be enhanced in various ways by technical experts *inside* Alpha, it is clear that in an industrial context this is a much more complex equation which, again, necessitates prior negotiation. Something that did not occur at Alpha, and that was evidently necessary, was the development of adequate tools for documenting just what was installed for later reference.

In relation to the prior point, the work involved in actually assembling the tools and parts necessary to undertake a specific a digital plumbing job should at times be specifically tailored to the task in hand, rather than simply going along with a generic toolkit. Tolmie et al. [355] suggest that a key part of this is not just assembling what is required, but what may be required. It would seem likely that this also featured in the work of the digital plumbers from Beta and Gamma, beyond just the assembly of the original sensors, etc. However, much of this work would have happened within Beta and Gamma themselves, so it was not available to observation.

If, as Tolmie et al. [355] assert, preparatory work is essential in the domestic context to offset the worst effects of problems arising on the ground, we have demonstrated that this work is even more crucial in an industrial context. Our observations presented us with numerous examples of how the absence of such preparatory work allowed difficulties to not only emerge but to be far beyond the competence of any single individual to solve. This latter point is particularly important. It needs to be recognized that a digital plumber, especially in large-scale commercial settings, cannot be a universal soldier. There is a need for either teamwork to manage arising contingencies or the provision of support tools that give access to other forms of expertise, such as those proposed for printer service engineers (e.g. see [32]) or amongst other kinds of maintenance personnel (e.g. see [294]). Therefore, we argue that Further studies of digital plumbing in industrial and commercial settings need to examine how the work is coordinated and accomplished beyond the nexus of the actual installation.

4.5.2. Supporting the management of contingency

Original studies in digital plumbing in domestic context stressed the need to recognize that contingencies will arise and that the best way to manage contingencies is to be as prepared as possible [148, 355, 357]. This reflects the fact that what is required is often only discovered either on the ground or after the fact. This resonates strongly with the findings above. An additional feature of commercial and industrial environments revealed by this study is that managing contingency can also involve dealing with different requirements that are only uncovered over the course of, or even after the installation.

Reflecting upon the difficulties that Alpha experienced in bringing an IoT network to life and making use of it to achieve their initial goals – i.e. provide evidence during audits that the company had been saving energy and, hence, was entitled to receive financial incentives in the form of tax reductions – it is apparent that Alpha underestimated the scale of the practical problems that digital plumbers might face as they went about installing the desired digital infrastructure. It is also noticeable that the company was not prepared for the management of contingencies during the installation and, as a result, the process took much longer than planned, leading to them having to postpone use of the infrastructure for the purposes intended.

In addition to that, troubleshooting and faultfinding have been found to be an inevitable part of the work of digital plumbing and that its successful realization is dependent upon the competence of the digital plumber [355]. However, our own work suggests that the level of technical knowledge required by a digital plumber in an organizational context might be of another order.

Due to the increasing uptake of IoT and IIoT technology, the problems and challenges we have recognized are not unique but will continue to arise over the coming years. The planning and approach to installing IoT-capable technologies in companies must change and current organizational structures must evolve or adapt in this respect. In addition, new skills are required amongst the relevant project managers and responsible parties. This, we argue, is as important as having the necessary the technical know-how. We would also argue that the issues that we highlight in this contribution are issues that must be taken into consideration by any company planning to engage in the digitalization of their processes. We emphasize the importance of adopting a socio-technical approach, involving a broad range of stakeholders and people with the right skills and competencies to design and deploy solutions that can actually lead to the desired results.

4.5.3. Supporting coordination and awareness

One other aspect of digital plumbing that emphasized in the literature is the need to track and manage the changes that are being made through the assembly of an appropriate record that is open to ongoing annotation [355]. We have already noted how the story of Alpha powerfully supports the need for this in an industrial context through its absence and the troubles that thus ensued.

The need for coordination and awareness across the digital plumbers involved in an installation, with it being important that they keep one another updated, also must be considered. This is both reinforced by our study and expanded upon. In a commercial and industrial context, especially in larger companies, this takes on a new complexion because of the need for coordination across multiple different providers and stakeholders. We have seen in the case of Alpha how this can implicate interaction between people with distinct organizational roles, between members of different organizational entities, and even between members of different organizations.

There are clearly issues that stem from organizational hierarchies and inter-organizational work that impose themselves on the process in various ways, giving digital plumbing in industrial settings its very own characteristics. For instance, it was the interaction between the electricians of Gamma and the IT-Department from Alpha that, over time, allowed for a better understanding of Alpha’s network restrictions, so that the problem preventing the data being collected from the sensors reaching Beta could be resolved. It may be recalled that this had to do with a special IP flag generated by the sensor software being blocked by Alpha's network, thus preventing the IP packages from passing out of the internal building network. This is enormously characteristic of the kinds of problems that can arise as a result of inter-, and even intra-organizational boundaries. These kinds of boundaries are one of the key differences confronting digital plumbing in industrial settings when compared to domestic settings, where scale and the way in which intra-family relationships and communications are conducted mitigate against the possibility of these kinds of problems arising.

Organizational divisions can also be geographically spread, as was the case with Alpha. This spatial distribution caused additional difficulties, such as the difficulty of transferring data to Beta, which was responsible for storing the data collected from the sensor technology.

An especially important feature is the need for the IIoT to ensure that its approach to storing and using the data collected is consistent with current privacy and security demands [218]: to whit, (1) identify the user whenever data is captured; (2) get the consent of the user for the data to be captured; (3) implement adequate security mechanisms (encryption); and (4) pay attention to legal requirements when collecting the data. These are mostly technical problems, solved through technical solutions. However, other problems with privacy and security are of an organizational nature and have to be handled through organizational change. In addition, regulations like General Data Protection Regulation (GDPR) [303] force companies to handle privacy and security in a consistent manner. This is only possible if the company has adequate resources in respect of manpower, time and money to deal with the upcoming tasks. In small and medium enterprises (SMEs), this is not always the situation. As we have seen, integrating IoT technologies into a network in a compliant way can result in a lot of organizational issues, even for relatively big companies like Alpha, and ongoing challenges in the field of security and privacy can be even harder for SMEs, such as craft businesses, to deal with [332]. For digital plumbers, these issues pan out in different ways in domestic and organizational contexts. In a domestic context, the data may be more sensitive, but the focus is upon constructing the right conduits and barriers for third parties to get sight of only what is sufficient for IoT-based services to be provided to the home [78]. In an organizational context, the problem is one of ensuring that the relevant protocols and procedures are identified in advance and adhered to, and that actions taken in respect of this are adequately documented and accountable to other organizational stakeholders (i.e. both inspectable and *intelligible*).

In relation to this, it is worth pointing out that it must be recognized that the plumbing is not done once and for all once an installation is completed but is rather an ongoing process, so there will be further change [355]. As noted, this needs to be anticipated and supported through the provision of an adequate record - recognizing in particular that future work may be undertaken by other people. Thus, in an industrial setting, digital plumbers need to take into consideration how to make the new infrastructure transparent and addressable and make sure that the right resources are in place to support its operation. This needs to include a planning and preparatory work element where digital plumbers are implicated in attempting to future-proof an installation by anticipating change. Whilst this is clearly of moment in domestic settings it takes on a new dimension in industrial settings because it operates at a different scale, requiring coordination across multiple parties with different organizational interests, not just the digital plumbers themselves. Ignoring this consideration also has consequences that operate at a wholly different scale in industry, because failure to attend to it can come at a huge economic cost, as was the case in Alpha (especially internal costs for fixing and re-working the system).

4.5.4. Accommodating different demands

Throughout the above observations, a recurrent concern is the incumbency placed upon those undertaking digital plumbing in commercial and industrial settings to take properly into account the diverse and even potentially conflicting demands of different stakeholders. It is wholly typical of organizations, especially those over a certain size, to be broken up into structural units to reflect the processes and division of labor involved in the work. These units can be more or less effectively articulated and can be geographically distributed to a greater or lesser degree, but structural divisions are always somehow present. As we have seen, this means that perspectives upon change, such as the installation of IoT systems, typically differ according to the priorities of the specific unit. The differing demands can be both operational and managerial but constitute a reality within which digital plumbers must work. In Alpha, the horizontal organization of the different departments and their very different requirements for information introduced a layer of unforeseen complexity. Complexity of this order is simply not present in domestic settings and it inflects every part of the plumbing process, from the planning and preparatory work, through the handling of contingencies, and into the practices adopted to ensure effective coordination and awareness. Above all other things, our findings here tell a story about the troubles arising from this complexity and provide useful information about the issues that can arise and deliver insights regarding how to manage the unfolding installation of an IIoT.

A cautionary tale, such as the one we have elaborated in this paper, should be instructive and valuable to the HCI community and, potentially, to commercial interests. It shows that the effort involved in deploying a digital infrastructure in a production company requires the development of methods, collaborative structures and IT-tools that support the individual competences of different stakeholders involved in the process, including preparations, installation, documentation and integration as well as coordination of installation activities. We are confident that the findings presented here will help organizations planning to invest in new IoT infrastructures to avoid many of the hurdles faced by Alpha and open up a new awareness of the potential impact of installing IIoT technologies and the practicalities surrounding it.

5. Role-Based Eco-Info Systems: An Organizational Theoretical View of Sustainable HCI at Work

So far, sustainable HCI has mainly focused on the domestic context, but there is a growing body of work looking at the organizational context. As in the domestic context, these works still rest on psychological theories for behaviour change used for the domestic context. We supplement this view with an organizational theory-informed approach that adopts organizational roles as a key element. We will show how a role-based analysis could be applied to uncover information needs and to give employee’s eco-feedback, which is linked to their tasks at hand. We illustrate the approach on a qualitative case study that was part of a broader, on-going action research conducted in a German production company.

5.1. Introduction

In recent years, sustainability in terms of energy consumption has become an important issue in preventing environmental pollution. By minimizing energy waste on the basis of more efficient use, a reduction of the carbon footprint should be reached. In the reviews and statistical reports of the European Union (EU), energy consumption is divided into seven sectors (industry, transport, households, service, agriculture, fishing and others) [198].

Seminal work has been carried out supporting people's energy saving in the household sector [135, 342, 85, 152, 288, 320]. This work was partially pushed by technological innovations making fine-grained consumption metering in real-time possible [87, 333]. A wide spectrum of domestic eco-feedback design studies explored these new opportunities, reaching from artistic solutions like the Power Aware Cord [152], through pragmatic ones like Watt-Lite [190], social norm-oriented approaches [127, 286] to HEMS integrating multiple features into a home-oriented system of services [320]. Further, several empirical studies demonstrate its effectiveness in not only raising awareness but also empowering consumers to implement savings as well [85, 87, 289, 320]. Conceptually, this research is dominated by psychological motivation and persuasion theories [98, 135].

Despite the domestic setting, there is growing interest in using eco-feedback at work [85, 87, 289, 320], especially because the industrial sector is responsible for 26% of the total energy consumption [198]. In addition, energy becomes an important cost driver so that conservation is not just an ecological demand, but also economically rational [172, 375]. However, compared to the domestic eco-feedback research, the number of studies is quite small. A careful reading further shows that these studies mainly adopt the psychological theories that are well suited for the domestic context.

As noted by Brynjarsdóttir et al. [45], a sole focus on persuasion is, however, likely to narrow our vision of sustainability. In particular, in the organizational context the isolated focus on motivation might lead to an overestimation of individual factors while underestimating organizational factors.

In this paper, we aim to extend and enrich our view by drawing attention to take both approaches (HCI and IS) into account while designing eco-feedback at work. We show within this paper how both theories can profit from each other. While Organization theory looks more on the organization as a unit with aggregates on people, HCI looks on people itself and their needs. These two approaches complement each other by looking close at the very bottom of an organization (people and their needs) to the very top (the organization as a unit).

5.2. State of the art

5.2.1. Eco-feedback at work

In this section, we want to give a brief overview of current research on designing eco-feedback and eco-campaigns in the organizational context. This issue is also linked to the design of Environmental Management Information Systems (EMIS) studied in the topic of IS [108, 323]. This research stream, however, is not further considered as it mainly focuses on the strategic level studying techniques and tools for the green business process management.

Matthies et al. [196, 238] conducted one of the studies looking at how ecological information works on the office hallway, by developing checklists, sample templates, etc. to use when conducting eco-campaigns in buildings. With emphasis on companies and enterprises, the German Agency for Energy Efficiency has developed a similar campaign toolbox called MissionE. Both approaches have not been considered smart technologies yet, but mainly focus on media such as posters, flyers, information brochures and letters from superior authorities to motivate employees to save energy by switching off energy consuming devices, turning the heating down etc.

In addition to focusing on traditional media, Azar & Menassa [11] have investigated into motivational eco-feedback in organizations. In their work, they have developed a framework, which supports the implementation of energy-saving measures in commercial buildings.

An attempt to provide general design guidelines for organizational eco-feedback was made by Foster et al. [128]. Based on a literature review about techniques of intervention appropriate for the workplace, they took the results from environmental psychology (like social comparison, goal setting, etc.) into account [2]. Yun et al. [385, 386] implemented a first functional prototype of an energy-dashboard.

In addition, there are some empirical studies evaluating organizational eco-feedback [53, 258, 319] with different results. For instance, by providing monthly feedback with motivating messages [53] or installing eco-feedback applications [258] a reduction of university employees’ energy consumption can be reached. But it is also noted that it is a complex relationship between feedback and behaviour and there are many reasons ‘not to switch things off’. Schwartz et al. [319] installed smart metering technology in a research institute and observed that workers take the responsibility for sustainable energy practices if their consumption is made visible and they are supported for example through feedback. That leads to significant positive effects as well, but the conservation fading slowly over time and were not sustainable in the long term.

Currently, we do not have sufficient evidence to make conclusive statements. Yet organizational eco-feedback seems to be a promising candidate for supporting energy saving at work. However, several challenges have still to be solved:

First of all, it seems that one size does not fit all; meaning feedback should be tailored and more action-orientated to reduce the complexity for the users and to enable them to make sense of it [258, 319]. At first glance, this confirms He et al.’s [165] seminal critique that one-size eco-feedback is not enough. However, their major argument is that design should consider people's individual stages in a multi-step behavioural change process [297]. In addition to this argument, we provide a further account as to why tailored information is needed due to people having different roles that call for different kinds of eco-information.

Another issue relates to organizational constraints and changing individual behaviour [53] as well as sustaining such changes [319]. These shortcomings are linked to general remarks that simply observing the individual is not enough [164]. However, with regard to the organizational context, this statement allows the assumption to be refined and to be made more operational: the alignment of individual changes in combination with organizational changes that influence the behaviour at work (and vice versa) represent a major challenge for organizational eco-feedback design. In other words: how could we support continuous improvement processes by bringing people and processes together, bridging the gap between the operative and the strategic level?

For these reasons, it is generally good advice to consider the specific nature of the context, starting by asking ourselves naively what an organization actually is.

5.2.2. Organizational Theory-informed Design

At a very general level, organizations are social aggregates that are structured and managed to meet a need or to pursue collective goals. Even if the goals may vary the central aspect of an organization is the coordination of people and resources [146]. Organization theory is a macro examination of organizations, because it analyses the whole organization as a unit with difference in their structure on analysis level [84]. Managers deliberately structure and coordinate organizational resources to achieve the organization's purpose. They are mainly defined by their internal structure and their inter-relationship with the environment in which they operate [171].

Applied management research mainly uses such structural views to analyse, manage and design organizations [158]. Here, organizational structure and business processes (sometimes also called operational structure) present key concepts [171].

The organization structure describes the static nature of organizations, breaking down the whole into smaller, manageable units like departments and sub-departments down to single positions. The organization chart presents a visible representation of the organizational structure with the underlying activities, processes and tasks of departments, units and jobs. The structure depends on the organization's objectives and strategy and is a product of business planning and strategic development. The planning typically covers four elements [8]:

- The assignment of tasks and responsibilities to define specific jobs.
- Clustering jobs into units and departments to form the organization’s hierarchy (departmentalization).
- Defining vertical coordination, such as the span of control.
- Defining horizontal coordination, such as inter-departmental teams.

In general, business processes describe the logical, sequential order of operational events using and transforming diverse resources to the main products or service outputs of a company [317]. “Resources” refers to any input used during the processes in order to generate output. Resources could therefore be anything from financial (e.g. capital resources), physical (e.g. machinery) and human (e.g. employees and managers) to organizational (e.g. logistic systems). Furthermore, they can be material (e.g. machinery) or immaterial (e.g. energy or information) [145] and can also come from outside the organization or can be produced internally as a product of a sub- or supplementary process. In larger companies, more and more of these resources are planned and managed in integrated enterprise resource systems (ERP) such as SAP [317].

Organizational structure and processes are strongly connected but complementary in nature [171]. Moreover, modern planning theories argue that the structure should be reflected and resulted from the deliberate optimization of the processes [158]. Both structure and processes are also of particular interest for organizational eco-feedback as they generally define the person's role together with the power and responsibilities that shape the information needs and the information flows within an organization [158].

This view is closely related to the Role Based Design as an idea for using business models as a conceptual framework to inform and inspire design [115, 317]. In addition to ERP systems, another prominent example for Role Based Design is the concept of Role Based Access Control (RBAC) [115]. The approach was motivated by the inflexibility of e.g. the access control matrix approach to manage permission in large organizations. The basic idea is not to assign permission to individual users but to roles (e.g. doctor, nurse, etc.). In a second step, users were assigned to these roles in order to gain the privilege necessary to perform his job, but not more. Doing this not only prevents misuse but also safeguards against information overload and feature creep as users gained access to a system tailored to their role and therefore better fitting for the task at hand [25]. Moreover, it simplifies administration as role permission can be modified to reflect organizational changes. As a result, a clumsy, time-consuming adjustment of individual permission became obsolete [276].

In the following, we intend to illustrate how a role-based lens could also be applied to uncover the different interests and needs in acquiring eco-feedback within an organization. Such analysis helps to provide tailored information that matches people's capabilities and motivations to save energy either by changing their individual behaviour or work processes.

5.3. Methodology

The presented study was part of a broader, on-going participatory design action research process [378, 379] under collaboration with Alpha, a production company in South Westphalia, Germany. The overall action research mainly follows the traditional action research methodology [348, 378]. As part of the diagnosis phase we apply a qualitative case study research methodology to investigate the particular context and generalize the findings to “theoretical propositions” representing our diagnosis about the case [382]. In particular, our empirical work aims to understand what the potential benefits, obstacles, needs and opportunities of eco-feedback are, as seen from the perspective of the organization and their practitioner. To gain such understanding, we used common fieldwork methods like participatory observation, document analysis, and interviews [301].

The cooperation was enabled by a three-year, publicly funded research project that aimed to improve the energy efficiency of enterprises by using advanced eco-feedback systems. Alpha is not a funded partner, but participated voluntarily due to the project goal being an important goal for them, too.

Alpha operates in the area of fastening technology and has more than 2500 employees in 30 subsidiaries in Europe, North America and Asian. All subsidiaries are part of a holding that is based in Germany. The company’s customers are from the automotive and supplier industry, telecommunication and consumer electronics industry as well as from the construction industry.

The company’s mission statement includes environmental responsibility and sustainable growth as a key point. Since 1999, the production sites have been certified in accordance with ISO 14001. Furthermore, the standards for conserving resources are reflected when new production centres are being considered. In addition, in 2009 the company initiated an extra project with the goal of handling resources in an environmentally friendly way. The company has a centralized energy management department, which is part of a shared service centre. It is responsible for managing all subsidiaries in this matter. In one subsidiary the company has also started to install smart meters to measure the consumption for most of the machinery.

Our aim was to study the various views of the different internal stakeholders. So, we conduct a stakeholder analysis together with the energy manager. The identification was on the one hand informed by the energy manager knowing the context and our theoretical consideration and on the other hand shaped by general organization research about hierarchical and divisional structure [273], as well as stakeholders mentioned in eco-feedback and EMIS literature [53, 108]. We further used a kind of snowball recruiting method [26] by asking at the end of the interviews, which other persons in the organization might find the topic of eco-feedback interesting and interviewing them in turn.

With the help of this method we identified a non-exhaustive list covering a wide range of stakeholders. Based on our stakeholder analysis we conducted

Table 4. List of the interviewed persons and their role

No.	Role	Interviewee
R1	Maintenance	P1, male P2, male P3, male
R2	Controlling	P4, male P5, male P6, female
R3	IT-Department	P7, male
R4	Purchasing	P8, male
R5	Environmentalism, Industrial Safty & Facility Management (EMS)	P9, male P10, male P11, female
R6	Business Division Manager	P12, male (Production) P13, male (Building fasteners) P14, male (Electroplating) P15, male (Engineering) P16, male (Screw) P17, male (Screw) P18, female (Hardening)
R7	Machine Operator	P19, male

19 semi-structured interviews with employees working in different departments and at different hierarchical levels in Germany (see Table 4).

The interview guideline rested on our previous knowledge and research interest, but was adapted in reaction to new insights gained from the interviews. In the end, major guiding questions were:

- What is the role or position in the organization and what is the field of duty;
- For which tasks could information about energy consumption play a role;
- What kind of energy information is useful? Why and how;
- What is your motivation to engage with the topic;

The interviews, which were conducted in the participants' workplaces, were audio-recorded and transcribed verbatim afterwards. The duration of interviews was driven by interviewees, and thus varied in length from 30 to 60 minutes. Our data analysis was based on common button-up coding techniques known in inductive content analysis [109]. After the interviews, we reviewed and coded the transcripts. At first, we composed categories (such as current energy practices, data needs, energy goals etc.) on the basis of the collected data. Then, we related those categories for our further research.

The following presents the empirical findings first, going on to discuss in detail the lessons learned with regard to designing environmental enterprise systems, taking psychological and organizational factors seriously.

5.4. Findings

In this section we describe the different views on organizational eco-feedback. Using roles as a structuring element, we outline what are current energy-related practices, the kind of eco-feedback our interviewees considered to be useful and what potential impacts that feedback could have on their practices.

5.4.1. Maintenance

The maintenance unit is responsible for the functional capability of the machine park and plays a key role in maintaining, optimizing and operating existing facilities. As became apparent during the interviews, the implementation of corrective actions in the area of maintenance is often based on individual employees' specific knowledge and particular experiences with the present machinery.

We observed that in addition to the purchase of technical equipment and systems, the department of maintenance also made great efforts to optimize the energy use of existing machines and plants in the course of their daily work. The maintenance employees mentioned that in regard to energy-related issues, the greatest challenge is a lack of information pertaining to the actual amount of energy consumed, which makes an assessment very difficult. Aiming to understand their local energy system, the employees highlighted the need of an eco-information system offering the possibility of making data visible for maintenance at an operational level. Employees in the area of maintenance expressed the potential and practical usefulness about the actual energy consumption in a way that renders this information helpful for detecting unusual consumption pattern as indicators for the necessity of actions.

> *P2: "in terms of predictive maintenance […] if the heating element has not 3.1 kW (power) anymore, but only 1.4 kW (power), then I can ask myself: maybe they are completely filthy that I had to make them clean again or (they) go slowly in wear and I have to replace them"*

They also mentioned that in order to supply such provision by energy data, the responsible employee needs a good overview of average consumption patterns in comparison with current energy consumption. Furthermore, they express that scheduling and following maintenance intervals could help when determining the operating hours of a machine based on energy consumption data. Here, for instance, one person suggested integrating the hours of operation into the Enterprise Resource Planning (ERP) system that created notifications at given points in time when a service is due or overdue.

It was also mentioned that, in case of failure, energy data would be helpful in identifying whether it is an electrical problem or maybe a leak at another critical production stage, e.g. the compressed air line due to a significant drop in pressure. Additionally, the system can send a message, which includes information such as meter readings or reactive power (power quality etc.) to support remote diagnosis.

> *P2: In case of machine error: "The colleagues go to the machine and do not even know what causes the problem, but with such system (Energy Information System), they can get much more information before being there like: [...] is it an electrical fault?"*

5.4.2. Controlling

The controlling department within the company Alpha is divided into central, international and business division controlling. Our interviewees are part of the business division controlling, which deals primarily with the value chain and manufacturing cost controlling. A major goal of the controlling department is the provision of a monthly business assessment for the different business divisions within the company.

At the time of our study, we discovered that the controlling department was using information about energy consumption based on informal communication with the manufacturing and purchasing departments. The controlling department collects this information once a year and takes it into consideration when compiling internal analyses and evaluation.

Firstly, the interviewees emphasized that the interest in energy data was growing increasingly as it became an ever more important cost driver in the production process. Secondly, they mentioned that the current challenges are to break down the energy costs among different business divisions as well as the use of energy information for future price calculations and the product-related estimation of energy costs.

As difficulties in implementing these concepts they express that it is hard to assign the cost of energy to individual business divisions etc. using the existing state of consumption information processing based on total aggregated energy data.

> *P6: "This (more detailed information) would improve all of our operational accounting, for example the direct costs per product that are currently calculated by estimation."*

5.4.3. IT-Department

The IT-department is responsible for the concern-wide IT strategy of Alpha. The highest priority of the department is to deal with the implementation of industrial data acquisition. Topics concerning energy are therefore less prioritized at the moment. This partially explains why a holistic information management strategy for energy data that covers all aspects of metering, storing, processing and application integration is missing.

On the other hand, however, our interviewee noted that for a comprehensive gathering of production inputs it is also important to consider energy data to provide more information for an operative support of optimizing operations in the manufacturing and production. In addition the energy data can be used to complement the current operation key performance figure systems (e.g. energy costs per produced article etc.).

5.4.4. Purchasing

The purchasing department is responsible for strategic purchasing and the purchasing of resources. This includes the assessment of the investment decisions of new facilities as well as the purchase itself.

In the field of energy supply, the purchasing department procures electricity and gas for seven subsidiaries and some minor points of consumption. The interview partner mentioned that the current procurement of energy is organized in 10 tranches per year, which are purchased on different timestamps before commencement of delivery.

In order to estimate the required quantities as accurately as possible, the purchasing department is dependent on good energy consumption forecast models. Currently, data is manually captured at a coarse-grained level, which makes an accurate view of the historical consumption very difficult.

From this backdrop, P8 saw the benefit of eco-feedback to obtain timely, fine-grained load profiles of recent years in order to improve current forecast models, even incorporating changes in the machine park. Moreover, for him as the energy purchaser, it is important to have information about the overload and the baseload. Hence, he was interested that eco-feedback systems could help to improve the accuracy of reports on this topic.

Additionally, the purchasing department has a strong interest in energy price forecasting. This would support price negotiations with energy suppliers. For this task it is essential to have a breakdown of the energy costs into the dimensions working price, KWK-apportionment, EEG-apportionment, offshore apportionment and energy tax.

Another request of the interview partner was the eco-feedback-supported assessment of the energy efficiency of the machine park, since there is currently no accurate consumption data that can be attributed to individual machines. As a result, a precise amortization period calculation is impossible. His vision of a future system is to determine the amortization period more precisely due to the calculation of the exact energy demand and the operating hours of the machine. Eco-feedback should actively and reactively inform investment decisions in addition to production efficient calculation.

5.4.5. EMS Department

The EMS department plays the central role in terms of energy management, which includes the planning, implementation and follow-up tasks. The interviewees divide their tasks into two major objectives. On the one hand, it is about the proof of legal framework conditions that must be met in order to obtain tax refunds, for example. On the other hand is internal and external reporting, which currently includes the following tasks: a quarterly management review, a monthly reporting to the business units, making information available on the intranet, provision of data to the controlling department and creating a table with environmental aspects for the department managers.

Within the legal frameworks, the company has to fulfil statutory requirements in order to gain tax advantages by demonstrating an improvement in energy efficiency. The EMS department therefore defines an internal efficiency target that should be achieved by the organization to meet the legal requirements. In this context, the interviewees expressed it to be essential that the current state be monitored continuously in comparison to the objectives, thus detecting causes for initiating measures as early as possible.

A particularity in terms of legal requirements is the electrical energy that is used for heating. If this consumption is recorded separately, further tax advantages can be claimed. As previously mentioned, the challenge here is to break down energy consumption into the forms of usage (e.g. heat, hydraulic, etc.).

In consideration of the continuous improvement process, an eco-audit is also conducted. Currently, the survey and evaluation process for the execution is done manually, which takes a great deal of effort since a large amount of heterogeneous data is needed.

Within the internal reporting, the interviewees noted that it is currently difficult to provide internal reports to the different business divisions since the granularity of energy data is not fine enough can’t be matched to the organizational structure. But to give machine workers and heads of business units data about their influenceable consumption is essential.

> *P9: "They (the workers) mentioned that they can't do something, without data."*
>
> *P10: "Nobody can tell me, what their machine really consumes."*

That makes internal benchmarking on factory basis difficult as well: since energy costs are determined by an allocation formula, the performance indicators cannot be calculated precisely for the specific departments and products.

> *P10: "We need to know what energy is really needed for a specific product. Not as it is right now [...] then I could imagine that maybe one or more products get pushed out of our product portfolio."*

For the department it is particularly important to increase the efficiency in the organization, but to develop measures for energy efficiency improvements, the major energy drivers have to be identified. On the other hand, information about load peaks must be recognizable in the production processes. As an internal reporting tool for efficiency measuring, the company's own key performance indicator (AlphaGreen) is currently used which sets the CO2 emission in relation to the profit and a reference value.

For external reporting and benchmarking across all industries, the interviewees mentioned that standardized reporting should be used in the near future. For this, key performance indicators of the Global Reporting Initiative (GRI) in version 4 should be used to ensure the comparability between companies. In this context, the calculation of a CO2 equivalent should be accomplished as well. Currently, the CO2 equivalent is gaining in importance for supplier evaluation and tenders.

Due to the fact that more and more companies demand the indication of a CO2 footprint from the suppliers, it is important in terms of industry tenders. A CO2 accounting with the calculation of the CO2 footprint should therefore also be implemented by the system.

In summary, the reporting has the highest priority in an energy information system for the EMS department, because the immediate success of the measures can be identified, benchmarking comes into operation and legal circumstances can be proven.

5.4.6. Heads of Business Units (Production)

The production business area consists of multiple business units, which represent different production stages. In our study, we interviewed the heads of five business units: building fasteners, electroplating, screw, engineering, hardening and the manager of the whole business area.

The production business area manager stated that he does not need special energy management. Production innovations are mainly driven by productivity improvements. Such an improvement, however, will automatically lead to higher energy efficiency. Nevertheless, he acknowledged that his opinion is based on current values calculated by an allocation formula and an exact consumption analysis to prove his presumption is not possible. In his opinion a monthly report should be enough to get an overview if anything went unexpected.

> *P15: "Yes it (monthly) will be enough [...] to determine whether there tends to be good or bad in terms of [...] energy use, with this indicator we have to deal and should it be deteriorate then we need to search for causes."*

Within the building fasteners, the most important energy resource is water, because the water quality has a direct impact on the production process. P13 perceives eco-feedback as useful for the director of the business unit and the sub-region conductors if it provides immediate and operationally useful information (e.g. using a traffic light metaphor when they have exclusive control over a plant, so that situated saving opportunities can be realized).

The electroplating business unit is decentrally managed and so it has several locations. The various locations cultivate an active exchange of energy-related information. Processes and machines are currently compared informally, so the challenge mentioned by P14 is to support this by sharing real consumption data of the plants and providing features to enable best practices to be shared.

The head of electroplating was further interested in calculating the energy costs that reflect the cost centre structure of Alpha. He was also interested in obtaining feedback about unusual behaviour or consumption levels (especially compressed air) so that necessary action can be taken quickly.

The business unit screw currently sees only a very small potential for saving energy. However, the interviewees noted that for a closer look at consumption optimization, they first need precise energy data to analyse the current processes within the department.

The hardening department is one of the most energy-intensive units of the whole organization. It has a high utilization of production capacity and strict specifications in energy use (exact heat on the basis of different chemicals). P18 assesses the saving potential as very limited. This also reduces her interest in and demands on obtaining more detailed eco-feedback. However, she did see the benefits of using the data to support investment decisions due to better return-on-investment (ROI) calculations.

Also, the engineering department thinks that eco-feedback would only help them marginally to act in a more sustainable way. However, intelligent analyses of consumption patterns were of interest to them; in particular in order to investigate if it is worthwhile to shut down machines when they are not in use or if the setting-up exceeds the saving effect.

> *P15: "I want to know about wastage, for example times of standby that are not allocated directly to a product."*

5.4.7. Machine Operator

The machine operators are responsible for the operation of the various production machines and are thus directly integrated into the production processes. In the interview it became clear that a large amount of informal knowledge in dealing with the machinery has become available through their daily work.

When employees discuss their experiences and best practices among themselves, energy is a common theme, but mostly at an abstract level since no accurate consumption data exists. P19 did, however, mention that real energy consumption data would be interesting for him so that he could explore how much energy individual procedures require.

5.5. Discussion

So far, the design of eco-information is mainly studied in the domestic context. Therefore, we want to discuss the lessons learned with regard to common topics, but also to seminal differences. Because of the differences it could have a negative impact to just apply the design concepts from the domestic context [53, 128, 135] or at least not fully develop it's potentials.

5.5.1. Comparing the domestic and organizational context

As in the domestic context [135, 321], our study shows that consumption data itself does not save energy, but must be contextualized before it became useful. Concerning this, organizational eco-feedback design will benefit from existing research, improving people's sense making of energy data [320, 322]. Additionally, like in the domestic context our study reveals not only to obtain absolute feedback, but getting relative feedback with regard to what is "normal". However, the devil here is in the detail. While the request seems to be general, the individual definition of people about what is "normal" seems to be highly context dependent [342]. Hence, we should investigate in context-dependent key performance indicators [317] for "normality" as well as providing feedback mechanisms that allow users to define their own concept of "normality" [322].

Another important difference between both contexts is the motivation of the people. In the home context, people are mostly motivated by ecological or personal economic benefits. In contrast, our interviewee mentioned that better energy-related information would help them to improve their work and increase the efficiency of the organization. This is related to the different needs concerning tailored information [2, 165]. In both contexts, the

Table 5. Summary of the various roles, their task and their environmental information requirements

Role	Task	Information Request
Maintenance	Ensure that the operational state is maintained (preventive maintenance) or to restore failures.	Trajectories of fine-grained energy consumption data for the detection of unusual consumption patterns Machine operating hours based on energy consumption Real-time information (e.g., meter readings, power quality) for error identification and error forecasts
Controlling	Systematic recording, monitoring and informational compression of data for report and cost allocation.	Energy consumption per produced output (direct cost allocation) Energy consumption by cost centres Energy driver + peaks
IT-Department	Oversight of all information technology equipment, configuring network access, setting up and making changes to existing workstations and assigning access rights at various levels.	Timely gathering of consumption for integration in operational data collection
Purchasing	Supplying the company with goods and services that are required but which could not be produced by the company itself in order to carry out the production process as well as the planning and controlling of material cost development.	Representation of the energy consumption compared to the acquired tranches Tranche-based and monthly-based forecasts of energy consumption
EMS	In addition to the tasks on occupational safety and facility management, the major tasks consist of the observance of official environmental concerns and ensure a sustainable environmental impact of company products and processes and the behaviour of its employees and stakeholders.	Timely energy consumption for reporting issues Fine-grained data at location level, business unit level, organizational unit level and hierarchical level Consumption by use (heat, mechanical etc.)
Business Division Manager	Planning and monitoring of the department to ensure that the strategic plans of the management are implemented.	Energy consumption of the business division Energy consumption at machine level linked with machine operating times for investment decision Information about the energy consumption from a machine with different states (e.g. hardening machine with different temperature settings)
Machine Operator	Responsible for the operation of the production machinery.	Real-time data for identifying optimization potential Sharing expertise using machines more efficient and knowledge about saving potentials

statement of He et al. [165] that one size does not fit all is true. However, in the domestic setting the tailoring is mainly resulted by individual-psychological factors (e.g. because people are in a different stage of a multi-step behavioural change process: [165]). In contrast, in companies the needs and motivations of people are much more shaped by the organizational structure (see also Table 5 for a survey of the information request). So in addition to individual-psychological factors, the information in organization must be tailored because of and with regard to the different roles and tasks.

Related to this, the situation within an organization can be characterized as different views on the same data stock. So instead of having a design isolated solution for each person, we should provide a kind of a central Eco-Data Warehouse, where the information is tailored at the logic and presentation layer [317].

Another important difference to the home context deals with the IT-landscape in organizations. Compared to the home context they are often quite complex, so it is not useful when eco-design merely add another detached application. Instead, the eco-information should be seamlessly linked and integrated into the existing applications in order to provide meaningful information within people's ordinary work context.

5.5.2. Implication for Design

In order to benefit from the research in IS and HCI, the design of Environmental Management Information Systems (EMIS) should take both the commonalities as well as the differences between both contexts into account. Concerning this, we argue for a two-step design approach where information tailored at both organizational and individual level: On the organizational level, the tailoring should first consider the horizontal and vertical dimension. As a rule of thumb on the operational level, information should be tailored to be action oriented, while on the strategic level it should be a more planning oriented. Next to this, we should closer investigate the functional role, the tasks and the particular work context. For the final polishing we should take personal preferences and individual-psychological factors into account.

In the following we outline this issues in more detail.

(i) Interactive, analytic tools at strategic level

Managers typically had a long-term oriented perspective on energy consumption. They do not therefore ask for real-time feedback, but for strategic decision support that makes use of the fine-grained data pertaining to organizational consumption. Here, interactive tools for reporting what is going on in subordinate divisions, forecasting consumption and scenario-simulations seem to be more suited. Also, getting information about costs was a common demand. EMIS should further breakdown strategic objectives into operational objectives, so that the level of achievement can later be reflected back.

In regard to benchmarking: standardized (external) reporting plays a crucial role. They allow the use of known practices for reporting environmental information and the comparison with other companies. In addition to such standard reports, tools for internal reporting are needed as well. As said, what is normal is highly contextualized. Our study reveals that managers want to supplement standards by own KPIs to better reflect the special context of the organization.

(ii) Simple, direct eco-feedback at operational level

At operational level, our study reveals that feedback is needed that helps people on the shop floor to save energy directly and in situ. Current approaches in HCI address this demand by using the concept of direct feedback [87, 135]. Here, the highest priority is to give simple information that can be interpreted immediately.

In the work context this general demand of simplicity have a high priority. For instance, we observe that a worker gets some basic information about the current state of a machine. This information should only be enhanced by the most important eco-feedback for this particular situation in order to prevent both information overload and a distraction from work. So symbols like a traffic light and/or easy-to-understand numbers seem to be best suited here. Nevertheless, also common eco-feedback design techniques [128, 135] such as using additional graphs, text, or symbols should be used, if it helps to make the information easy to grasp. Additionally, the visualization should contain supporting elements, such as alarm functions that attract attention if action is necessary. In contrast, more complex information should only be visualized on request.

At the operational level cost calculations and money-based feedback seem not that important as it is on the strategic level. One reason might be that planning costs was not in the responsibility of the people and there was no direct personal economic benefit by saving energy. So instead of getting economic feedback, people were interested in energy informations that help to increase there work effectiveness. This shows that we should reduce the design of EMIS on the operational level, not just on motivating workers to behave pro-environmentally [53, 128], but first of all to analyse what value such information could have for them to improve their work.

(iii) Roles for task-oriented visualization

Within this binary division, process and role model descriptions of a company help to customize role-based eco-feedback. Especially, the role's sphere of influence is very important, to provide only information that can be influenced by the users.

> *P10: "The people always say to me that they don't want key performance indicators that they cannot influence"*

Additionally, the process and role model description can give further insides into the working context, the used information systems and the used machines of the users to enrich energy-data to better fit in daily practices.

In the extreme, such role-based tailoring leads to each role in the company having their own view. It is, however, much more compact for each role to have their own view than for each person [115], this is also true for the administrative costs of such a system in practice.

(iv) Individual Level

Here at the individual level, the final polishing of design benefits from proved eco-design strategies like gamification, goal setting, persuasion, etc. to improve the individual motivation to save energy [2, 135]. In addition, designs should provide tools to support common sense-making strategies of people making consumption accountable, e.g. by comparing devices, people or routines [322]. In addition, the system should not just provide tailored information, but provide means so that users could tailor them to their personal preferences and the local context [223]. In this respect, we see a high potential for HCI to contribute to current EMIS research [108] to make this systems more usable and persuasive.

5.6. Conclusion

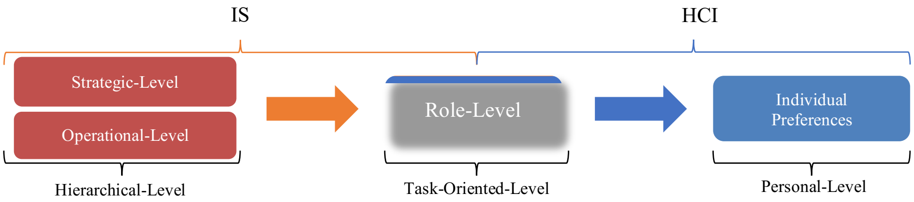


Figure 4. Using IS research in HCI for designing eco-feedback at work

We contribute to eco-feedback research by supplementing the common psychological, persuasion-oriented lens [53, 128, 135] by an organizational, role-oriented lens [8, 115, 317] (see Figure 4). Using lenses helped us to uncover the different views on organizational consumption within the company, especially motivations and needs that go beyond "save-the-earth". Such analysis informs us how to outline a role-based design approach that prevents the one-size-fits-all shortcomings [165]. We further outlined a realization concept relying on the common software-architecture pattern providing a central database with various views [317].

We have further argued that these views should be tailorable at two levels: At the organizational level, eco-feedback should be adapted to the hierarchy level and the diverse roles in the organization. At the individual level, it should be modified to personal preference and situated needs.

Our study further reveals that we should distinguish between operational, direct feedback supporting short-term savings and strategic, analytic feedback supporting long-term savings. Most approaches today focus just on the first, but neglect the latter. This has partially resulted from the psychological lens. However, we view the psychological and organizational lenses as not being mutually exclusive, but as supplementing each other in order to enlarge our design visions in sustainable HCI [45].

6. Eco-InfoVis at Work: Role-based Eco-Visualizations for the Industrial Context

Currently, there is a broad range of studies dealing with the design and visualization of energy consumption data for the domestic and increasingly for the office context. However, studies addressing the industrial context are quite rare, and due to the diversity of machines, processes, tasks, personal motivations, teams and the specific organizational culture of companies, it is not sufficient to provide only consumption data. For an adequate consideration of these factors, detailed design guidelines and system concepts are currently missing. However, this study shows the potential that a common understanding of consumption data can emerge through suitable visualization to support everyday work and possibilities of data sharing. Therefore, we show exemplarily how a design can be derived from empirically collected requirements and how a system concept can look like that enrich current eco-feedback design research for the industrial context.

6.1. Introduction

The human-computer interaction (HCI) community, especially in the field of sustainable interaction design (SID), has long been concerned with the question of how people can be supported and motivated by technology to use energy more sustainably [31]. Research on how to make people aware of their energy consumption and empower them to make better-informed energy-related decisions has hitherto focused primarily on the domestic context. HCI and environmental psychology researchers have used eco-feedback systems to provide direct feedback about energy consumption and therefore motivate sustainable behavior [133]. However, only a small number of studies have dealt with eco-feedback systems for workplace settings [197]. Mostly, these studies have focused on the office context, where information about the consumption of individual devices and/or shared devices is made available to the employees (e.g. [183, 187, 319]). To the best of our knowledge, however, only a few studies have considered the industrial context to cover the needs and motivations of different employees and stakeholders. With 26% of the total energy consumption [198] and rising energy costs, the industrial sector is becoming increasingly interesting from both an ecological and an economic perspective [172, 375]. In addition, as mentioned by Wittenburg et al. [371], the industrial sector shows even greater leverage for potential energy savings than any other. Therefore, it remains an open question to answer what the equivalent challenges might be in the industrial context, as the framework conditions might be expected to differ significantly from the office case.

In addition to possible energy savings, maximizing the usage efficiency in industrial contexts offers further benefits, such as reduced environmental impact, improved maintainability of machines, and optimized product quality as well as advantages in the context of public tenders, for example, by the proof of an ecological CO2 footprint [299].

Currently, most studies that have dealt with the workplace (office) context have adopted psychological and persuasion theories (e.g., [98, 135]). However, focusing only on motivation (individual factors) may neglect the organizational factors in industrial settings [45]. Therefore, it is insufficient to only provide consumption data [56, 58, 144]. Within the industrial context, specific tasks, power, and individual motivations must be taken into account and appropriate visualizations must be designed in such a way that they fit into the daily working practice of employees. In this paper, we report on an ethnographic case study conducted in a regional German production company - referred to hereafter as Alpha - to identify the potential of energy consumption data in daily work practices, the organizational impact on energy consumption data needs, and the underlying motivations of employees to use energy consumption data. Therefore, our qualitative workplace study at Alpha is guided by the following research questions: *(1) How can we consider the individual and organizational factors and structure the design process for eco-feedback in industrial settings? (2) What form would a system concept take that accounts for changing and different consumption data needs and ensures flexibility?*

To provide a well-structured design method with regard to these aspects, we rely on the information visualization (InfoVis) discipline to offer an approach to the design of eco-feedback elements for different tasks of different stakeholders in industrial contexts. We first provide an overview of energy-related HCI research in the workplace context to identify specific problems, main challenges, and open research questions within this field. We then describe the methodology used for our case study, after which we demonstrate how InfoVis methods and techniques can be used to create eco-visualizations for different roles within the industrial context. Roles determine the tasks, responsibilities and work areas of employees. Furthermore, we determine the requirements for a software implementation and explain how we transform these into a prototype. We conclude with a discussion about the lessons learned. Thus, our key contributions to the HCI community in this paper are as follows:

- The presentation of a structure for the design of eco-feedback elements for individual and work-specific requirements;

- The design requirements for eco-feedback tools in the industrial context;
- The demonstration of a flexible system concept, taking into account changing and specific data-related needs; and
- The guidelines and lessons learned for the design of an eco-feedback system for the industrial context.

6.2. Research Background and Related Work

Motivating people to act sustainably in their own household differs significantly to motivating them to do so in their working environment, as in contrast to the private domestic environment, acting sustainably in the workplace has no direct positive or negative economic consequences for employees [197]. In this respect, Yun et al. [384] and Hargreaves [159] mentioned that applying effort to save energy is a significant barrier for workers, because it is not their primary task and could challenge their professional status, competence, and personal success in various ways. That is why a user-driven approach is necessary to reduce barriers and support people's tasks. In this respect, there is a long tradition in HCI research of examining the effects of eco-feedback in supporting energy-efficient behavior by raising awareness of energy consumption (e.g. [29, 61, 87, 135, 319]). Early systems for presenting energy consumption data in the domestic context were simple energy monitors that displayed the raw consumption data of the whole household on a screen [190]. Today's feedback systems are more advanced and aesthetically pleasing, as design-centric surveys have shown (e.g. [134, 288]). Additionally, a series of design studies have elaborated guidelines [165, 232] and suggested design frameworks [29, 123, 309] for visualizing consumption data. Current studies dealing with the workplace context often use this feedback approach and persuasive systems that are used in the home context to provide users with environmental information for changing their behavior.

Simon et al. [330], for example, developed a persuasive game for office workers with quests and challenges that led to a reduction in energy consumption. Yun et al. [384] investigated the effect of online manuals and automated controls for employees in an office setting. In their study, they revealed that this led to more energy savings than by only providing feedback. In the work of Katzeff et al. [197], the authors designed different types of energy visualizations for the working context. Similar to the observations in households, they found that appropriate consumption feedback leads to more awareness and knowledge among workers, but due to a feeling of powerlessness, it is difficult for them to make changes.

A common view in the literature is that people in the working context fail to act sustainably due to a deficit of information and thus the absence of an awareness of energy consumption in the workplace. In this regard, Filonik et al. [117] indicated that the visualization of energy-related data is necessary to overcome the information deficit of users, especially with immaterial and invisible sources, such as electricity. This is supported by a study by Sieroet et al. [329], in which employees received information about their energy consumption and that of a competitive group and significantly changed their energy-related usage behavior as a result. Rohdin et al. [312, 313] examined existent barriers that hinder people's ability to act sustainably in factory settings. They indicated that the insufficient availability of quantitative energy consumption data is the main problem with regard to enabling employees to make more energy-conscious decisions.

However, only providing environmental information does not save energy. Granderson et al. [144] conducted case studies within the working context to examine energy information systems (EIS) and argued that the availability of information does not guarantee shared knowledge or actionable information. How well information is understood and what features are used in such a system depends heavily on the user and context. Casado-Mansilla et al. [56] considered that tailoring seems to be a good approach to overcome such problems. Thereby, they stressed the importance of providing only meaningful information so that users are able to understand the connection between action and energy consumption. Kara et al. [195] also argued for the importance of an appropriate representation of metering data in adequately quantitative ways to turn invisible and unquantifiable energy data into transparent information. In a literature review, Bunse et al. [48] argued for addressee-oriented key performance indicators (KPIs) to enable the effective monitoring of energy consumption.

Brynjarsdottir et al. [45] stated that the approach of persuasive eco-feedback has a limited focus on certain aspects of sustainability and human behavior while neglecting other influences. Therefore, when designing eco-feedback for the working context, it is necessary to consider factors that go beyond the individual. In this respect, for example, Foster et al. [128] claimed that cultural and organizational settings play an important role in designing such interventions. Simon et al. [330] also suggested that such systems must focus on groups, respect workers' privacy, not distract them from work, and be aligned with the culture of the company.

Most of these studies examined energy consumption in an office-like setting. However, in an industrial production context, further influences on the design of eco-feedback require consideration. Bogdanski et al. [34] underlined the finding that organizational factors, such as roles and hierarchies in industrial settings, have to be considered. Therefore, the specific tasks and the hierarchical levels of employees must be taken into account when designing eco-feedback systems. Therefore, we endorse this view and argue for a separation of office and industry in designing for the workplace.

The task of designing eco-feedback information that takes into account the context of an industrial company with all its social, organizational and cultural factors and is also tailored to the needs and motivations of the different employees within a company is therefore quite complex. Currently, the organizational factors when designing appropriate visualizations to support the goals of a role, procedural models and recommendations for the design of such systems are often neglected. Furthermore, from an architectural point of view, the question arises as to how these systems should be designed to take account of this complexity and the special individual requirements of people in the workplace.

The findings of Bogdanski et al. [34] reveal valuable insights into individual perspectives and their organizational interplay. In the pre-study of this paper [58], we were able to identify the same phenomena. Among others, there is an individual as well as an organizational perspective; the individual perspective takes into account the needs of individual actors. The experience and knowledge of the individuals, therefore are of decisive importance. Individuals' experiences in the context, for example, of the processes and workflows that are carried out in the company lead to a profound knowledge of interrelationships, etc., which also influence which information can be used and how. In addition, individuals' handling of - and experience with - existing infrastructures and IT systems influence the ideas about the form that an eco-feedback system should take. From an organizational perspective, permissions, workflows, responsibilities, and workplace objectives have a major effect on the required consumption data. For example, managers often perform tasks with a strategic focus and therefore require long-term consumption data, whereas the workers at the machines have tasks that have a short-term view and therefore need short-term consumption data.

The organizational perspective is well-defined, in contrast to the different individuals' views. Therefore, in our pre-study [58], we argued that this organizational perspective should be systematized by using roles as an overarching concept to consider workplace-specific factors. The role defines the tasks (activities related to the completion of a person’s work), responsibilities, and goals of a workplace and can, therefore, reflect this perspective effectively.

6.3. Methodology

In its design and structure, the research process follows the methodological approach of grounded design (GD) [311] and can, therefore, be described as evolutionary and multi-cyclical. With this approach, it is possible to bring users, groups, and technology together with different stakeholders from research and design in an open design process [126], while supporting long-term cooperation, co-design, and in-situ exploration. In this way, users are integrated into the continuous evaluation of the designed artifacts from the very beginning of the study [23]. The heuristic approach of GD is based on established investigation methods and thus makes use of methodological tools of ethnographic field research, participatory design (PD) and action research. By means of various ethnographic methods, such as (participant) observation, (expert) semi-structured interviews [10] and design workshops, the implicit and difficult to specify requirements are made observable and used to construct a deep contextual understanding of the users and their needs in order to inform the design and deployment of socio-technical systems and to assess their appropriation [380]. This methodology allows us to explore the individual needs of each employee. As an overall framework, we use the concept of a design case study as defined by Wulf et al. [380]. Design case studies are divided into three phases: an empirical pre-study, a technology design phase, and an evaluation phase (Figure 5) [380]. In the empirical pre-study, the researcher should gain a deep understanding of people's practices, the context, and situated needs. The technology design phase contains the specific design process, whereby the identified practices and problems are mapped to technology. In the evaluation phase, the appropriation and usefulness of the designs should be evaluated.

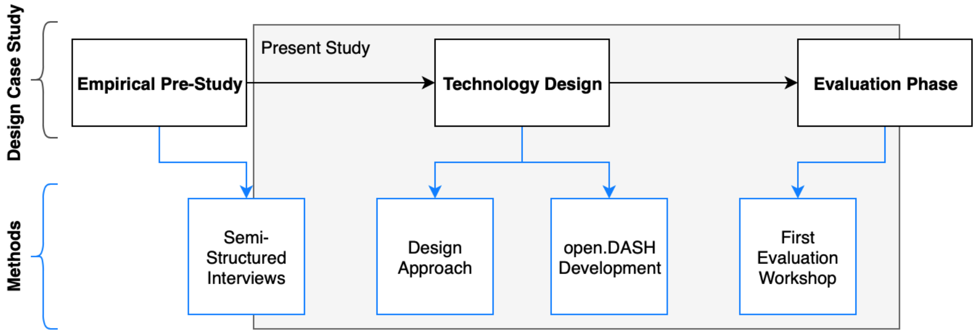


Figure 5. Study Design

6.3.1. Research Background

Our design case study is part of a research process in collaboration with Alpha, a production company in southern Westphalia, Germany. The cooperation is rooted in a four-year, publicly-funded research project that aims to improve the energy efficiency of enterprises by designing and developing advanced eco-feedback systems. Alpha has more than 2,500 employees in 30 subsidiaries in Europe, North America, and Asia. All subsidiaries are part of a holding company in Germany. The company's customers are from the automotive and supplier industry, the telecommunication and consumer electronics industry, and the construction industry. Alpha employees were involved in all three phases of a design case study (pre-study, technology design, and evaluation) [379]. These were mainly employees from the Environmental Protection, Industrial Safety and Facility Management (EMS) department. They were involved at an early stage in the planning of the empirical investigations (e.g., in the selection of interview partners) as well as in the technology design stage to iteratively identify new requirements and further develop the concepts.

Our approach included a preliminary study [58] of Alpha from 2015. The goal of the pre-study was to develop an understanding of current practices, especially concerning the handling of energy data in an industrial context (Figure 5). Based on this, factors were identified that had an influence on the needs of the different employees, and we found that roles had a major impact on working practices. Therefore, we concluded that a role-based concept is suitable for determining consumption data needs from an organizational perspective. Furthermore, we were able to determine the initial role-based use-cases that the employees had in terms of energy data. In addition, the following initial implications for eco-feedback design were identified: (1) simple and direct feedback for operational-level individuals for fast in-situ interpretation; (2) analytic tools for strategic-level individuals for monitoring organizational goals; (3) the use of roles to identify tasks to support these aforementioned individuals; and (4) allowing users to tailor data views and use sense-making strategies [58].

6.3.2. Research Activities

Based on the findings of the pre-study, this paper represents the second phase of the design case study (technology design) and the beginning of the third phase (evaluation). Based on the identified role-based use-cases, we consider the explicit requirements in terms of the task description and data needs to develop the initial design concepts using the InfoVis model described. These concepts were sent to the contact people at Alpha, who then provided us with hall plans, etc., to adapt the concepts to Alpha's conditions and to receive initial feedback. Subsequently, the open.DASH framework was developed and initial concepts were prototypically implemented (see Chapter 5). Afterward, this implementation and the other concepts were presented and discussed with the employees of Alpha within a workshop.

(i) Semi-Structured Interviews

In total, 19 semi-structured interviews with company employees were conducted to highlight and understand the requirements and objectives and to gather information about the employees' energy-related practices, work contexts, tasks, needs, and motivations to analyse the problem area in which they work (see [76, 154]) (Table 6). The participants of the interviews were selected together with our contact person at Alpha (the energy manager) to involve a range of experienced and newer employees from various essential departments (age and years of affiliation could not be fully captured). The initial design ideas were discussed in the explorative interviews. The interviews followed a qualitative participative approach in which the interviewer (the expert of the design space) and the interviewee (the expert of the problem space) enrich each other. We selected the interviewees from a wide range of hierarchical levels. The interview length ranged from 30 to 60 minutes and they were audio-recorded and transcribed for posterior analysis.

Table 6. List of the interviewed persons and their role [58]

No.	Role	Interviewee
R1	Maintenance	P1, male P2, male

		P3, male
R2	Controlling	P4, male P5, male P6, female
R3	IT-Department	P7, male
R4	Purchasing	P8, male
R5	Environmentalism, Industrial Safty & Facility Management (EMS)	P9, male P10, male P11, female
R6	Business Division Manager	P12, male (Production) P13, male (Building fasteners) P14, male (Electroplating) P15, male (Engineering) P16, male (Screw) P17, male (Screw) P18, female (Hardening)
R7	Machine Operator	P19, male

We used a common PD coding approach to cluster and categorize our findings, and our data analysis was performed under the auspices of thematic analysis (TA) [40]. This approach entails a set of well-established steps involving open coding of the data material, systematic revision of the coded segments, and identification of code-families and their relationships in search of themes that enable the elaboration of a deep understanding of the explored contexts [40, 141]. By following this approach, we developed higher-level thematic fields that comprised specific characteristics and details in terms of content and on which we oriented ourselves in the analysis and presentation of the results.

(ii) Designing Visualizations for Eco-Feedback Systems

To provide a well-structured design method that considers all relevant aspects, we relied on the InfoVis discipline to offer an approach to the design of eco-feedback elements for various tasks of different stakeholders in industrial contexts. The tasks were derived from the roles of the users, as these provide a valid abstraction as well as a precise definition of the working activities. InfoVis is an interdisciplinary field of research that is strongly influenced by HCI and has a long tradition in various research areas (e.g. [69, 167]). InfoVis involves "the use of computer-supported, interactive visual representations of data to amplify cognition" [52] and the process of producing effective visualizations, making sense of information, taking users' needs into account, and illustrating good practical visualization procedures [326]. Using this approach in interface design can provide visual representations of the data intended to help people carry out their tasks more effectively [305].

For the visualization of data, there is a growing body of far-reaching models and recommender systems for creating adequate visualizations [176, 234, 252, 373]. The recommender systems mainly use machine learning or rules to make suggestions for visualization. In this way, however, the specifics of the contexts remain unnoticed. Furthermore, these are not specialized in time series data (e.g., consumption data). Munzner nested model [256] provides a good overview of the different aspects that must be considered in the models and the challenges that exist, but focuses on the evaluation of every phase and otherwise remains rather superficial in the description of the phases.

Therefore, our approach followed that of Aigner et al. [3], which focused on time series data and enabled the consideration of different time characteristics and the integration of different task models (especially low-level task models). This approach allows designers to design for specific contexts. In our research, we used the defined tasks and data belonging to the roles to create the final implementation of the design concepts using existing visualization concepts from the eco-feedback literature in the domestic context (e.g. [59]).

Aigner et al. [3] described a method to systematically develop visualizations for a particular problem through the analysis of the tasks and the consideration of necessary data, including questions on the dimensions of task-level (*Why should it be presented?*), time and data (*What has to be presented?*) and on visual representation (*How should it be presented?*).

Thus, for each goal, we systematically created a task model that was grounded in the findings of the qualitative study. The task model helped us to structurally frame the goal that the eco-visualization aimed to achieve. In the visualization domain, mostly low-level task descriptions are used. We utilized the task model of Andrienko and Andrienko [7] because it is a formal framework that allows a precise consideration of the visualization of tasks [3]. The task model consists of three levels (Figure 6). On the first level, the model subdivides tasks into two classes: elementary and synoptic tasks.

Elementary tasks address individual pieces of data separately and not as a whole. They are further divided into lookup, comparison, and relation-seeking tasks. Lookup tasks are defined as the search for data characteristics where a graph and a time are specified by direct lookup and the attribute value is required. In contrast, the inverse lookup task's purpose is to find points in time at which a given attribute value exists. Direct comparison tasks describe a comparison of attribute values, while inverse comparison tasks interrelate references. Relation-seeking tasks search for the occurrence of relations specified between data characteristics or references.

Synoptic tasks contain a general overview and therefore consider sets of data in their entirety. They are categorized into descriptive and connectional tasks. Descriptive tasks, in turn, have the same subdivision as elementary tasks. The direct lookup task can be described as a pattern definition where a set of references is specified and the task is to find a pattern. In terms of a pattern search, inverse lookup can be described as the search for the time at which a given pattern occurs.

The search for trends within primitives with multiple points in time is defined as relation-seeking. The task of direct comparison can also be called direct pattern comparison, in which two data sets need to be compared. Inverse (pattern) comparison, in contrast, can be described as the matching of characteristics. Connectional tasks consider the relational behavior of two or more variables. The distinguishing feature here is whether the data originate from the same or different sets and are therefore to be regarded as homogeneous or heterogeneous.

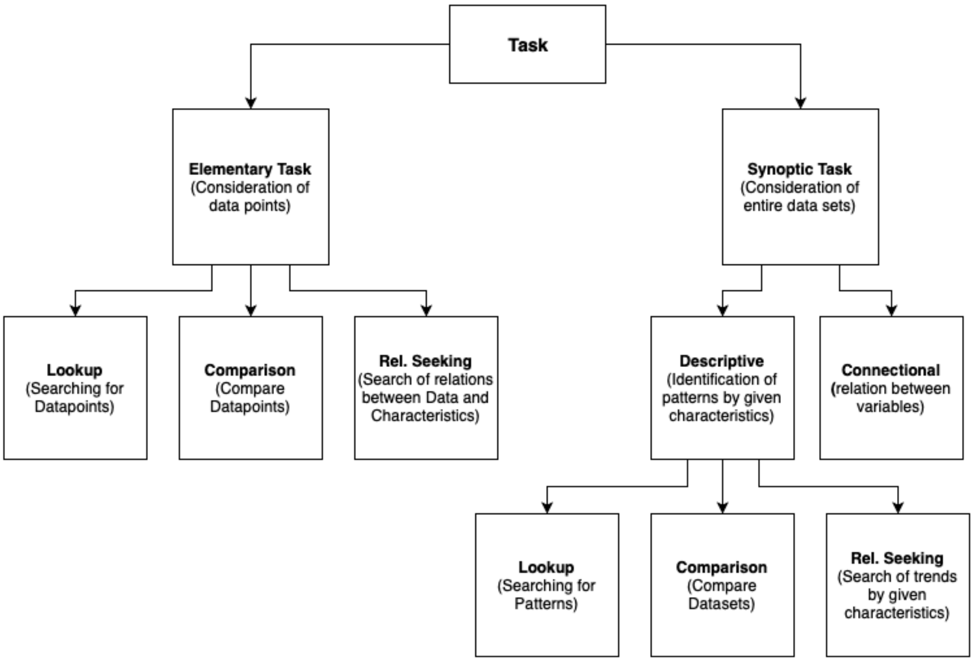


Figure 6. Simplified representation of the levels in the task model with description [3]

An analysis of energy-related practices reveals similar structural configurations and categories. This led us to align the empirically grounded categories with the aspects of the task model. We focused on the practices that refer to the dimensions of elementary versus synoptic tasks and lookup versus comparison versus relation-seeking tasks (versus homogeneous behavior versus heterogeneous behavior). We then conducted a closer analysis of the empirical findings to identify the required data and sources.

When we refer to consumption data, we are dealing with data that has a strong relationship to time and is therefore also referred to as time-oriented data. The specific characteristics of data and time provided us with more information about the most appropriate representation. The InfoVis literature already provides attributes for characterizing time and time-oriented data [3]. With a focus on energy data, we neglected the scale of time because it is always continuous, the point of time because it is always ordered, and the scale of time-oriented data because it is always quantitative. For the design of time, we had to consider its scope and categorize it into point and interval-based time domains. Point-based time domains do not provide information about regions between two points. In contrast, interval-based time domains relate to subsections of time and therefore present information about the region between two points. The second design aspect of the time domain is the arrangement of time. Linear time corresponds to an ordered time model that extends from the past into the future, while cyclic time domains describe time in natural cycles such as shifts, days, weeks, etc.

To characterize time-oriented data, we had to consider further aspects. The first characteristic describes the frame of reference. Therefore, time-oriented data can be abstract or spatial and related to a place. Consumption data are always related to a place; therefore, these characteristics initially seem to be clear. In this case, however, whether we should use a special visualization that takes into account the spatial characteristics is dependent on the task. Furthermore, consumption data can be distinguished according to its type; whether it is a continuous state or an event defined as a state change [3]. The number of variables is the last and one of the most important characteristics, especially in the contextualization of consumption data. If only one variable per timestamp is connected, this is termed univariate data, while if there are multiple data per point in time, this is referred to as multivariate data. In general, we considered the following data and time characteristics:

- Time
    - Scope: point-based vs. interval-based
    - Arrangement: cyclic vs. linear
- Time-Oriented Data

- Frame of references: abstract vs. spatial
- Kind of data: states vs. events
- Number of variables: multivariate vs. univariate

(iii) Workshop

In a two-hour workshop, we presented our concept and our prototype to the Alpha employees. Among the participants were seven employees of different roles, all of whom were also participants in the interviews. All roles from the interviews were represented, except for the machine operators, whose representative was replaced by another employee from the EMS department. In the first part of the workshop, we presented our findings and a running prototype with the real consumption data of the company. Afterward, we discussed our concept and our prototype to gain deeper insights regarding further development. In the workshop, we pursued three interlocking objectives: *(1) we wanted to relate our understanding and identified needs to the employees to either confirm them or correct misunderstandings; (2) in an initial review, we wanted to determine whether our prototype implementation made sense to the employees and could address their needs; and (3) we wanted to identify further needs and suggestions for improvement for further iterative development*.

6.3.3. Limitations

This study followed a qualitative research paradigm, which allowed the insights into the field and the results to be presented in detail. However, limitations are present in the transferability or general validity of the results. Through the concept of roles that also exist in other companies, it is easily possible to spread and explore this concept further. This also applies to the completeness of the results, as they regard a specific case (i.e., Alpha). In this article, we have attempted to raise awareness of some of the issues surrounding the design of consumption data in the industrial context. However, we are confident that our findings provide a perspicuous example that at least shows how eco-feedback systems could be designed for the industrial context in a way that considers individual and organizational needs.

6.4. Findings

Based on the identified role-based use-cases of the pre-study [58], we applied the InfoVis method (described in section 6.3.2) to create a design concept that visualizes the data in a target-oriented way. Therefore, in this section, we first provide a short overview of the role itself and then closely examine the identified use-cases of the role to identify tasks and necessary data. Afterward, we apply the InfoVis method to identify suitable visualization features. Furthermore, we present the form that a design can take to fit into daily work practices, prevent information overload, avoid distracting employees from work, be easily interpretable, and show the relevant information in an application-oriented and task-oriented fashion to assist users in achieving their goals. For the final concept, we orient ourselves on existing and established eco-feedback designs (especially from the domestic context [59]) that meet the identified requirements.

6.4.1. Roles and Use-Cases

(i) Maintenance

Employees of the maintenance role are responsible for the functional capability of the machine park. Therefore, they play a key role in the optimization and operation of existing facilities. Our observations and interviews show that the implementation of corrective actions in the area of maintenance is often based on the very specific knowledge and experience of individual employees with existing machines.

Trajectories of fine-grained energy consumption data for the detection of unusual consumption patterns

The maintenance employees commented on the potential and practical benefits of actual energy consumption in such a way that this information helped to identify unusual consumption patterns as indicators of the need for action. Employees want to maintain machines preventively, so they need information about the "normal" state compared to the current state of the machine to know whether the current consumption behavior is unusual since this could be an indicator of wear. Additionally, the geographical allocation is highly important for the fast classification of the machine.

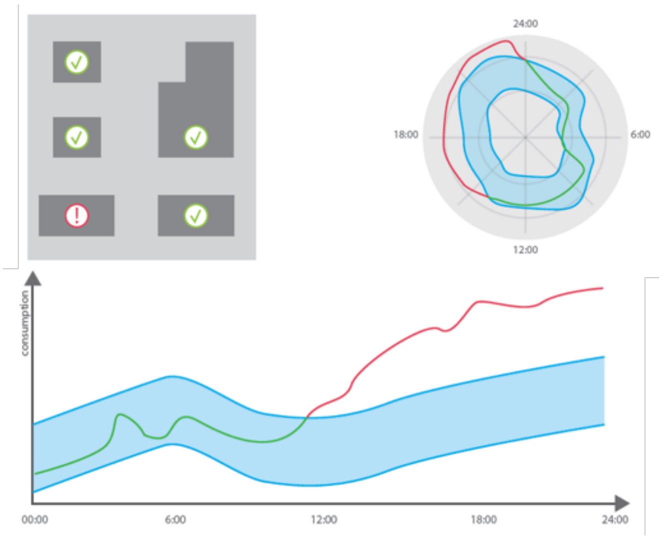


Figure 7. (top left) icons on map to quickly localize unusual patterns, (top right) spider chart for the assessment of errors in the timely cyclic context, (bottom) line plot for the assessment of errors in the timely context.

Therefore, a concrete pattern is given, and the task is to search those reference points that do not exhibit the pattern (synoptic task, direct comparison). For this goal, fine-grained historical consumption data at the machine level are required (interval-based, cyclic, spatial, univariate) and normal pattern stages must be calculated from these data by processing them. Furthermore, real-time energy and quality data are needed to compare these "normal" patterns with the current state (interval-based, linear, spatial, univariate).

For the visualization of this goal, a kind of factory plan can be used to take the spatial characteristics into account (Figure 7, top left). This plan shows all of the company's machines and uses a traffic light system to indicate whether anything unusual is happening within the energy data. The user can select a machine to obtain further details (Figure 7, top right and bottom). Taking into account the cyclical characteristics, the deviations between the regular and current usage pattern can be identified. In particular, to find unusual values as patterns and thus support the task of localization, it is important to focus on deviations. This can be achieved by using vivid colors that convey the impression of an error.

Machine operating hours based on energy consumption

The employees stressed that scheduling and following maintenance intervals could be improved by determining the operating hours of a machine based on energy consumption data. For example, one employee suggested that operating times could be integrated into the enterprise resource planning (ERP) system to create notifications at given points in time when a service is due or overdue. To enrich the machine data for the planned maintenance and workload overview, the employees demanded detailed "energy states" of the different machines. This means that employees need to know whether a machine is switched off, on or in standby mode. The task can, therefore, be described as an elementary direct lookup task.

For the calculation of the real operating hours, fine-grained historical consumption data at machine level are required (i.e., interval-based, linear, abstract, states, and univariate). In addition, events such as the change between switching on and off are also required (i.e., point-based, linear, abstract, events, univariate). For providing an overview of the actual operating hours and the occupancy of a machine, the visualization should represent the duration of various states of a machine with state changes (i.e., events). To support this task, the accumulated hours can be quantified exactly in addition to the various states (Figure 8). Colors can be used to support the differentiation of states.

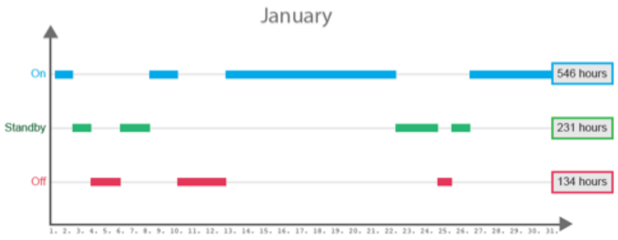


Figure 8. Timeline to visualize the status and duration of machine states

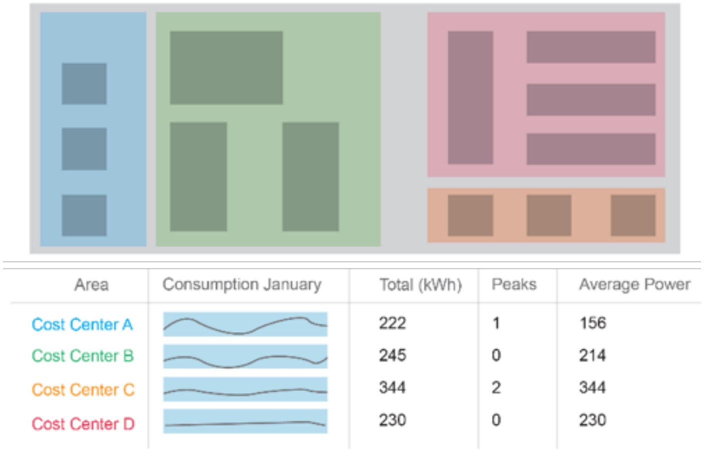
(ii) Controlling

A key objective of the controlling department is to provide a monthly business assessment for the different divisions within the company. Currently, the controlling department collects this information once a year and takes it into account when compiling internal analyses and evaluations.

Energy consumption by cost centers

Another important demand is the accurate breakdown of energy consumption to single departments or cost centers. In this way, the responsibilities can be more effectively distributed and the reporting for the individual business units can be made more accurate. This task can be understood as a synoptic direct lookup task. Information is needed about the assignment of machines to their responsible cost center.

The data that are needed are historical consumption data at the machine level in payroll periods (i.e., interval-based, cyclic, spatial, univariate). Here, too, the spatial characteristics are taken into account by providing an organization map, which is enriched by the addition of sparkline graphs (Figure 9). The colored map allows a visible assignment of organizational units. Additionally, the map builds a visual relationship with the sparkline table, which provides detailed information about historical consumption as well as relevant KPIs for the controlling department.



Area	Consumption January	Total (kWh)	Peaks	Average Power
Cost Center A		222	1	156
Cost Center B		245	0	214
Cost Center C		344	2	344
Cost Center D		230	0	230

Figure 9. Icons on maps with a sparkline legend for historical and statistical data for spatial data

Identify energy drivers and peaks

A further improvement in reporting is accurate information on energy drivers and peaks. This is important for both cost allocation and for reporting to the respective business division manager and cost center. This is an elementary/synoptic inverse lookup task whereby an employee wants to know the times at which energy peaks and hours of high consumption have occurred.

Identifying energy drivers and consumption peaks requires real-time and historical data at the machine level (i.e., point-based and interval-based, linear, abstract or spatial, multivariate).

To display the disaggregated consumption and the total consumption simultaneously and to recognize peak values, we can use a layer area graph. Zoom and filter interactions allow further details of individual machines to be displayed for a more accurate comparison (Figure 10). In addition, other information like the peak border has been added to support the user.

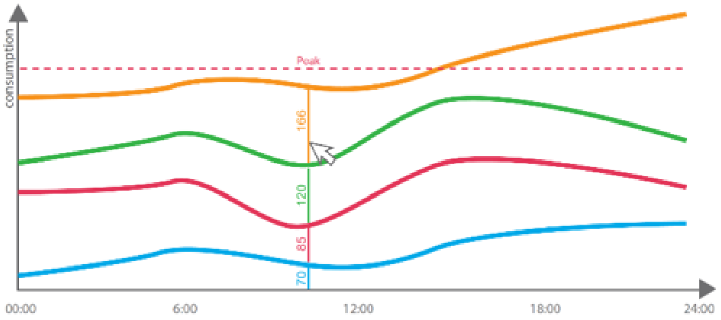


Figure 10. Layer Area Graph that shows different variables as layered bands while emphasizing the total consumption and peaks

(iii) Purchasing

Purchasing staff take care of purchasing and the procurement of resources. This includes the assessment of investment decisions for new facilities as well as the purchases themselves. In the field of energy supply, purchasing is responsible for procuring electricity and gas for seven subsidiaries and several smaller consumption points.

Representation of the energy consumption compared to the acquired tranches

Electrical energy is bought via tranches beforehand. Current energy procurement is organized in 10 tranches per year, which are purchased at different timestamps before the commencement of delivery. The department relies on effective forecasting models for energy consumption to estimate the quantities required as accurately as possible. To control the efficiency of tranches and to obtain a better estimation of the energy needed, a representation of the energy consumption compared to the acquired tranches is needed. The objective here is to compare two values. Therefore, we can define this goal as an elementary direct comparison task. Currently, the data is manually collected at a rather coarse-grained level, which makes an accurate view of historical consumption very difficult to obtain. Energy tranches apply to an entire location and are purchased months in advance. Therefore, the historical total consumption is needed on a monthly level (i.e., point-based, cyclic, abstract, and univariate). At the same time, we need the appropriate values of the purchased tranches (i.e., point-based, linear, abstract, and univariate).

The main role of visualization, in this case, is to show the difference between purchased and spent energy and display it in a time reference. An easily intelligible option is to use a stacked bar chart (i.e., point-based, because there is no information between two points) with color coding to support the visualization task (Figure 11).

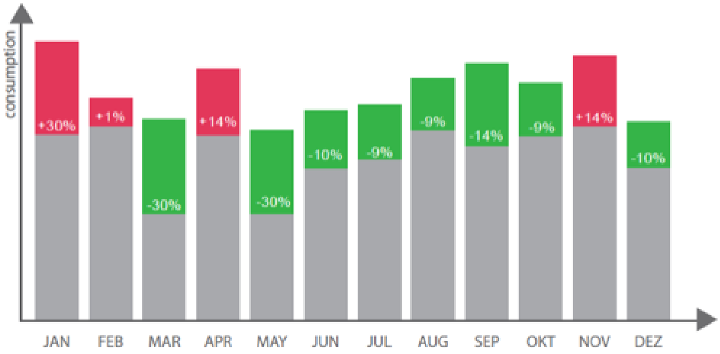


Figure 11. (Stacked) Bar Graph to depict monthly consumption values including the relative deviation from the purchased amount of energy

Validity check of tranche-based forecasts

Tranches are purchased every month according to historical consumption and planned order forecasts. To assess the reasonableness, additional comparative values, such as the forecast of consumption and produced orders, should be made available. The task of comparing past consumption and past production with predicted consumption and predicted production can be described as a synoptic task of direct pattern comparison.

For this task, the forecast for the coming month and the production forecast on a monthly basis are required (point-based, linear, abstract, and multivariate). Additionally, to conduct plausibility checks, the employees need historical data on a monthly basis, including production-related data (interval-based, cyclic, abstract, and multivariate).

The aim of the visualization is, therefore, to provide historical consumption and production values together with the forecast values to enable a validation based on past relational effects. A stacked mixture of bar and line charts allows for easy comparison of the relation between consumption and production and also means that we can combine interval-based and point-based data (Figure 12). Moreover, it is possible to compare the single forecast values with the fine-grained historical data.

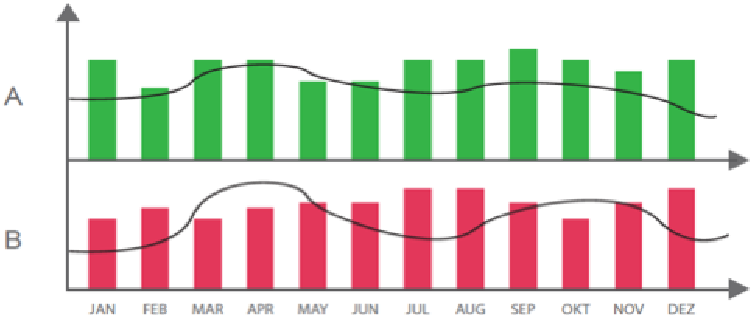


Figure 12. A mix of bar and line chart to identify the relation between consumption and production

(iv) Environmentalism, Industrial Safety and Facility Management (EMS)

In energy management, which includes planning, implementation, and follow-up tasks, the EMS department plays a central role. The workers divide their tasks into two main objectives. One of their tasks is to comply with the legal framework in order to obtain tax refunds. On the other hand, they have to report current energy-related key figures internally and externally, which currently includes the following tasks: a quarterly management review, monthly reporting to the business units, the preparation of a table with environmental aspects for the department heads as well as the provision of information on the intranet and data for controlling..

Fine-grained data at location level

Within the legal framework, the company must meet the legal requirements to obtain tax advantages by demonstrating an improvement in energy efficiency. The EMS department, therefore, has defined an internal efficiency goal to be achieved by the organization. In this context, interviewees consider it essential to continuously monitor the current state compared with objectives to identify the need for initiating measures as early as possible. The goal here is to gain an overview of the energy consumption within the organization to assess the energy consumed by different parts, machines, and organizational areas. The task for the visualization can, therefore, be described as a synoptic direct lookup.

Like the first user goal, this objective includes all available energy-related data, but with spatial considerations (interval-based, linear, spatial, and univariate).

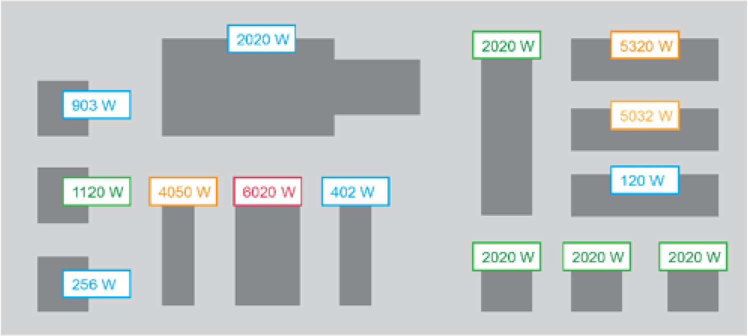


Figure 13. Icons on map show current spatial consumption values

A shop-floor map (Figure 13) can be used as an initial structural element that considers the spatial characteristics of the data and the task. The electricity consumption of the meters can be included in the map to extend it effectively. To facilitate interpretation and clarity, and to ensure that the lookup task can be performed efficiently, colors can be used to evaluate the active power. A zoom-in function can be implemented to show additional historical information and KPIs for selected parts that are necessary for reporting problems.

Consumption by use

The third goal of this role is to prove that the company has met the legal requirements since German companies receive tax refunds if they can identify which energy is used for heating. If this consumption is recorded separately, further tax benefits can be claimed. The challenge here is to divide energy consumption into the various forms of usage, such as heating and hydraulics. With a view to a continuous improvement process, an eco-audit is also carried out. At present, the survey and evaluation process for the execution are carried out manually, which means a great deal of effort because a large amount of heterogeneous data is needed. As part of the internal reporting process, interviewees find that it is difficult to provide internal reports to the different business divisions because the granularity of the energy data is not fine enough and cannot be sufficiently matched to the organizational structure. However, it is regarded as essential to provide machine workers and heads of business units with data on their controllable consumption. In the interviews, it the interviews employees stated that the workers mentioned "[...] that they can't do anything without data" and that in this context, "Nobody can tell [...] what their machine really consumes." Therefore, the task of the visualization is to compare the different types of usage and make them quantifiable (synoptic task and direct pattern comparison).

In this case, the tax refund is annualized. To simultaneously uncover irregularities, the historical consumption data on a usage level can be displayed in a more fine-grained manner (interval-based, linear, abstract, and multivariate).

For this goal, a combination of a Sankey diagram and silhouette graph seems suitable. The Sankey diagram shows the deviation of energy consumption in terms of use and at the same time the ratio of the individual types of usage (Figure 14, left). The silhouette graph extends this view by providing a history of usage to show changes over time (Figure 14, right). In this case, the graph is particularly suitable for the comparison of multiple time series [3].

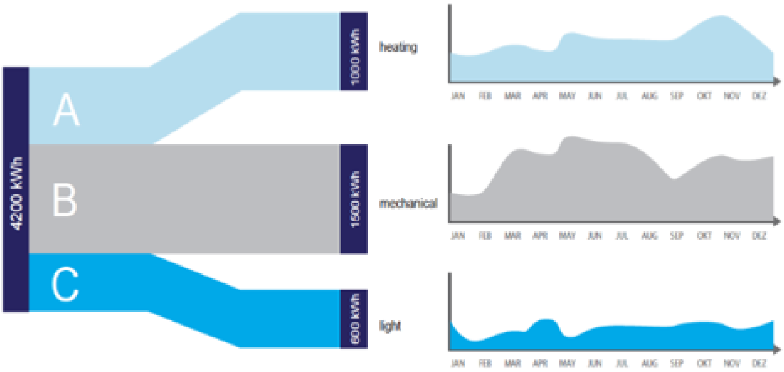


Figure 14. (left) sankey diagram in which the width of the arrows is shown proportionally to the energy consumption to demonstrate deviations in end uses, (right) additionally silhouette graph for enhancing the comparison of multiple time-series

(v) Machine Operator

The machine operators are responsible for the running of the various pieces of production equipment. In our interviews, it became clear that a large amount of informal knowledge is deployed in dealing with the machines through daily work. When employees discuss their experiences and best practices among themselves, energy is a common topic, but since there is no accurate consumption data, this is usually done on an abstract level, such as in discussions about machines that are left on standby consuming energy. However, interviewees mention that real energy consumption data would be useful to investigate in order to determine how much energy individual processes require.

The second identified goal is to prevent energy peaks and gain an understanding of what causes high energy consumption. For this goal, it is important to obtain an overview of the current total consumption to determine whether switching on an additional machine produces a peak. This task can be described as an elementary direct lookup task in which the current consumption value is needed to identify potential reserves.

The data required for these tasks is the current total consumption (point-based, linear, abstract, state, univariate).

To create a user-friendly and clear visualization that does not distract from work and can be quickly interpreted, a gauge graph is an effective way of monitoring one variable. Gauge graphs are well-known in cars and are easy to understand. Due to the use of colors, the user is assisted in the assessment of consumption.

6.4.2. System Requirements

In addition to the concrete requirements for the visualization of consumption data, the interviews also raised further requirements, which were mainly directed at the functionalities of an eco-feedback tool for the industrial context.

Firstly, although a role provides a concrete overview of the tasks, the information needs may differ between employees within that role. This is often due to the existence of different ways of working or different knowledge or experience; thus, there is not a one-size-fits-all solution for all users within the role, so in addition to standard role-inspired visualizations, it should be possible to individually configure these visualizations.

Secondly, the different consumption data requirements within roles also require the capability for individuals to freely design their consumption data views. Therefore, it is important that the user can easily select which visualization is the most important to his or her role. Additionally, it should be possible to change the preferences in the system quickly and easily, for example by changing requirements (e.g., due to new production orders). This also implies the possibility to view different data when looking at different devices (e.g., mobile devices).

Thirdly, the orientation of the role (i.e., strategic or operative) plays a decisive role in the consideration of time horizons. Operational tasks often require the simple observation of real-time consumption data, whereas a strategic alignment requires the view on to a longer period of consumption.

Fourthly, it became clear that the employees often did not know what information existed within the data. To enable users to gain awareness of the data, a system should provide the opportunity to freely visualize the data to allow exploration, promote transparency, and enable the identification of new use-cases.

Fifthly, the integration of additional indirect energy data is also very important. In many cases, direct energy data are influenced by indirect energy data. This requires the consolidation of different data sources, which can be freely linked and related to each other. In the interviews, this was particularly clear in the fact that the employees' primary goal was not to save energy but to use the data to make their work more effective.

Sixthly, when interviewing different users within a role, we recognized that employees with more experience could name more possible use-cases. Especially in the discussions with our contact people at Alpha (the EMS department), we recognized that there is an exchange between the different employees, especially about the consumption data. The requirements to enable the collaboration among employees in working with consumption data follow from this, where the sense-making of data has often been referred to as a collaborative activity. People should share their creations, data analysis, data knowledge, and understanding and be able to discuss their findings within the data.

6.5. System Concept and Realization

From the various data needs of the individual roles, users, and groups, different requirements for a system for energy data analysis can be derived. In the following section, these identified requirements for a system's architecture and concept are presented and our developed prototype for such a flexible system is described.

We developed a dashboard-based web application (Figure 15) that allowed us to implement our general idea of customizable data views. Dashboards are already known in the industrial context and additionally allow the personal composition of widgets, which can also be changed quickly. Through the implementation of the dashboard as a web application, the tool is also independent of end devices (see the second requirement). To meet the identified needs, we relied on a dual approach. On the one hand, there are pre-defined visualization components that provide solutions for the identified use-cases on a general level, and on the other hand, we implemented end-user-development (EUD) based assistance, whereby users and groups can freely create new visualizations and explore the data.

Additionally, the architecture of our web-based prototype includes all three layers (model-view-controller) known from classic system architectures. This makes it possible to connect different data sources on the model level, consolidate the data, and transfer it to a standardized format. The system, therefore, makes no distinction between direct and indirect energy and consumption data and it is possible to use, visualize, and link different types of data (see the fifth requirement).

Figure 15. open.DASH Prototype

An open-source user management [279] was implemented to completely take into account the authorizations, power, and areas of a role. Each user had his own account in which to create his or her data views. In addition, the roles in the company were mapped 1:1 in the user management system. Thus, the users of a role only had access to the relevant data and information. This has the advantages that only relevant data sources can be selected (other data sources do not appear in open.DASH, which reduces the risk of an information overload) and that the hierarchy of the company can be transferred to the digital infrastructure.

6.5.1. Pre-Defined Visualizations

Pre-defined widgets can be dynamically added to the dashboard. Here, we implemented most of the design concepts derived from our data analysis. In addition, we added some standard visualizations for KPIs. To bridge the gap between minimal and complex visualizations, the visual information-seeking mantra of "overview first, zoom and filter, then details on demand" [326] was considered in the design phase. The user can select the different pre-defined visualizations from a catalog, whereby each visualization contains a screenshot, a title, and a short description of the use case for a particular data representation. To consider different needs in terms of time dimensions and data aggregation, it is possible to configure these pre-defined visualizations in various ways. It is, therefore, possible to change the data source, the time dimension, and in some cases, indirect data can also be included (see first and third requirements). The size and position of the widget can be freely changed. This makes it easy to change the look and feel of the dashboard and quickly modify it as new data requirements arise or as data changes.

6.5.2. End-User-Development (EUD) Visualization Tool

We developed a step-by-step digital assistant to enable users to freely map the data to different visual representations. Thus, they can visually explore the data in an easy manner and create personal visualization that fits to very specific needs. For the design of the interaction concept best practices from the literature are taking into account. Therefore, we implemented simple click/touch interactions instead of more complex operations such as drag and drop [154] and the tool follows the visualization pipeline process by Card [52].

The visualization creation process (Figure 16) consists of five-steps: selecting data (data analysis), selecting time (filtering), selecting chart, configuration (mapping) and adaption (rendering). The user's first step is to choose which data should be visualized, by choosing one or many data sources from a list. In the second step, the user must specify when the data is aggregated by choosing between an absolute or a relative time-span (e.g., the last four months). In the third step, the user can select the type of visualization; we implemented six different types of charts to cover the most common purposes. The fourth step contains the special configuration for the selected chart type, such as whether data should be mapped onto lines, points, etc., on a timeline chart, or how data should be aggregated to meet the requirements of the chart. After the user completes these four steps, the chart is rendered

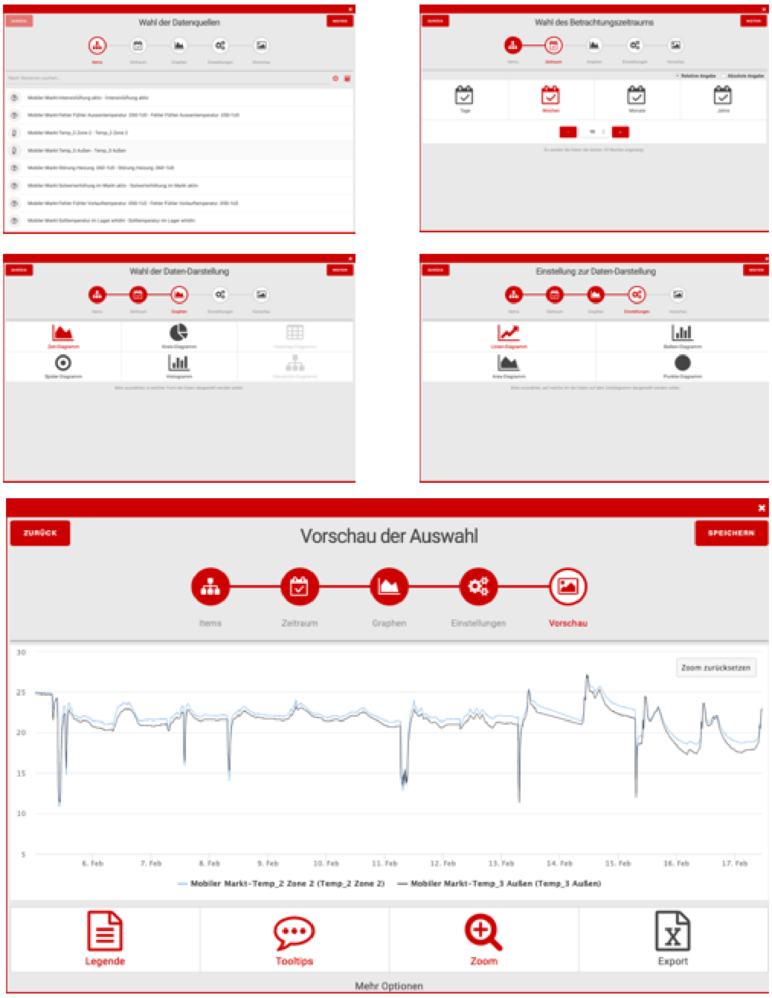


Figure 16. Visualization Creation Process

for the selected parameters. Here, interactions such as zooming, selecting or hovering over points are possible to generate a tooltip with information. This step mainly supports task-driven adjustments, such as for localizing or identifying data [3]. From this step, the user can return to the four previous ones to change settings or configure the interaction or layout of the chart (e.g., by changing animation settings or allowing/disallowing zoom). The user can decide whether to insert the chart as a widget into a dashboard or discard it. This tool, therefore, allows the user to freely explore the data (see the fourth requirement).

6.5.3. Sharing and Collaboration

The system requirements clearly show that sense-making, in particular, is a collaborative process [282] in which experiences are exchanged to interpret data. In the interviews, however, it also became clear that a certain exchange is part of current working practice (e.g., internal reporting). Thus, we implemented various functions that enabled common sense-making and also support between employees in creating individual data analysis and data visualization components (see the sixth requirement) and therefore supported cooperative work with computers [292].

On the first level, we implemented a function for the areas of knowledge sharing and awareness. Employees can take screenshots of their visualizations directly in the application and send them to colleagues or supervisors, who can then view them directly in open.DASH. This allows for different use-cases to be addressed. On the one hand, it is possible to share a screenshot in case of detected anomalies (in power consumption), which should serve as an example for conspicuous behavior (to make it recognizable by other employees later). For example, energy waste can be reported to avoid it in future. On the other hand, the function can also be used to share anomalies that cannot be interpreted to determine the cause collaboratively with other employees.

On the second level, it is possible to share configurations of individual visualizations (that have been created) or entire dashboard compilations that other users can easily adapt (like in [193]). This allows individual practices to be exchanged so that experienced employees can show new employees how to proceed. By simply sharing the configuration, employees of other roles can also apply this directly to their data sources. For example, views on general topics (such as finding wasted energy for certain types of machines) could be transferred to other employees and departments. Furthermore, expert users can provide advice and support to other users with the configuration of the dashboard, which is an important aspect of collaborative systems [104].

On the third level, we also implemented functions that support continuous collaborative work. It is possible to create shared dashboards that serve as a common workspace alongside individual ones. Thus, different users can work together on the dashboard layout and create their own visualizations, which supports the exchange between colleagues [104] as well as collaborative tailoring [376]. This makes it possible for employees who are working on common tasks to use the same view and customize them together. In addition, group goals can be monitored together and analyses can be performed and created together. Above all, this should lead to the promotion of a common understanding. The process of collaboratively examining and working with data (on the same data basis) should contribute, for example, to a growing understanding of energy consumption among users to allow them to jointly identify efficiency potential.

Through the implemented functions, we support a "ticket-to-talk" approach on two levels [349]. Sending the screenshots, for example, triggers an explicit collaboration in which users can discuss the sent artifact. The possibility of working together in a shared workspace also promotes collaboration, as the possibility of seeing how others proceed and work creates an appropriation awareness [104] and enables over-the-shoulder learning [362].

6.6. Workshop Results

In the workshop, we were able to recognize - especially at the strategic level - that individual machines did not operate at the level expected by employees in such a system. We noted that systems and tasks depended heavily on the structure of the departments and not on the machines themselves. Therefore, it was suggested that a selection of single machines was not sufficient in most cases and that for a first view, higher aggregation levels should be used, which could then be broken down into more fine-grained levels. This also led to the suggestion that the top area of the dashboard should be used to fully structure the dashboard at the department level and therefore strengthen the link between physical location and digital data. The idea was to implement a navigation in this top area, where departments and containing areas could be selected and this selection could then affect the widgets below.

The participants liked the concept of a dual approach with pre-defined visualizations but also a tool to freely map data. Especially for irregular requirements (such as reporting obligations), the EUD environment seemed to be a suitable starting point to obtain the required data, when needed. The flexibility to quickly and easily create completely new data views to respond to changing requirements was also positively highlighted.

In particular, the possibility to view the data visually led directly to discussions between the participants. Typical questions such as "Why is the energy consumption in your department so high?" promoted the exchange between users and increased transparency and understanding for other areas of the company. This also made it possible to recognize that working with data has a strong collaborative character, which particularly concerns joint sense-making, and that the interpretation of the data requires a knowledge of the context.

In addition, it was noted that the catalog with the pre-defined visualizations was confusing, and it was unclear which visualization could be used to solve a given data-based task. Here, it was suggested to work with examples and arrange the visualizations in the catalog according to categories. In this case, it seemed logical to subdivide the visualizations into direct and indirect feedback or to distinguish between operative tasks (real-time) and strategic tasks (long-term). This could also be mapped onto the role model, as the higher the role in the hierarchy, the more strategic it is.

Based on the discussions in the workshop, the understanding of consumption data needs, especially when working with data in an industrial context, could be extended. The mental models of the employees (thinking in structures and processes) are an important point of consideration for the future development of the tool. The mixture between configurable pre-defined visualizations for general use-cases with the roles and the possibility to have flexible access to the data and be able to work with it was recognized as meaningful in the initial discussions.

6.7. Concluding Discussion

We demonstrated a potential structure for eco-feedback systems in the industrial context that can be used to consider both individual and organizational factors in the design process. In addition, we showed how analytical and design techniques from the InfoVis discipline can be applied in sustainable HCI to contribute to current eco-feedback research by efficiently embedding energy data into working practices. Furthermore, we presented a system concept for the implementation of such designs in a flexible information system. We proceeded to discuss our findings against the backdrop of the existing literature and the implications for designs of future research.

6.7.1. Analysis of Results and Lessons Learned

The literature on eco-feedback systems has already shown that the focus in the industrial context should not only be on individual motivation, but on the integration of consumption data into everyday practices and work processes [45, 56, 58, 144, 322]. In this vein, we found that the initial motivation of the employees was not primarily to save energy, possibly because they would experience no direct benefit from saving energy [197]. However, Filonik et al. [117] have noted that information on energy consumption must first be available in order to foster and establish awareness. The integration of flexible tools for free exploration makes this possible, and we noted in the workshop that this also raised concrete questions about energy consumption.

In this respect, we found that the employees wanted to use the data to support their work (which was also recognized by Yun et al. [384] and Hargreaves [159]). Moreover, with regard to the concrete areas of applications, indirect energy savings can also be identified. For example, through improved maintenance, quality improvements, and support in machine parameterization, products are produced more efficiently, which not only saves resources but also energy through less reworking, which can be labeled as an efficiency improvement. Through the simplified possibilities of reporting, further effects of energy consumption, such as CO2 emissions [299], also become visible, which continues to lead to an increase in awareness.

Furthermore, with regard to how these consumption data can improve the work of the employees, we can conclude that the data should be used as an indicator for decision support. In areas of process planning, for example, this has direct effects on efficiency, and when consumption data are used as decisive criteria, it is also economically beneficial.

As HCI mostly focuses on psychological approaches and behavior change models to motivate sustainable behavior, we argue that this view should be extended to designing eco-feedback tools for the industrial context by focusing on indirect efficiency improvements through work practice support. According to Fogg's behavioral model [125], simplifying tasks can also lead to long-term use of such systems, which is fundamental to increase knowledge and sustain awareness to be able to identify energy-saving potential.

Another result of our study is that it is also not always possible in an industrial context to provide the consumption data with sufficient context to make them directly meaningful. The knowledge and experience of the employees are necessary to interpret them and then, if necessary, identify potential savings (supported by [144]). Here, we could realize great potential in collaborative work with consumption data (see [330, 356]), which could also support the transfer of knowledge.

Returning to the research questions that guided this paper: (1) On the one hand, we can summarize that roles are suitable to use as a lens for the organizational perspective. The roles of employees include the main tasks of a workplace (e.g., maintenance is responsible for the functioning of the machines, purchasing is responsible for the planning and procurement of resources and energy, the EMS department is responsible for the compliance with legal regulations, etc.) and also contain the definitions of associated data (i.e., which machines are assigned to a role). By knowing the task and data, the proposed procedure from the information visualization community is suitable for creating task-oriented visualizations. By the addition of flexible possibilities, which support sense-making above all, the individual level is also considered. We propose that InfoViz can supplement sustainable HCI research by providing systematic design methods and techniques that contribute to the current challenges in eco-feedback design for the industrial context.

(2) Many of the findings concerning system design relate to how employees work with data in an industrial context (this has already been investigated for domestic contexts [119, 356]). The functions of open.DASH also show that the generally valid statements (e.g., individual changing needs and task/activity-oriented visualizations) also take place in other contexts [165]. The integration of a user management system - which allows roles to be mapped directly in digital form - is a special feature of the implementation. This allows the above concept to be used without application, for example, to display only meaningful data [56]. The higher-level architecture of open.DASH also allows the identified role-based visualizations to be

integrated as pre-defined widgets to adapt them to the specific application of consumption data in an industrial context. Therefore, we can show how both organizational and individual perspectives could be integrated into one system.

6.7.2. Implications for Design

(i) Consider Organizational Context and support Tasks

On the first level, we agree with Bogdanski et al. [34] that different stakeholders need different information. However, we go one step further by adding another dimension, using the role of employees as a structuring element for an eco-feedback system. The specific role provides us with information about the tasks, power, and responsibilities of employees. We also found that employees in industrial settings, unlike office workers, have little control over their appliances. Therefore, they are interested in supporting and improving or simplifying their work through the use of energy data, as also suggested by Yun et al. [384].

(ii) Systematic Visualization for specific Roles

The review of the literature and our further analysis have highlighted that it is not sufficient to display only raw energy data (e.g. [56, 144]). To create appropriate visualizations, we proposed using InfoVis methods to systematically design eco-feedback elements tailored to the identified goals. In this respect, we found that the underlying data and structures have a significant influence on the choice of visualization form and type. For example, data with cyclic characteristics can be visualized by a spider, clock or spiral graph, while point-based values can be displayed by bar charts, and spatial data can be shown by maps. The formalized tasks mostly influence the design process by adjusting visual variables. For a comparison task, a stacked visualization of different graphs can be an effective solution, while a sparkline table can be used to compare multiple KPIs. Another example is the use of color coding for lookup tasks [358].

(iii) Taking the time for Interpretation into account

Considering one of the greatest barriers of using eco-feedback, namely the fact that that employees often fear that eco-feedback will distract them from work and require much effort [159, 384], such systems must be easy and quick to interpret. Feedback must, therefore, be designed in such a way that information does not appear to be overloaded and not too many visual variables are presented simultaneously. At the same time, all relevant information and data must be available when needed. This corresponds with the InfoVis guiding principle: "overview first, zoom and filter, then details on demand" [326]. Here, we could identify that the hierarchical level is an indicator of the time that the employee has to process the data. At a lower level, data-supported decisions must be made quickly, so special attention must be paid to creating a simple representation. At the management level, where much data is used for decision support, this data should also be easy to interpret, but with the ability to allow more complex representations.

(iv) Flexible Design and Customization

In industrial contexts, the tasks to be performed are very different between departments and roles. This also applies to the data needs and information requirements as well as their appropriate representation. To enable individual data views, we argue for the design of a flexible system in which employees can easily select the data visualization that they require and, if the data requirements change, adapt it accordingly.

In addition, we identified a positive response to the assistance-based end-user development tool that allows employees to create customizable data views to adapt to individual or infrequent data tasks. Furthermore, the possibility to freely explore data to identify new use-cases or to discuss the scope for optimization was highly appreciated by employees.

(v) Allow Collaborative Data Work

Interpreting and drawing the right conclusions from digital energy data often depends on the experience of the employees, but also on their expertise to adequately use the appropriate visualization with the given data. Another feature that can support this is the possibility to collaboratively use such systems. This allows employees to work together, for example, on solutions for unusually high energy consumption or ways to make work easier by using digital energy data [356].

6.7.3. Summary and Further Research

This research presents a new approach to eco-design in the industrial setting, using an organizational perspective (task- and data-oriented) as well as an individual perspective (taking individual knowledge, experience, and demands into account). In could be seen that the visualization and sharing of eco-data is a first step in the process of making sense of the data and to develop a common understanding. During the process, broader support may be noted if it is perceived as useful by users and thus to become part of their working practices. Furthermore, based on this approach, we present a prototypical development of an eco-feedback system that considers the identified requirements. Additionally, we conducted an initial evaluation with the employees of Alpha to gain a first impression of the usefulness of our approach.

The impact on the employees' daily work at the company is non-trivial and further long-term studies will be of central importance in future research. Therefore, we suggest that further research should conduct studies with a focus on the long-term appropriation of the tools to gain a deeper understanding of how people use these in practice. This could answer the questions of whether and how people increase their awareness of energy consumption, how indirect efficiency improvements affect general consumption, and how people make sense of consumption data, both individually and collectively.

II. Data Analytics and Visualization

II.II Home Context

7. Information Visualization at Home: A Literature survey of consumption feedback design

Designing consumption feedback to support sustainable behavior is an active research topic. In recent years, relevant work has suggested a variety of possible design strategies. Addressing the more recent developments in this field, this paper presents a structured literature review, providing an overview of current information design approaches and highlighting open research questions. We suggest a literature-based taxonomy of used strategies, data source and output media with a special focus on design. In particular, we analyze which visual forms are used in current research to reach the identified strategy goals. Our survey reveals that the trend is towards more complex and contextualized feedback and almost every design within sustainable HCI adopts common visualization forms. Furthermore, adopting more advanced visual forms and techniques from information visualization research is helpful when dealing with ever-increasing data sources at home. Yet so far, this combination has often been neglected in feedback design.

7.1. Introduction

In this decade, sustainable interaction design has become an outstanding trend in Human-Computer-Interaction (HCI) [31, 98, 143]. In the wake of this trend, consumption feedback (CF), also known as eco-feedback (EF), has been extensively researched as a means of motivating eco-friendly behavioural change. Yet CF can and should not be reduced to a mere component of sustainable HCI [98] as it represents an important topic in itself [135].

CF has a long tradition dating from the first oil crisis in the 1970s. Since that time, environmental psychology has taken an interest in the influence of behavior on energy consumption and has investigated CF as a means of encouraging energy conservation [39]. While in the 90s interest waned slightly, research got its second wind this decade through new digital possibilities of smart metering [87]. Several meta-analyses within environmental psychology [1, 86, 87, 107, 110, 118] have demonstrated the positive effect of CF on energy savings.

Originally, feedback design was often quite simple and unsightly. Since then a series of design studies, elaborated guidelines [165, 232] and suggested frameworks [29, 123, 308] have meant that feedback systems are now more advanced and aesthetically pleasing. Although design-centric surveys of that research have been provided, among others by Pierce et al. [288] and Froehlich et al. [134, 135], in light of rapid advances, they are now slightly outdated.

Considering the progress made in design and research, the goal of this paper is twofold: First, to provide an update on the number of new design studies published in recent years. Second, to take a closer look at information design, outlining the lessons learned. From this stance we conduct a systematic literature review [204] that covers the following:

A literature-based design taxonomy that categorizes current eco-feedback design [280];

Based on that taxonomy, an overview and summary of existing design strategies, output media, data sources and visual forms;

Open trends and gaps in current research and thus suggested areas for further research [207].

Our survey extends previous findings and reveals that studies on motivational effects and short-term appropriation of eco-feedback in the home context still dominate sustainable HCI [85, 134]. Our survey shows that novel and innovative design concepts are also identified as the most challenging aspect in current research. Within the studies, we observe a trend towards more advanced solutions including multiple data sources, data pre-processing and mobile, cross-device feedback with a special focus on design. In particular, interactive and context-aware feedback have become more popular.

Despite the existing trend towards more complex and holistic solutions of eco-feedback with a design based focus, we were surprised to uncover that a link to the existing information visualization (InfoVis) [52] discipline, which deals with methods and techniques for complex data visualization, is relatively weak. Almost every design within sustainable HCI adopts simple and common visualization forms that are also a subject of research in InfoVis (e.g. Bar-, Line- or Gauge-Charts), but without explicit references. That missing link might be a reason why sustainable HCI is currently neglecting a more systematic adoption of analytical and design techniques developed in time-oriented InfoVis research [3, 52, 326].

In conclusion, we believe that sustainable HCI would benefit from eco-information visualization [3] as the next step towards increasing the information value of metering data at home and beyond.

7.2. Related Work

7.2.1. Research Outside HCI

Studies on eco-feedback have a long tradition, especially in environmental psychology. The primary research question here is to evaluate if and to what extent eco-feedback has an effect on people's individual motivation and actual behavior. To answer this question, controlled experiments are ordinarily conducted, with feedback as the independent and behavioral change as the dependent variable. Literature reviews echo this research design. On the whole, surveys are meta-analyses [82] that contrast and combine results from different studies to identify patterns or disagreements among study results and other insights gained by comparing multiple studies. An illustrative example is the much-cited review by Abrahamse et al. [1], focusing on the effectiveness of different interventions strategies including eco-feedback.

A more design-oriented survey was conducted by Darby [86], who reviewed research from 1975 and 2000. She developed a taxonomy of feedback types, aiming to obtain a more detailed understanding of the relationship between feedback and behavioral change. On an abstract level, she simply distinguishes between direct and indirect feedback as the two main groups; on a more fine-grained level, she distinguishes basic metering, key meters, direct displays, TV or PC feedback, disaggregated feedback and ambient displays as forms of feedback. Darby extracted best practices from the literature, concluding that feedback works best when it is accessible, attractive and clear. An update published in 2006 [87] includes dynamic tariffs as an additional factor. In a similar fashion, Fischer [118] reviews studies from 1987 to 2007, asking which kind of feedback is the most successful. She developed a taxonomy of feedback attributes that might have an impact. Her survey suggests that an ideal design does not seem to exist, even though frequently given feedback and allowing user interaction seem to be key success factors.

A detailed review over the long span of 23 years (1974-2010) is provided by Ehrhardt-Martinez et al. [107], who cover not only direct and indirect feedback in the residential sector but automation systems too. Focusing on the impact on energy savings, they compare smart feedback with other types of feedback such as enhanced billing, estimated feedback, daily/weekly feedback, aggregated real-time feedback, disaggregated real-time feedback and different motivational elements such as goal-setting, competition and social norms. They further use cross-tabs to find dependencies and synergies. For instance, they uncover that real-time plus feedback tends to generate the highest saving among the feedback types but that the feedback has to work together with other factors.

Another, more recent, survey is the EPRI study [110], reviewing studies from 1978 to 2009. That survey merits mentioning as it also outlines blind spots where further research is required, e.g. participation, feedback delivery mechanism, persistence of feedback, dynamic pricing and demographic considerations.

7.2.2. Research Within HCI

In comparison to environmental psychology, HCI is a relatively multi-disciplinary research area with a stronger design focus [54]. It is therefore not surprising that eco-feedback research within HCI has a slightly different focus, as outlined by Froehlich et al.: “The difference between the HCI and the environmental psychology literature is the emphasis (or lack of emphasis) on the visual design of the eco-feedback interface itself” [135]. In particular, a rich corpus of design studies exists in HCI that - among others - explores the design space and realizes novel concepts. DiSalvo et al.’s survey [98] shows that – for better or worse – by far the most design studies are concerned with CF based on persuasive technology. They are supplemented by guidelines, frameworks and design space analysis [134].

He et al. [165], for instance, outline a catalogue of design guidelines with regard to designing tailored feedback. Loviscach [232] explore the design space as related to personal energy conservation assistants distinguishing between feedback, advice and automation. Fitzpatrick et al. [123] outline basic CF-features. Bjökrskog et al. [29] provide a seven-dimensional feature matrix for conducting market surveys. They further elaborate a generic three-layer architecture, with a sensing, a service and an application layer, to realize energy awareness systems. Rodgers and Bartram [309] suggest a fivedimensional framework for analysing and designing CF, with a special focus on eco-feedback.

In addition to these theory-driven and experience-based design guidelines, a few reviews exist that use the literature review methodology to explore the design space and common design practices. Pierce et al. [288], for instance, survey diverse studies on eco-visualization, with a special focus on design strategies. They split the complex into three parts: feedback covering data and visualization; context of use, taking the axes dweller and third-party control into account, and strategies for designing effective visualizations. Each strategy is discussed and illustrated by examples.

Another notable survey is by Froehlich [134], who reviews 44 papers from HCI and 12 from environmental psychology ranging from 1976 to 2009. His review is divided in two parts: One deals with the differences between environmental psychology and HCI while the other reviews the design space for eco-feedback. From the comparative analysis, eight dimensions emerge that feedback design should consider. These include motivational strategies, display medium and data representation.

In summary, the existing surveys on CF, design guidelines and elaborated frameworks [29, 86, 87, 107, 110, 118, 123, 134, 165, 232, 288, 309] provide good information for the design of eco-feedback systems. However, a systematic review focusing on design from recent years is missing and therefore newly emerged or improved concepts are neglected. In this regard, this survey provides a much-needed update and furthermore a literature-based analysis of the information design of the various solutions.

7.3. Methodology

To provide such an overview of current information design approaches and to show open research questions and areas, we apply a common methodical proceeding of literature reviews [27, 207].

Scope and period: The review scope was informed by our research goal to uncover trends and patterns in modern CF design. Other reviews [110, 118, 134, 288] have addressed this goal in part, although the period of those reviews ended, at the latest, in 2010-2011.

In our review, we therefore focus on the period from 2009-2015. Our research question guided our selection of keywords and libraries for our systematic review. We used the following digital libraries for our literature search: ACM Digital Library[2], IEEExplore Digital Library[3] and Google Scholar[4], arguably covering the most popular sources of HCI literature.

As there is no unique nomenclature, we also used synonyms and related terms as search keywords. We used the follow keywords: “HEMS”, "eco feedback”, "energy visualization”, "energy monitoring”, "energy feedback”, "consumption feedback”, "consumption monitoring”, "domestic energy" AND YEAR > 2009

Exclusion and Inclusion Criteria: The manifold studies we found using these keywords made us define several criteria for including studies into or excluding studies from the review. Inclusion criteria included a contribution having been peer reviewed, being available online and being written in English. Other selective criteria included a very rough thematic selection by title and abstract and by skimming over the text and whether it was positioned within HCI.

After this pre-selection, we carefully read the remaining papers and refined our inclusion criteria to the following:

- Established in the home-context
- Consists of a CF prototype or final product

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[2] http://dl.acm.org/ (01.06.2018)
[3] http://ieeexplore.ieee.org/Xplore/home.jsp (01.06.2018)
[4] http://scholar.google.de/ (01.06.2018)

We then divided the results into two categories. The first included all the studies in which the CF system was used in a real-world field study and was evaluated by households. The other category included the papers in which CF systems were developed and evaluated in a lab or by other methods.

Data extraction: In the next step, information from studies was extracted in a standardized way [27], culminating in over 250 pages of extraction forms: From each paper, we first collected general information. Additionally, we collected information about the data sources, covering data collection, storage and granularity. We studied how the data layer, data processing, and presentation layer were realized in terms of display, feedback type applied, general design patterns and design elements used. In the studies with field trials, we collected additional data about the participants, the method of the study and the prototype evaluation process.

Literature: Our final corpus consisted of 68 papers (see sections 7.4 and 7.5) with 62 different eco-feedback systems. The studies took place in different countries, for example in England, Sweden, Finland, Italy, Denmark, Portugal, the United States of America, China and Australia

7.4. Outlining a Design Taxonomy

As existing research in CF needed to be structured for the analysis, we searched first for a suitable categorization strategy that could be apply in our analysis.

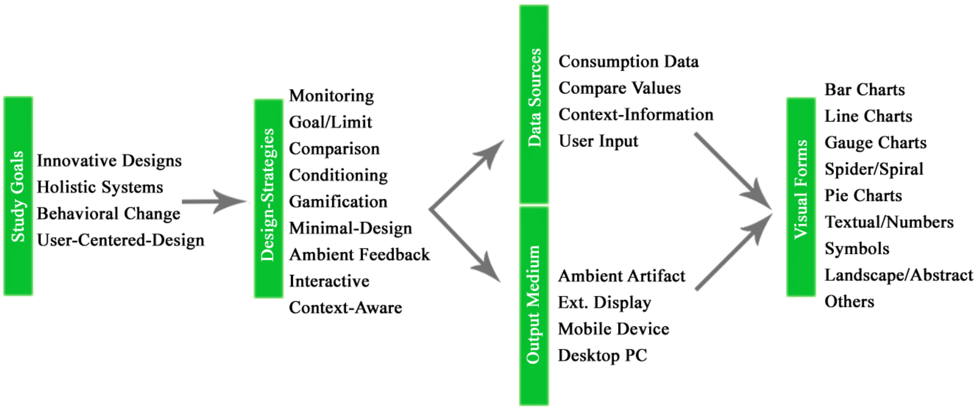


Figure 17. Literature-based design taxonomy for eco-feedback systems

This initial search revealed a broad mass of wide-ranging approaches to the topic. The literature contains several strategies and frameworks for classifying CF systems. These range from a simple method of distinguishing between direct and indirect feedback [86, 87] to more refined methods using a fine-grained classification [110], a feature matrix [29] or an elaborate, multi-dimensional design-space [134, 309]. Each method has its own particular advantages, but since design is becoming increasingly complex, more specific methods are needed.

Our aim was to provide a literature-based taxonomy that covers the design aspect in more detail and allows a holistic view of the connections between different parts of design. We therefore considered the commonly used design strategies as the major design-driving factor and extended this factor by adopting an informative design-centric view informed by Card et al.'s information visualization reference model [52] to take well-known design techniques and methods into account. From this stance, we studied in detail which *data sources*, which *media* and which *visual forms* are commonly used in the literature to shape the overall design concept and design objectives (Figure 17).

7.5. Survey of Consumption Feedback Technology

We used the identified taxonomy to focus more explicitly on studies of CF within HCI literature (Figure 17). In the following, we go through each taxonomy category systematically, describing the implementations and characteristics of the individual elements from the past few years in eco-feedback research.

7.5.1. Study Goals and Contribution

First, we analyzed and uncovered existing objectives and goals from the wide range of studies. In particular, we looked at what the authors claimed to be their contributions and research interests. As a result, we were able to identify four major non-exclusive types of study goal and contributions.

(i) Novel and Innovative Design Concepts

The biggest group claimed new design concepts [15, 16, 42, 63, 75, 137, 147, 150, 152, 153, 169, 184, 214, 228, 233, 235, 247, 270, 284, 287, 367, 368] or systems that "go beyond past examples" [147]. The goal of these design concepts is to extend the state of the art of CF design by novel features and functions. Some design approaches address a new usage scenario in the home context, such as pricing models, dormitories or Off-Grid homes (e.g. [214, 228, 247]); others focus on new single design elements (e.g. a practice view that allows users to compare what-if scenarios) [75, 184, 235, 284] and some use new techniques in their CF systems such as integrating one-dimensional and multi-dimensional comparative feedback in one application (e.g. [63, 147]).

(ii) Holistic Systems / Infrastructural Issues

In contrast to the first group, there were also a large number of studies that focus on a holistic approach for designing CF systems and less on specific design elements and functionalities (e.g. [68, 194, 216, 222, 268, 283]). This type of study focuses more on hardware and infrastructural issues of CF technology, including new concepts of home automation and low-cost solutions (e.g. [16, 268]).

(iii) Behavioral Change

Studies in this group examine how people use the eco-feedback system to change their energy-related behavior (e.g. [85, 209, 285, 286, 324, 387]). The studies focus on persuasive technology to change user behavior and "to investigate if, and how, people use the systems" [324]. This category is highly inspired by Fogg's behavioral model [124].

(iv) User-Centered Design

A few studies (e.g. [85, 285, 286]) go even further, emphasizing the importance of considering individuals user's or user group's needs. The key conclusion here is that "a one-size fits-all approach for home energy monitors cannot be justified“ [85].

7.5.2. Design Strategies

Second, we analyzed the existing research regarding the type of design strategies applied as an important characteristic within the design process [134, 135, 288, 308].

Our survey revealed that strategies are not mutually exclusive and boundaries are blurred. Moreover, we uncovered two main clusters of strategies: *motivation-centric strategies* including goal-setting, comparison, conditionals and gamification and *design-centric strategies* including monitoring, minimal design and ambient and interactive feedback, which focuses more on how to visualize the information. In the following, we describe the implementation of each strategy in more detail.

(i) Monitoring

Monitoring aims to inform users as precisely and accurately as possible about their consumption. This strategy relies on the information deficit hypothesis that feedback fills an "information vacuum": Additional consumption information increases awareness or knowledge about both household consumption and individual appliances, which incentivize consumers to use less energy [370].

Addressing the rational consumer, the design is typically sober and clear. Users should be supported in making informed decisions concerning current consumption (e.g. via direct feedback) or future consumption (e.g. by providing a forecast and return of investment calculation). Monitoring is widely seen as a basic feature, such that it is available in nearly every system reviewed.

(ii) Comparison

People use various forms of comparison to make energy consumption accountable [322]. The most important forms are normative and social comparison: Normative comparison is used to compare a consumer's own present and past consumption [184] while social comparison is about comparing oneself with others. A further comparisons is that between individual vs. individual and individual vs. group comparison [147].

Most studies focus on social comparison, the major challenge of which is to ensure the comparability of the compared categories and to consider household context (e.g. the number of adults/children in a household or the size of living space should be the same) [147, 184, 209, 227, 286, 300, 347]. Mostly, comparison data is simply integrated into standard monitoring visualizations (e.g. [184, 286]). Some social comparison approaches integrate their information into social media platforms such as Facebook [127, 227].

User preferences are diverse: some like comparison with people they know while others prefer large user groups [287]; others prefer benchmarking with a known average [286] and wish to remain anonymous [147]; others object to everything as they feel their particular life-situation is not comparable [322] to others or they feel demotivated when others are constantly “better” [181]. These factors make normative feedback appear preferable [227], although others report that social comparisons are reasonably effective [147]. These mixed findings make universal recommendations difficult and indicate that user satisfaction and design effectiveness (measured in energy savings) should be treated as two independent factors.

(iii) Goal-setting

In environmental psychology, goal-setting is a well-known strategy for promoting energy conservation [1]. It is defined as making a desire explicit to reach a certain future state [181]. There are various ways to implement goal-setting features [83, 181, 209, 214, 228]. For instance, Kugler et al. [214] allow limits to be set by usage – i.e. maximum consumed energy in a given period or for a fixed amount of money - that should not be exceeded or undershot. EnergyLife [181] use goals and sub-goals as part of a gamification strategy, whereby a particular goal must be attained to access a higher level. In addition, lights are dimmed as an ambient signal that a goal has not been reached. T. Liu et al. [228] discuss prepaid electricity tariffs as a special form of goal-setting that ensures a pre-defined limit is not exceeded. However, to prevent such strict power cut offs, T. Liu et al. [228] allowed users to set a limit before their credit expired. Critical design issues cover goal-definition, whereby a good heuristic seems to rest on earlier periods (e.g. use 2% less than last week) [83]. A further issue relates to the kind of feedback (positive or negative) and when it is given. Here, guidelines - such as providing a continuous reminder [209] - are close to those outlined for designing conditioning (e.g. rewards or penalties [135]).

(iv) Conditioning

Conditioning refers to using incentives/disincentives and rewards/penalties to motivate pro-environmental behavior. A good example of a social punishment is given by Foster et al. [129]: When a user saves too little, a random embarrassing song is posted on the user's Facebook wall. An example of conditioning strategy focusing on learning is given in Cowan et al. [77]: When a user boils too much water, the kettle stops working until it is filled with the right amount of water. The various forms of conditioning are discussed by Froehlich et al. [134, 135] in more detail. Overall, conditioning seems to work well for some users, but nor for all [206]. Some users note that negative messages motivate them while others simply get frustrated [209]. An alternative is only to reward good behavior [300]. Also, using humor seems to be a strategy that frustrates users less [129].

(v) Gamification

Gamification has become popular in recent years. In a broad sense, it refers to using motivational, competitive elements known from games, including goal-setting, social comparison and conditions. In this section, we use a narrower view, looking only at single and multi-player games.

The Tamagotchi genre presents a popular single-player gamification strategy in which a digital avatar is influenced by energy consumption [151]. In single-player games, users can archive rewards and earn scores by energy savings and quizzes [137, 181, 184, 235].

Multi-player gamification usually adopts the quest genre, often supplemented by rankings. A connection to social comparison can be recognized here, ensuring that participation and the comparison between several people motivates efficient behavior. Furthermore, commenting on each other was highlighted as a fun-enhancing feature to increase motivation and intensity of usage [127, 286]. In general, users can play against each other, but team challenges are also popular, in which families, friends etc. have to reach a common goal [83, 147, 153]. Quests can take various forms but are typically related to energy conservation, e.g. reducing lighting one day or heating on another [153]. Game design is generally faced with undesired cheating effects. Gustafsson et al. [153] report that, when a quest only determines specific time-slots (e.g. 8 a.m. – 10 p.m.), some users start to wash at night to win the quest.

Concerning user satisfaction, challenges seem to be well rated [235] but preferred more by experienced energy users [286]. Also ranking is rated positively [127], especially if the 'opponents' are known [287]. Instead of just providing a ranking list, Kjeldskov et al. and Petkov et al. [209, 286] suggest that ratings should provide feedback on whether a user’s consumption is high, low or medium.

(vi) Minimal Design

Minimal design aims to provide less information which is easy to understand and most relevant for the user context [85, 387]. Even this small portion of information can still be effective – especially as the information is enriched by people's interpretation [387].

Comparing lights and numbers as a feedback form Mann et al. [233] further show that the minimal light design is suitable for giving quick feedback. It causes only a small cognitive load (in comparison to visual information such as numbers) and users are less distracted because no direct action is necessary to inform oneself.

(vii) Ambient Feedback

Ambient feedback is characterized as “abstract and aesthetic peripheral displays” [237] that are set at the periphery of a user’s attention. Ambient feedback is often minimal and realized by extra artifacts; other output mediums are even generally possible [205]. Visualizations are either abstract, e.g. colors [247], or naturalistic, e.g. showing the “destruction of nature” [205, 264, 308].

Ambient feedback counts as being easy to understand [264, 308]. The design must, however, be unobtrusive, minimal and only subconsciously noticeable [233, 308]. Hence, a general design tradeoff must be made between unobtrusiveness and attracting attraction. For instance, a “dramatic” change helps to touch people emotionally [264]; by the same token, it could lead to stress and guilt [205]. Abstract forms are easier to design and also seem to be preferred over natural ones [308].

Another tradeoff relates to the amount of feedback information. There is a tendency to provide additional information, especially if the user is already energy conscious [205, 264]. However, care must be taken not to destroy the overall design. The right design also seems to depend on the type of user, e.g. Malkonin et al. [236] report that busy people prefer simple feedback, younger people prefer bright colors and older people prefer dark colors.

(viii) Interactive Feedback

Interactive feedback is defined as feedback that implies a proactive action by the user to generate energy information that is more valuable to the user. This strategy covers e.g. tagging, whereby users can tag or add events directly in a time graph [75, 153]. Tagging helps users to link energy consumption to something understandable (such as activities or special events) [153]. One variant allows users to define groups aggregating individual consumers at room-level or with regard to their purposes (e.g. entertainment, cooking, etc.) [321]. Another interactive feature suggested by both Jain et al. (Jain et al., 2012) and Weiss et al. (Weiss et al., 2011) is active measuring. This feature allows users to record time-periods e.g. to uncover the consumption of specific devices (e.g. switching a light on/off) or specific actions (e.g. making coffee). It improves the breakdown of consumption, making use of user’s context knowledge, while for the users it is playful and increases the perceived control [184, 368]. Another feature discussed by Jain et al. [184] is active comparison, whereby users add their energy consumption data manually to compare it with that of other people or other devices.

As feedback grows more complex and becomes part of complete home control systems [63, 185], it seems that interactive features such as tagging, configuring or active measuring will become more important in the future. However, as the corpus of studies is still small, it is currently difficult to outline best practices.

(ix) Context-aware Feedback

Context-aware feedback gathers additional information to enrich consumption information, e.g. a user's position or activities. The most commonly used context-information is the location of the user/users, e.g. using RFID [150], doorway sensors [221] or WiFi-fingerprinting [60]. This information allows the interface of mobile devices to be adapted, showing the consumers only in their direct surroundings [182]. Castelli et al. [60] demonstrate how user location can be used to alert to current wastage outside the room; furthermore, the percentage of used energy is shown in the historical feedback, when no one was in the room. Neustaedter et al. [260] use personal calendars as an additional source to enrich the feedback. This connection helps users to link the data to activities when reflecting on past consumption. Kjeldskov et al. [208] use additional information to forecast energy prices, to enable users to plan their consumption.

As context-aware feedback is relatively new, little is known about its effectiveness on saving, learning and user satisfaction.

7.5.3. Data Sources

The third category describes the kind of *data sources*, which play an important role in information design. The primary sources used in the literature are fine-grained consumption data about the total household (collected e.g. by Smart Meters) or individual consumers (collected e.g. by Smart Plugs). More modern energy management systems also integrate multiples of these sources. This combination provides new opportunities, e.g. for comparative design but also makes the design more complex, and the risk of information overload increases when too many sources are available [181].

We also observed a trend to include further data sources including comparative values from other households or statistical data on average consumption [347], user input to tag, aggregate or break down consumers and context-information about the users, e.g. their presence [62] or their activities based on calendar entries [260]. Some studies additionally make use of current and forecast data for weather, electricity, price, date etc., but so far these are generally found in the area of home control [304, 392].

Overall, metering data serves as the basis for all CF design. From a visual stance, it presents a time-oriented data source with special characteristics: *linear time* [3] from past to future; and also *cyclic organization* [3], composed of a finite set of recurring time elements (days, weeks, months etc.). Linear time models are mostly used, with few exceptions (such as the Energy Clock [42]) that make use of the *cyclic* organization to visualize consumption patterns and rhythms.

The visual design must further decide if time series should be presented as *point-based* or as *interval-based* values [3], providing information over subsections in time. Related to this is the *updated rate* [3], ranging from nearly real-time to seldom, irregular updates. In addition, when dealing with time, it has proven helpful to consider different level of abstraction using different *granularities* (seconds, minutes, hours, etc.) [3]. Most studies rely on fine-grained updates ranging from every minute, every 10 minutes, every 15 minutes or hourly. This data is mostly used to calculate higher granularities, such as days, weeks etc.

Consumption could further be viewed as an *abstract entity* [3] not connected to space or place or in combination with additional data as *spatial* [3] (e.g. taking the location of consumers into account). Furthermore, it matters if we are dealing with *univariate data,* where each time primitive is associated with only one single data value or with *multivariate data,* which has to represent multiple data values [3]. Early energy monitors, mainly based on univariate data, show only single devices or the total consumption. In comparison, our survey shows that *multivariate data* approaches are increasing due to the disaggregation of consumption data. In most cases, tables and lists are used to visualize multivariate consumption data. Using charts and more advanced visualizations tend to be the exception.

Early monitors also show consumption as an abstract entity [96]. Our survey indicates a slight increase of systems that consider the consumer location [60, 182]. Related to this increase, the number of time-based space and/or hierarchical approaches is also increasing. For instance, to aggregate consumers at room-level [60] or to subsume them under pre- and user-defined categories [321].

7.5.4. Device Types / Output Medium

Besides the data sources, the *output medium* is another important factor that heavily influences design. Information design focusing on desktop PCs has a long tradition. However, our survey reveals that desktop PCs are not always the best solution in terms of output medium. Feedback can often be more effective in various locations on different devices. Four main mediums are described in literature.

(i) Ambient Artifacts

Ambient artifacts are artifacts that have been specially designed to provide feedback. A variety of forms and styles have been studied, e.g. Broms et al. [42] used a clock-based design artifact that was integrated in everyday life since they were already accustomed to looking at a clock. The Monster study [206] is another example of layering known artifacts. Making use of the metaphor of the evil monster, the authors motivate users to act sustainably so that the monster is not annoyed. Another popular output medium is colored light, realizing ambient feedback in an abstract fashion [233, 288]. Here, the color typically indicates actual or cumulative consumption.

(ii) External Displays

External displays can be installed on a wall or can be freely placed within the home. They show less but are tailored and typically easy to use [347]. Most often, they are located in the kitchen or living room, as generally a lot of energy is consumed in these rooms [236, 308, 387]. It is important to take account of movement patterns, so that the display is located where the user can see it. On the other hand, conspicuous places might also stress users because, when they see the display, they may feel under pressure to save energy [42]. Displays located directly on the electricity meter are technically preferred but are often not easily accessible for users [283]. The same holds for sockets, as displays might disappear behind furniture [169].

(iii) Mobile Devices

Often mobile devices such as tablets and smartphones are used. Here, feedback design must consider the common guidelines of mobile and responsive design concerning screen size, interaction modality and context support [142].

Regarding appropriation, mobile Feedback is used more often but usage duration is shorter and savings are higher [228]. Further, Yun [387] reports that mobile feedback is primarily used in the discovery phase by consumers walking around and checking. After this phase, the mobile device was partially used as a stationary display as well [387]. In addition, smartphones seem preferable to tablets [209]. This preference is also because smartphones are more ready-to-hand. For instance, Kjeldskov et al. [209] observed that users look at them in idle times e.g. when waiting for a bus.

(iv) Desktop PC

For complex tasks, PCs have some advantages due to screen size and computer power. This medium is mainly preferred by highly motivated users who use their computer on a daily basis [147] and who want more and detailed information on their consumption [57, 347]. For this group, there are few access barriers [228], especially if feedback is provided by widgets that fit in with daily computer use [205, 383]. However, PCs as an output medium are not recommended for less motivated and non-regular computer users.

7.5.5. Visual Forms

The last step within our taxonomy is to consider the various visual forms used in the literature. The quality of information design is based mainly on the appropriate mapping of data sources to visualize forms, taking into account the design objectives and the user's context, preferences and capabilities [3, 52]. This section provides an overview of the visualization techniques commonly used in feedback design to motivate and inform the user.

(i) Bar-Graphs/Charts

Bar charts are the elements most used to visualize consumption. Most often they are used to give historical feedback [137, 147, 268, 278, 286, 342, 367, 368]. Some studies add extra information to the bar graph, such as color bar graphs displaying low, medium and high consumption [216] or average consumption [184, 209]. Bar graphs are also used for the representation of non-time-oriented data, e.g. comparing the consumption of devices [347], per person [150] or to other households [83]. In addition, vertical bar charts are sometime used for ranking [270, 284].

(ii) Line-Graphs/Charts

Line charts are another popular way to visualize consumption. Plain line charts are mostly used for displaying historical data [129, 184, 188, 209, 245, 300, 367]. In some cases, they are extended by comparison values e.g. from other households or averages [85, 95, 228, 347]. Line charts are also used for real-time feedback [194, 324]. In a few cases, we also found special line charts, e.g. using area charts for historical value [170, 324] or area stacked line charts for non-time-oriented data, to show the relation of total savings between multiple areas [147].

(iii) Gauge Charts

Gauge graphs are well known from dashboards e.g. in cars to show current speed. In feedback design, they are mainly used in a similar fashion to show current consumption [127, 130, 216, 367, 368]. Gauges can also be enriched by additional information, particularly to support comparison. For instance, to show whether historical consumption is lower, the same as or higher than present consumption [209].

(iv) Spider/Spiral/Clock Charts

Time has the singular property of being a linear flow but is simultaneously also cyclic (day, week, etc.). As a result, temporal data such as energy consumption has cyclic patterns [3]. One common way to visualize patterns such as these is to use clock/spider/spiral charts [3]. In our survey, we discovered some studies that adopted this strategy [42, 216, 264]. In three cases, the hours were colored to represent low or high consumption [264] or varying tariffs [216, 298].

(v) Pie Charts

In our survey, pie charts were seldom used. Only two studies used pie charts, either to show the division between devices [137] or to show the consumption of different household members over a fixed period of time [150].

(vi) Textual/Numerical Elements/Tables

Textual elements were often used as an additional element to complement other visualizations. Numbers are mainly used in simple displays to show the exact value of current consumption [15, 75, 85, 137, 278, 286, 388] or to show historical consumption [127, 286, 388]. Sometimes numbers are also used quantitatively to compare consumption with other households or one's own average [127, 286]. Two studies used text in the manner of story-telling [227, 285]. Tables are mostly used to represent ranking in a social comparison challenge setting [285, 287]. Timetables are a special table form, which e.g. Kunold et al. [216] use to balance planned energy-related actions in order to support load-shifting and forecasting.

(vii) Symbols

Visualizations are often enriched by symbols to increase the emotionality and interpretability of feedback. For instance, emoticons are popular symbols used to report a good, normal or negative consumption level, partly by social comparison [85, 127, 209]. Others use colors [209, 284] or arrows [285] to indicate performance in terms of current or historical consumption. Costanza et al. [75] use icons to tag input sources and show them in a time graph as additional contextual information. Symbols can further be used as units; for example, real-consumption appears only in the form of points [170] or leaves [286].

(viii) Landscapes and Abstract Forms

Landscapes and abstract forms are usually used for ambient visualization strategies. Manifold landscape schemes have emerged, ranging from ice-bears [96]; highlands with green grass and cows [264]; an underwater coral reef with fishes [205]; trees [316] etc. However, the main principle remains the same: A beautiful, healthy, clean environment disappears or turns ugly when too much energy is used. In addition to naturalistic forms, abstract forms are also popular as feedback [236, 308]. The primary goal is to achieve aesthetically pleasing visualizations, yet sometimes other objectives are also addressed, e.g. Crowley et al. [83] used bubbles with different colors and rotating speed to depict current consumption to make it easy for users to rate it.

(ix) Others

We also uncovered other, specialized forms of visualizing consumption: Sundramoorthy et al. [347] use a clinical thermometer metaphor to display the average and highest consumption compared to other households. Costanza et al. [75] use boxes of each device, where the size depends on the energy needed for a specific action. One feature of this visualization is to support mental “what-if” scenarios: When deleting a box (“not using the device”), the users see the impact on the overall consumption. Castelli et al. [60] use alerts in the smartphone status-bar to inform the user about potential spenders when leaving a room. Paay et al. [277] use boxes in a timeline to show the duration of the on- and off-status of a device.

7.6. Common Issues, Trends, Gaps

As mentioned above, design issues and evaluation methods are major structuring elements within sustainable HCI. In the following, we highlight and present common issues, trends and gaps based on our analyses.

7.6.1. Design Issues

Common issues: Figure 18 shows that various hot spots exist in feedback-design research, where more research has been done than in other areas. In particular, a major hot spot is shown up by the monitoring strategy. Addressing the rational consumer [342], the major design goal is to provide accurate and correct feedback. To attain this goal, common design elements such as bar graphs, line graphs and text/numbers can be used. Most designs are quite complex and tend to adhere to the slogan "the more, the better". The counterpoint is the minimalist design, which applies the golden rule "as much as necessary and as little as possible". In terms of the amount, however, minimalist design seems to be an exclusive concept.

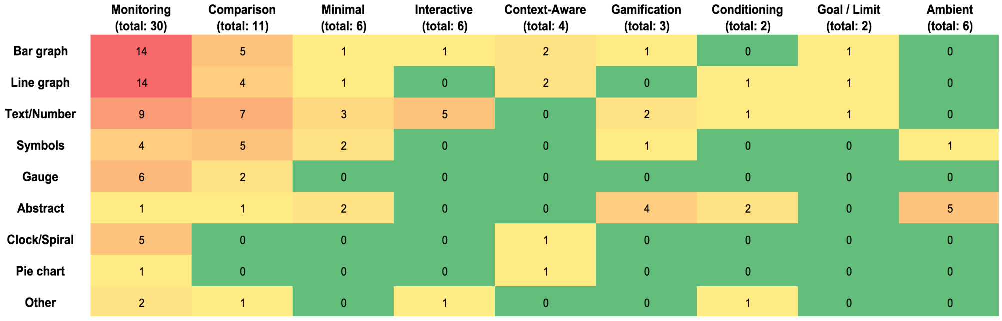
Another hot spot is presented by persuasion strategies focusing on the social norms and man's instinct to play. Figure 18 shows that comparison presents a popular persuasion strategy, supplemented by conditioning, gamification and goal-setting. Most studies use tables and lists to visualize how a user’s consumption compares to that of others. This visualization often takes the form of a ranking list enriched by symbols such as badges, credits, etc. as well as numbers e.g. information on total or relative consumption. Social comparison is rarely realized by charts, which are more popular for comparative time series visualization.

Ambient design constitutes the third hot spot. Addressing the peripheral perception and the emotions of human beings, the primary focus relates to aesthetics. In contrast, issues such as unambiguousness and accuracy are less important. In realization, these issues are manifested by the preference of expressive, naturalistic and abstract forms in design.

Trends: Advanced monitoring, supplemented by such technical trends as more sensors, computer power and wearables at home, describe one particular trend. One issue associated with this trend is preventing information overload [181]. We identified two strategies to deal with this overload issue (somewhat analogue to the direct manipulation vs. interface agents distinction [327]).

One camp focuses on intelligent agents to provide contextualized and intelligent feedback beyond simply visualizing raw data, for instance, using sensors for heating, presence, door- and window-status to detect intention-behavior gaps and to make users aware of actual wastage (e.g. switching devices off) [60] and to recommend practices that promote lower consumption (e.g. concerning heating). The transition to home-automation is blurred and the challenge is how to cleverly combine intelligent feedback, advice and automation [232].

The other camp allows users more control to enrich and tailor the feedback concerning local needs and personal preferences. For instance, tagging consumers [75] so that they are easier to compare or to aggregate and can therefore enrich the interpretability [321]. In principle, interactive feedback could be applied to both minimalistic and complex design. However, the greatest potential seems to be to visualize complex issues and to support complex analytical tasks. Interactive feedback has the additional potential to bridge the gap between minimalist and complex visualizations according to the InfoVis mantra *overview first, zoom and filter, then details on demand* [326].



	Monitoring (total: 30)	Comparison (total: 11)	Minimal (total: 6)	Interactive (total: 6)	Context-Aware (total: 4)	Gamification (total: 3)	Conditioning (total: 2)	Goal / Limit (total: 2)	Ambient (total: 6)
Bar graph	14	5	1	1	2	1	0	1	0
Line graph	14	4	1	0	2	0	1	1	0
Text/Number	9	7	3	5	0	2	1	1	0
Symbols	4	5	2	0	0	1	0	0	1
Gauge	6	2	0	0	0	0	0	0	0
Abstract	1	1	2	0	0	4	2	0	5
Clock/Spiral	5	0	0	0	1	0	0	0	0
Pie chart	1	0	0	0	1	0	0	0	0
Other	2	1	0	1	0	0	1	0	0

Figure 18. Heat Map bringing Design Strategies (total number = studies with strategy elements) and Visual Forms together (red = high amount of studies, green = no studies in this category)

Concerning output media, most designs are implemented as web-apps to provide information independently of individual platforms. Mobile devices including tablets and smartphones are becoming more popular as output media and may be extended in the future to include watches and glasses too. However, designs and usages differ among the devices, e.g. smartphones are used in idle moments [209], displays before bed time [85] and so on. In this regard, guidelines and best practices would be useful to fit the design to the different mobile usage scenarios.

A further trend is the connected home and the use of home clouds. Related to this trend, security [147, 347] and privacy [127] topics are emerging, e.g. privacy-preserving technologies for smart metering [347] or providing advanced access control mechanisms [340] to regulate social comparison information disclosure. Another issue is to improve accessibility in a broad sense. Complicated log-in procedures [42] present barriers, and deterrents such as long response time [75] could lead to non-usage. However, accessibility in the traditional sense has mainly been neglected in feedback design so far.

Research gaps: If the information deficit model [370] is taken seriously, feedback design is largely a special case of information visualization. We were therefore surprised to uncover just one, weak, link between feedback-design and information-visualization research in general [52], and to time-oriented visualization in particular [3]. This missing link could well be the reason why feedback design uses standard visual forms while more advanced forms, such as TreeMaps and RiverGraphs, are neglected –they are, after all, established approaches in other areas for dealing with hierarchical and time-oriented data sources [3]. The same holds for interactive visual analytics techniques such as brushing, filtering, focus and context [326]. Feedback design would benefit from adopting such techniques to improve interactive CF [75, 153], especially because new innovative design system concepts are the biggest group to have emerged in recent years in the field of CF research. This finding points to *visual eco-analytics* research that supports users in exploring and analyzing interesting consumption phenomena. Such approaches, for instance, offer support when making more long-term decisions, e.g. when replacing old devices or switching electricity tariffs [322]. In addition, such approaches are also suitable for the area of organizational eco-feedback where multiple stakeholders, manifold data sources and various organizational demands [58] must be considered.

7.6.2. Evaluating Design

Common issues: Concerning design evaluations, Froehlich et al.'s remark [135] is still valid that HCI studies focus on short-term oriented laboratory studies or qualitative field studies. The studies tend to be informal in nature, seeking feedback on the designed artifact as users perceive it. In addition, 20% of the studies were work-in-progress without any evaluation at all.

Regarding the methodological approaches, the reported interest in motivational factors [228, 236, 308, 347, 387] is not just rhetoric; quite the contrary, in fact. Artifacts are evaluated from this motivational stance, asking users e.g. if the design would motivate them to save energy or examining in short-term studies whether an energy-saving effect can be observed.

Trends: One major trend is to draw attention to the diversity of users by taking into account gender [5], age [308], motivation type [286, 324, 347], attitudes [147], prior knowledge [150], saving experience [75, 286] and energy awareness [209, 387]. All these factors seem to affect both the effectiveness of feedback and user preferences. For instance, Mahmud et al. [5] report that male and female perceptions of CF differ. Petkov et al. [286] remark that users experienced in energy saving preferred kWh while inexperienced users prefer CO2 or money as units. Makonin et al. [236] observed that feedback effectiveness depends on the busy-ness of the users. Kirman et al. [206] stress that persuasion design could benefit from adapting individual preferences.

A special focus is on *low-motivated* users. This user group uses feedback systems less frequently and usually for a shorter time period. Based on this observation, Grevet et al. [147] argue that feedback should relate more strongly to common habits and technology such as using mobile phones in idle times, which also influence the design. For instance, Broms et al. [42] recommend providing *less information first,* to illustrate if everything is “normal”, but showing *detailed information on request*. Another promising approach is to *periodically or event-driven remind the user* [228]. Pereira et al. [283] also gathered positive experience with low-energy consumers. This group also tends to believe they cannot increase their savings much more.

Another recent topic is *trustful processing showing what is normal*. This processing refers to the recurrently reported observation that simply visualizing raw data is insufficient and that meaningful information is requested. A common way to do this is therefore to *process the data,* classifying consumption as high, low or normal. Evaluations have demonstrated that people find this type of classification helpful. However, some studies also report skeptical users who mistrust the construction of normality. This mistrust especially holds when systems become increasingly complicated or rely on external data either from unknown users or on the statistical data of the average person [322]. In addition, if the processing is not transparent, users experience difficulties in relating the feedback to their own life and developing a feeling for their own consumption behavior [169, 321]. This mismatch points to the tradeoff that, on the one hand, data processing is becoming increasingly important to minimize the information overload and to maximize the information value while, on the other hand, the control and the power of interpretation must remain under a user's control. However, future studies should evaluate in more detail the data-processing procedures employed by users when exploring and interpreting CF.

Research gaps: Usability, user satisfaction and user acceptance have represented for a long time the standard evaluation criteria in HCI. Insofar it is surprising that only 11% [137, 181, 284, 324, 347, 368] of reviewed studies take these issues explicitly into account. Others might consider them indirectly, arguing they are the precondition for successful persuasion. For example, Selvefors et al. [324] show user acceptance and usage barriers are partially related to users’ initial motivation.

7.7. Conclusion

Our paper contributes to the fast-growing field of sustainable HCI by highlighting current trends and research gaps of the last five years based on a systematic literature review.

We developed a taxonomy that focuses on design and identifies hot spots using current design strategies, data sources and visual forms. In addition, a trend was visible towards multiple data, mobile output media and the use of interactive and contextualized feedback-design strategies.

As our findings show, CF design unconsciously adopts concepts from information visualization, but a systematic adoption of proven designs and analytical techniques is missing today. Therefore, we suggest addressing the new complexity of multivariate, hierarchical data by studying information visualization at home in general and visual eco-analytics in particular. This could be a promising research area in the future.

8. What happened in my home?: An End-User Development Approach for Smart Home Data Visualization

Smart home systems change the way we experience the home. While there are established research fields within HCI for visualizing specific use cases of a smart home, studies targeting user demands on visualizations spanning across multiple use cases are rare. Especially, individual data-related demands pose a challenge for usable visualizations. To investigate potentials of an end-user development (EUD) approach for flexibly supporting such demands, we developed a smart home system featuring both pre-defined visualizations and a visualization creation tool. To evaluate our concept, we installed our prototype in 12 households as part of a Living Lab study. Results are based on three interview studies, a design workshop and system log data. We identified eight overarching interests in home data and show how participants used pre-defined visualizations to get an overview and the creation tool to not only address specific use cases but also to answer questions by creating temporary visualizations.

8.1. Introduction

Smart home systems and smart devices have become increasingly available and affordable. These smart home technologies are collecting large amounts of data (e.g. on brightness, temperature, humidity, energy consumption and movement) through a wide variety of sensors, actors and other Internet of Things (IoT) devices within the home. Data include comprehensive information about the habits and routines of people and information about the current and historical status of the personal home itself [120]. Visualizing this data appropriately enables people to discover more about themselves and their homes and allows them to satisfy data-related requirements.

There are established research fields within human computer interaction (HCI) that deal with the visualization of individual use cases for the domestic context (e.g. eco-feedback and ambient-assisted living) and that uncover highly individual information demands. However, so far, research on integrated smart home systems has focused more on enabling technologies and automation, thereby ignoring potential to make home data accountable.

To close this gap, we conducted an 18-month qualitative study with 12 Living Lab households equipped with smart home technology. Our objective was to understand what specific data-related use cases our participants were interested in. Furthermore, we developed a flexible smart home interface that allows users to build customized and personalized visualization dashboards based on their needs and to evaluate our prototype over a period of three months.

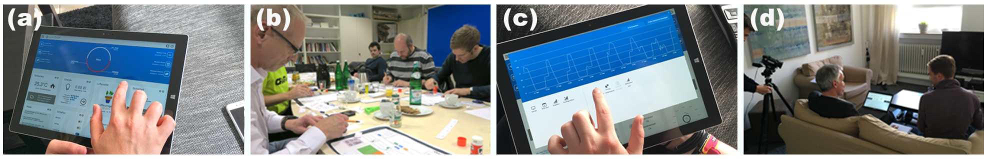


Figure 19. (a) open.DASH dashboard interface (b) households create paper-based smart home visualizations (design-workshop) (c) creating a new visualization with the EUD environment (d) usability test of open.DASH with participants

Our main contributions in this paper are:

- to provide data-related use cases and related information necessary for a user to satisfy a specific need;
- to demonstrate the concept and development of a hybrid interface that includes pre-defined visualizations and a visualization creation tool that lets users without programming skills extend the system (end-user development);
- to provide information on using and integrating the *open.DASH* prototype and on the appropriation of our approach for visualizing smart home data.

8.2. Related Work

Research into the topic of home automation or smart homes that support their inhabitants in their daily lives through the use of technology has been available for several years [6]. Smart home research addresses various issues at different levels of abstraction [240]. Since we cannot give a complete overview of all smart home and home automation research, we focus on studies related to our work and give a brief overview of enabling technology, smart home usage and visualization of domestic sensor data research.

8.2.1. Enabling Technology (Data and Infrastructure)

Smart home research has a long tradition that focuses on enabling technology, including smart home hardware and infrastructure to collect and transfer data and to set up a smart home.

In the last few years, new developments, especially in the field of wireless network technologies and IoT, have prompted new research. These new technologies and the increasing availability of sensors for retrofitting have also introduced new challenges, e.g. the complexity of, and technical challenges to, running a smart home network or the inflexibility of commercial systems that limit usage [106, 148, 242]. Thus, research has focused on ensuring that technology is in line with daily routines and habits by simplifying the installation and administration of IoT for the home and on customizing the technology to support experimentation and innovation [240]. Along with these efforts, there are an increasing number of do-it-yourself (DIY) solutions for hardware and infrastructure [242]. This trend is facilitated by advances in affordable microcontrollers, such as the Arduino and by DIY platforms such as LilyPad [46]. These advances enable users to create their own systems. Mennicken and Huang [240] state the importance of supporting these tech-savvy users, who are willing to program and create custom solutions that fit to the existing infrastructure and the needs of individual households.

8.2.2. Smart Home Usage (Configuration and Processing)

Another popular smart home research agenda deals with the control and processing of smart home data e.g. by focusing on tools that enable users to configure their smart homes [240].

Brush et al. [44] observed two levels of configuration required to automate actions in the smart home. The first level is the combination of different actions that are executed when the user manually carries out one specific action (e.g. a switch for turning on all lights). The second level involves rule-based systems to define conditional rules based on contextual events. Several studies deal with tools that let users define rules and scenarios when customizing the behavior of their smart home (e.g. [90, 93, 177]). In this area, end-user development (EUD) is one of the most relevant research topics, letting end-users define their own rules for their smart home [186, 374]. The most popular example of a rule-based system (that includes home automation) is *if-this-then-that* [180] (IFTTT). IFTTT allows users to create programs that perform actions when a certain event occurs. Another prominent example is iCAP [93], a rule-based system for smart environments, where users can build trigger-action programs.

8.2.3. Designing for the Smart Home Context (Visualization)

A third category deals with representing and monitoring smart home sensor data and the role of data visualization. So far, little research has been conducted in this area [35] even though informing inhabitants about the collected data and executed events play a major role in context-aware systems [22, 241].

Unlike in the other two categories (enabling technology and automation), up to now, there is no EUD or DIY community dealing with visualizing smart home data. Although there are approaches, e.g. by the Information Visualization community, to support the user in creating visualizations for different applications [167] (e.g. the InfoVis Toolkit by Fekete [114], the XML Toolkit by Borner et al. [19] or Prefuse by Heer et al. [167]), they are very generic and aimed at programmers. This is also true for visualization tools such as Grafana [353], which require an understanding of databases.

Currently, commercial smart home interfaces often provide user interfaces with static elements that display raw data as numbers, text, tables or log entries [241] and focus on data that are isolated per device and not linkable to other data [356]. These deficits can lead to a loss of user trust and of acceptance of smart home systems [225] and, moreover to unused system potential [175]. Recently, more advanced smart home visualizations have been developed, e.g. by Mennicken et al. [241], who integrated smart home data into a digital calendar to improve the linking and contextualization of domestic data with everyday activities. Related work revealed that users' motivation for the smart home differs as well as their technical background, and the resulting different requirements have to be considered in the design of smart home interfaces [240, 241, 390]. Other work on the visualization of domestic sensor data has otherwise typically been conducted separately for two specific use cases, outlined in the following.

(i) Eco-Feedback

There is a long tradition in HCI research looking at the effects of eco-feedback in supporting energy-efficient behavior by raising awareness of energy consumption (e.g. [29, 61, 87, 135, 320, 321]). Early systems for presenting energy consumption data were simple energy monitors that displayed raw consumption data of the whole household on a Screen [190]. More sophisticated feedback systems use smart plugs to provide consumption data at a device level and therefore allow the visualization of different aggregation levels [315]. Today's feedback systems are more advanced and aesthetically pleasing as design-centric surveys (e.g. [134, 288]) show. Additionally, a series of design studies have elaborated guidelines [165, 232] and suggest design frameworks [29, 123, 308] for visualizing consumption data.

A major trend in eco-feedback design is to draw attention to user diversity, taking gender [5], age [308], motivation type [286, 324, 347], attitudes [147], prior knowledge [150], saving experience [75, 286], and energy awareness [209, 387] into account. All these factors seem to affect both the effectiveness of feedback as well as the users' preferences and needs. Kirman et al. [206] stress therefore that persuasion design could benefit from adapting to individual preferences.

(ii) Ambient Assisted Living and Aging

Ambient Assisted Living technology (AAL) is another active community dealing with technological support for a comfortable and independent life of elderly people in the home [72, 346]. The overall framing for such systems is highly dependent on the user, user groups and their role, which influence the motivation for such systems. Primary users are the care recipients themselves, but the user list also includes formal care givers, remote care givers and family, neighbors and friends [255]. Furthermore, Stein et al. [336] show that, within the different user groups, there are still more finely categorized use cases that have to be considered, when designing smart home systems for elderly people, e.g. awareness, safety, health, emergency and enhancing of wellbeing.

The consideration of these factors can be seen more easily in the progress of systems that have evolved from simple telecare systems to more sophisticated ones. Takács and Hanák [351] developed an ambient facial interface (a digital human face) that used facial expressions to display emotional information about the current state of care recipients or of information on products they interacted with. Truong et al. [359] presented a more user-centered and interactive system that allowed users to write their own applications for scenarios in daily life. Mulvenna et al. [255] support this effort and suggest developing adaptive interfaces that target the specific needs of different users.

8.2.4. Challenges for Visualizing Smart Home Data

The known issues in the design of interfaces and the visualization of domestic sensor data call for human-centered approaches. Research in smart home enabling technologies (including hardware and infrastructure) as well as in smart home usage (including configuration and processing) tend towards customizable and DIY approaches, such as EUD, that let users adjust the smart home to their needs and ensure an inhabitant-centered design [90]. According to Newman [261], end-user configuration capability is a key factor in smart home systems. On the visualization level of smart home data, no EUD approach has yet been discussed in literature, but much work deals with static visualization elements. These studies provide best practices and design implications mostly for specific use cases (e.g. energy, security, health, etc.) or for specific users. These works highlight that visualization play a crucial role in domestic systems. Furthermore, research shows that, even in these specific use cases, the needs, interests, capabilities and goals differ between users (“one size does not fit all” [165]). These needs and interests could also change over time with the use of such systems, and they depend on the user’s current situation [209]. This variety of parameters is challenging when designing smart home visualization. Users need flexible tools for customization, data comparison and annotations that make the data understandable and to support sense-making [14].

Our *open.DASH* system (see Figure 19a) combines these two approaches: integrating pre-defined visualizations based on gained insights and experience in specific domestic areas and additionally allowing free customization based on an EUD approach [223]. Our goal is to provide tools that allow users both to explore their smart home to gain further insights into their routines, habits and the home itself and to adjust their smart home interface to fit their specific needs.

8.3. Methodology

In our study, we followed the user-driven design approach proposed by Stevens et al. [339] and Wulf et al. [377, 379] to inform the design of our smart home interface. Thus, we applied a Living Lab approach to understand users and their contexts and to investigate the use of smart home systems in real-life environments [112, 126]. With this approach, it is possible to bring users and technology together with different stakeholders from research and design in an open design process [126]. Living Labs support long-term cooperation, co-design and in-situ exploration and therefore the integration of users into a continuous evaluation of the designed artefacts from the very beginning [24]. They also allow early discussions of new concepts, testing not fully operative prototypes and field tests for long-term appropriation of new smart home systems. Especially for the smart home, it is important to investigate users' needs and the contexts for which systems should be designed [271].

8.3.1. User Sample

We focused on gaining a heterogeneous user sample to have as many different users and types of households as possible. After a multi-stage recruitment process, including newspaper ads, local radio features, etc., we made a pre-selection based on spatial proximity and conducted telephone interviews with 63 interested households (from over 100 registrations) to gather an impression regarding motivation for participation, willingness to actively participate in the project and technical and smart home related foreknowledge. Twelve households with a total of 29 inhabitants were selected, varying in terms of age, living style (rented or owned home, house or flat), rural or urban residential area as well as technical level (see Table 7).

Table 7. Overview of Living Lab user sample

#	household size, living style, location	tech. knowledge
H1	2-pers. household, apartment, city	Yes
H2	3-pers. household, house, rural area	Yes
H3	3-pers. household, house, rural area	Yes
H4	3-pers. household, house, rural area	Yes
H5	4-pers. household, house, rural area	Yes
H6	2-pers. household, house, rural area	Yes
H7	2-pers. household, apartment, city	No
H8	1-pers. household, house, rural area	No
H9	3-pers. household, house, rural area	No
H10	2-pers. household, apartment, city	No
H11	1-pers. household, house, city	No
H12	3-pers. household, house, rural area	No

8.3.2. Study Design and Data Collection

We conducted a two-stage qualitative empirical study, which is illustrated in Figure 20. All interviews were audio-recorded and transcribed verbatim. In addition, the design workshop and usability evaluation were video-recorded to facilitate subsequent analysis.

(i) Phase 1: Understanding and Requirements

We started with an explorative on-site study with a semi-structured interview (**T0**). Our main goal was to gain an understanding of the participants' homes, their daily routines and habits as well as their information needs, interests and

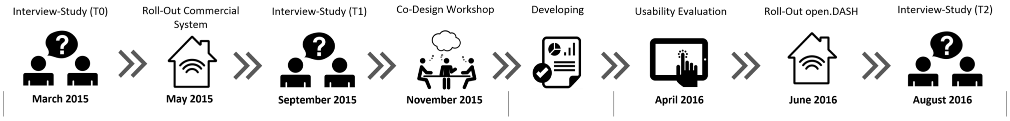


Figure 20. Methodology timeline

ideas for use cases of a smart home system. Afterwards, we provided them with an “off-the-shelf” smart home solution that is currently available on the market. This Z-Wave-based (wireless communication protocol) plug’n’play smart home platform system was used as a technological probe (consisting of 6-36 components per household, selected from a wish list). Three months after the installation, we conducted a second interview study gathering experiences, demands, limitations and gained insights when using the smart home system in participants’ everyday life (T1). After a further three month period, we conducted a design workshop with five households with the goal to validate requirements identified in T0 and T1 and to gain insights about the design needs. The gained understanding (T0), the mentioned experience and demands (T1) and the design needs from the workshop drew a first set of requirements for our *open.DASH* prototype.

(ii) Phase 2: Evaluation and System Usage

After the development, we conducted a three-stage usability evaluation to ensure that the prototype was usable during the households’ everyday life (see Figure 19d). In this evaluation, users had to perform two scenarios based on T0 and T1 with overall 12 tasks. We first conducted a heuristic usability evaluation with three usability experts from within the university, using Nielsen’s usability heuristics [262]. Afterwards, we repeated our usability evaluation first with five and then again with six participants from our Living Lab. We used thinking-aloud to see how users interact with our developed interface [262]. Having addressed all problems mentioned, we rolled out the prototype in 10 out of our 12 Living Lab households (due to sickness and to technical problems, we were unable to install/run our developed interface in two households). Our system was installed as a supplement to the commercial smart home system and was connected to the same sensors and actors, thus used the same data. The participants used the *open.DASH* interface over a period of almost three months. Subsequently, we conducted a third interview study (T2) to gather experiences regarding the use, limits and desired extensions of our *open.DASH* interface.

8.3.3. Data Analysis

Our analysis is based on all Living Lab research activities during the 18 months, including T0, T1, and T2 interviews, design workshop results and field notes from visiting the households. All transcripts were analyzed by two researchers independently using thematic analysis with an inductive coding process [40]. After each of these research activities, code categories were consolidated and developed iteratively. We also internally discussed gained insights with researchers not involved in the project. We recognized the need for some degree of inter-rater reliability and so enlisted other internal researchers that are not involved in the project to check our coding decisions. Additionally, for the evaluation of our developed prototype, we collected quantitative data on the number of site visits, visiting time, duration and customization activities.

In the analysis, we looked for common information needs and interests, actions related to information provided through the system and how the participants configured their smart home. Furthermore, we looked at the integration of smart home data into everyday life especially when users were interested in smart home data, and what questions they wanted to be answered. All quotes in our findings section were translated from the German by the authors.

8.4. Information Demands on Smart Home Data

In this section, we present findings from the analysis of Phase 1 that resulted in requirements for the first prototype of our *open.DASH* interface.

8.4.1. Information Needs and Scenarios

Our analysis resulted in three overall topics for the use of smart home sensor data, which are outlined below.

(i) Events and Home-Status

A frequent information need was about the current status of the home, especially in the "*leaving-home"* scenario. The participants wanted to know if they had forgotten something such as electric devices or radiators that were still on or open windows and doors: *"Is everything O.K. when I am not at home? Did I forget something?"* (H8, T0). Although motivation varied, nearly all participants mentioned that immediate information about the current status of the home would give them a feeling of security. Another related demand dealt with situations where the participants were *away from home for a longer time*, e.g. when on vacation. Here, the focus shifted, and it was more important for participants to get information on events that happened in the home than on the home's status: *"When we are on vacation, the events are more important, for example if there is movement or if a window or door was opened"* (H8, T0). After installing the commercial smart home system, some participants mentioned that they looked regularly at their event diary, even if they were at home, to get a feeling about what was happening in the home.

(ii) Energy and Performance

Another recurring demand of households dealt with energy efficiency and performance. Before the installation of the commercial smart home system, there was a great need to check whether the devices in the home were energy efficient or not: "I don't know how much energy is consumed by my devices, I have no possibility to check it" (H9, T0). "It is interesting to track what we have to pay for energy every week" (H7, T0). "I want to track my standby consumption" (H12, T0). Most participants mentioned interest in feedback on energy consumption data. With the commercial system installed, requirements towards consumption data tracking and visualization turned out to be very individual. While some participants continuously tracked their consumption, a few households would only check consumption data occasionally, i.e. when they got a new device or when receiving their electricity bill: "[Energy] is only interesting if we have a new device" (H6, T1).

Besides electricity, heating was a very personal topic for the participants because most participants had their own "feel-good" temperature and it sometimes was difficult to quantify this optimum temperature: "What is the real temperature? […] How does the sun influence the inside temperature? […] What effect does an open window have?" (H9, T0). Therefore, it was also difficult for them to define criteria for performance or efficiency of their heating routines: *"For example, when I have invested, let's say into my heating, I want to know: Does it pay off?" (H9, T0). "I don't know what the influence of my heating routine is" (H8, T1). When the participants could see the real temperature in their rooms, they developed an awareness and could identify anomalies by looking at the current temperature. That was also true for energy consumption. After gaining an awareness of energy consumption and temperature levels, participants looked at the data to see whether everything was o.k. and, if not, they tried to find reasons: "If the [energy] trend is negative then I want to check why"* (H6, T1).

(iii) Awareness of my Smart Home

The installation of the commercial smart home system also resulted in new requirements related to the configuration and automation of the smart home. Because the participants initially lacked trust in the system, they were concerned about false behavior of the smart home and checked the information on the smart home interface to see if their configuration and defined rules were working properly (this is also mentioned by Mennicken et al. [241]): *"I check the system to see if something has failed, like my heating control at the beginning"* (H3, T1)

Furthermore, data served as information about the right configuration, e.g. if the defined rules worked the way the user wanted them to. The information was also used to gain awareness and for participants to build their perfect configuration: Which brightness level is enough and when should the light automatically turn on? How long does it take for the rooms to heat up? Generally, the households used a trial-and-error approach to adjust the settings step-by-step until they were satisfied with the result.

8.4.2. Implications

The findings so far have shown numerous overlaps of needs and interests between participants, but also some opposing opinions. Overall, we identified eight questions that our participants had for smart home data visualization:

- What (has) happened in my home?
- Did I forget something?
- Are my devices energy efficient?
- Am I energy efficient?
- Is everything o.k.?
- What is the current status of my home?
- Does my smart home work as expected?
- Is my configuration appropriate?

Although, these questions were not always applicable, they were a good starting point to categorize use cases for home data. Not all participants were interested in all of this information, and the information needs could change over time. Besides personal interest, there were multiple other factors that influenced the information needs such as when the participants were on vacation or by seasonal effects: *"[interests in] brightness in winter [its getting dark earlier] and the window status in summer [for fresh air]"* (H1, T1).

Therefore we can further divide information needs into *long-term information needs* and *temporary (short-term) information needs*. Long-term information needs are interesting for participants over a longer period of time, e.g. for the routine to check if something was forgotten in the leaving-home scenario. Temporary information needs are irregular needs that only come up at specific times, e.g. when getting the electricity bill to check what devices are responsible for the consumption.

Especially after installing the commercial smart home, new requirements for smart home data monitoring were identified. The ability to collect data raised interest e.g. in long-term analysis of energy consumption or the combination of multiple devices for comparison or identification of relations between them (which was not fully supported by the commercial smart home system): *"For me, smart home is the connection of multiple devices […] I don't want a single view, but to see things together, combine things and to visualize them."* (H8, T1).

In general, we can confirm findings from the literature insofar as our participants had individual and personally-motivated information needs [165, 308, 336]. But we could further see that our participants had also overlapping data-related interests and use-cases. To validate our findings and to identify these mutual information needs, we conducted a creative design workshop, where participants could develop their own paper-based smart home interfaces (see Figure 19b). In the workshop, we could see that the participants were generally interested in overviews on the topics of energy, temperature and security. Furthermore, we found that people also wanted further, external information implemented into their smart home interface, such as information about the weather or a news feed. Additionally, the workshop revealed preliminary insights into exchange of experience between participants and participant interested in use cases from other participants, to develop new ideas. The concurrency of mutual interest in information, as well as the individual interest in specific information, suggest a hybrid system that includes (1) pre-defined visualizations that can be configured by users and (2) a custom tool for building custom visualizations, fitting needs and interests and allowing a detailed view of the collected data.

8.5. Design and Implementation of *open.DASH*

Based on these findings and on relevant literature, we designed a flexible and highly customizable prototype to gain insights about how people use smart home data with our system in real scenarios (Figure 21).

The system is based on a dashboard concept, allowing us to realize our general idea of multiple visualizations for the participants' needs and use cases as single web components that could easily be exchanged or configured during runtime. The header section allows direct access to the menu and customization settings. The blue-colored area shows real-time information on room level. We chose rooms as a structure because studies show that rooms build an appropriate ordering of the home [66]. A single click allows the navigation between rooms. Overall, this header section allows values in different rooms to be compared and provides an overview of the *current status*, *if everything is o.k.* or *if something was forgotten.* The customizable widget section begins under this blue-colored area. Widgets can be dynamically added, rearranged, changed in size or deleted.

8.5.1. Pre-Defined Visualizations

Pre-defined widgets can be dynamically added through a widget-chooser in the side-menu. In the first draft, we included five pre-defined widgets that were inspired by the design workshop, including a news widget where an RSS-feed can be included to get current news of the preferred news portal. The development of the pre-defined visualizations was steered by the Visual Information Seeking Mantra by Shneiderman [326] to first provide an overview of the related topics and filtering and details on demand.

The energy widget provides information about the current consumption level of all devices, the current amount of money for this week's energy consumption, a trend indicator that shows if the consumption of this week has a positive or negative trend in contrast to an average weekly consumption and abstract indicators that showing the consumption for up to five single devices. Thus, this widget provides quick information about devices that are currently consuming energy (*Did I forget something?)*, about the relation of consumption between devices (*Are my devices energy efficient?*) and about the usage of devices (*Am I energy efficient?).*

The temperature widget indicates the current average temperature of the home. The user can individually configure which sensors should be included in this calculation (e.g. to exclude sensors in the basement). Additionally, the outside weather and the forecast of tomorrow's weather is shown. The close link between inside and outside temperature allows a quick comparison and an overview of the *current status*. Furthermore, the user can see whether the minimum temperature is maintained (*Does my smart home work as expected? Is my configuration appropriate?*).

The security widgets provide an overview of the last (security-related) event and the time it occurred. As participants mentioned that events are more important when not at home, especially movement and door/window status, this widget shows only the last movement or door/window status event, including whether it was an opening or closing event (*What (has) happened in my home?).*

The diary widget shows information about every single event that has occurred in the home, without any historical limitation. The events are placed on a time-series of one day (00:00 to 23:59), and the user can click through each day. To improve readability, the events are aggregated on an hourly level


Höchste Temp. 2016-08-28 - 26.4°C
Meisten Events 2016-09-17 - 393 Events
Höchster Verbrauch 2016-09-17 - 4.38 kWh
Akt. Temp 34.6°C
Luft Feucht. 27.6%
Helligkeit 8.32%
Niedrigste Temp. 2016-09-05 - 22.8°C
Wenigsten Events 2016-09-10 - 4 Events
Niedrigster Verbrauch 2016-09-10 - 1.42 kWh

Temperatur
24.7°C
Durch. Innentemperatur
17.5°C Aussentemperatur
93% rel. Luftfeuchtigkeit
Trend Morgen: 18.81°C

Energie
342.38 W
Diese Woche: 2.47€

News
Mit zwei Beiträgen auf der Mensch und Computer 2016
Neue Ausgabe des Magazins „WISSENSCHAFT TRIFFT PRAXIS“
Veranstaltungshinweis: Get smart – Die Zukunft im Smart Home Markt
Welche Rolle spielt der Mensch bei der Entwicklung von Technik?

Sicherheit
Wohnzimmer
vor 2 Minuten
Heizung (Büro): 52%
Heizung (Wohnzi): 64%
Raumthermo (Wohnzi): 77%

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30-08-2016

Figure 21. open.DASH - interface

and the number of times an event has occurred is mapped through the height of the bar (*What (has) happened in my home?*). Additionally, events from configured rules or time control are visible, allowing users to check whether the smart home works properly (*Does my smart home work as expected?*).

8.5.2. End-User-Development Visualization Tool

To allow a very personal customization and a detailed exploration of smart home data on demand [326], we developed an EUD environment to create custom visualizations of smart home data. As EUD for the smart home is currently a highly topical theme, we developed our environment with consideration of best practices from the literature. Therefore, we developed a guided step-by-step creation mechanism that supports the users. Furthermore, we provide simple click/touch interactions instead of more complex operations such as drag & drop [90].

Our visualization creation process consists of five-steps (see Figure 19c, Figure 22), following the visualization pipeline by Card [52]: selecting data (Data Analysis), selecting time (Filtering), selecting chart, configuration (Mapping) and adaption (Rendering). The first step is to choose which data should be visualized. The user can choose one or many devices and sensors

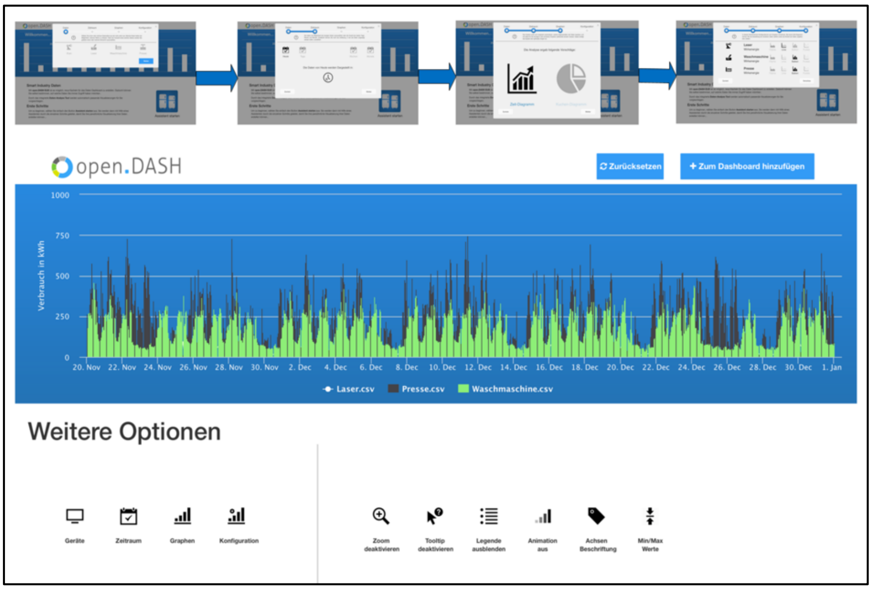

Figure 22. Five-step process for creating an own visualization

from the list, which contains all of the installed sensors in the home. The second step is about when the data is aggregated. The user can choose between an absolute timespan (e.g. for the exploration of a specific billing period) or a relative timespan (e.g. the last four months). After these two steps, the user can select how the data should be visualized. We implemented an algorithm that analyzes the selected data source and timespan to automatically suggest appropriate chart types. The algorithm is based on Aigner et al.'s [3] characterization of time-oriented data, and checks whether the data are univariate or multivariate, interval or point-based and whether cyclic time domains exist (e.g. for univariate data the system would not suggest a pie chart). Additionally, it checks whether data could be easily summed up (energy consumption could be aggregated to hour values by summing minute-based values). The fourth step contains the special configuration for the selected chart type, e.g. whether data should be mapped on lines, points etc. on a timeline chart. After these four steps, the user gets a preview of the chart, where interaction such as zooming or selecting or hovering over points to get a tooltip with information is possible. This step mainly supports task-driven adjustments, e.g. for localizing or identifying data [358]. From this step, the user can go back to the four previous steps to change the settings or can configure the interaction or layout of the chart (e.g. changing animation settings, allow/disallow zoom). The user can decide whether the chart should be added to a dashboard as a widget or discarded. If the user wants to add it to a dashboard, a title can be added and the size defined.

By using the flexible tool, participants were able to get detailed information on questions concerning *are my devices and I energy efficient, what has happened in the home*, *does my smart home work as expected and is the configuration appropriate or not*.

8.6. Results

In this section, we present the results of our Phase 2 studies. Before we installed our *open.DASH* interface in the Living Lab households, we conducted a three-step usability test to minimize system usability or acceptance issues that could have influenced its usage. The heuristic usability evaluation showed some issues regarding the navigation inside the page, the wording of some features and labels, the font-size and the choice of symbols. Additionally, some parts of the EUD assistant were too complex and not clearly understandable. To overcome these issues, we implemented more filters to the interface elements to automatically hide unnecessary items. Overall, we reduced the number of symbols and text, ensuring a clearer interaction design.

8.6.1. User Experience, Appropriation and Use

After three months of use, we had a total of 1,394 page visits of the *open.DASH* interface, with 70.09% from a desktop computer, 24.10% from smartphones and 5.81% from tablet PCs. In the first two weeks, the average visit duration was significantly longer than in the remaining time, which could be explained by the novelty factor and the testing of all functions. Overall, 60.47% of the visit duration was under 10 seconds and 28.43% were over three minutes.

From the T2 interviews, we found that the first impression of *open.DASH* was consistently positive. The participants liked the design and its simplicity: *"The design is very good, very clear [...] I can also customize and set up many different things [...] Here you can do that intuitively and very quickly"* (H10, T2).

Participants reported that they liked the room-based overview, allowing them to look into every room and get aggregated information about its current status. We found that aggregation of data (to the total amount or into smaller units such as rooms) was perceived as useful (in the commercial system, the devices are isolated and participants had up to ten sensors measuring temperature and 20 sockets that measured energy consumption). This aggregation improved the ability to quickly "*get an overview*". Additionally, it reduced the amount of information displayed to the user: *"I had no total consumption with the [commercial] system, I had to sum up the single values manually"* (H3, T2).

The graphical visualization of sensor events in the diary widget not only made patterns and regular times of action visible but was also used to clarify the information value of smart home data, thus, letting people think about the effect of the digitalization: *"After looking at the diary widget, I realized what information the smart home collected. Especially, in terms of motion profiles, because this is safety-critical information"* (H7, T2).

The hourly aggregation of event data within our diary widget was experienced as an obstacle for some participants, as it allowed neither a fine-grained retrospective of action nor, especially, whether the configured rules were working properly. Another drawback to our system was the missing ability to switch devices directly from the interface, which meant that if a participant recognized some energy wastage, he or she could not act directly.

8.6.2. How People Customize Their *open.DASH*

As He et al. [165] mention, there is no system that fits to the needs of all users. We thus were interested in how people customized their *open.DASH* to fit their needs and to get (only) the information they were interested in.

(i) Customize the Pre-defined Visualizations

Nearly all (9/10) households adjusted their starting dashboard in some way. This also included configuring pre-defined widgets and deleting or moving existing widgets.

Households deselected devices for the average temperature calculation to only include "*important rooms*" (H2, T2) and entered their city details to get weather information for their location. Three participants also reconfigured the news-feed to get news from their preferred news portal (the initial news feed was the one from the project itself). The households also rearranged widgets to see their most important information first. Some households also deleted pre-defined widgets because they were not interested in that kind of information or because they did not have enough sensors in their home to get an added value from the generated information: *"Temperature is not interesting for me neither is the news-feed."* (H6, T2). *"I've deleted the security-widget, because I have too few sensors for this widget"* (H3, T2). *"There is information about energy consumption and a diary of smart home events, I don't need more for this household"* (H1, T2).

Overall, the participants liked the idea of the temperature widget and excluding specific sensors for the calculation of the average temperature, but they also would have liked to see this configuration ability in all other pre-defined widgets. For example, two participants used a motion sensor at their television that detects whether a person was sitting in front of it. As long as a person is in front of the television the system kept the lights on. In this example, the motion detector was partly triggered over 200 times in one hour, which had a negative influence on the diary visualization. Thus, the households in question wanted to exclude this sensor from their diary widget.

(ii) Making Own Visualizations

During the three months with *open.DASH* the participants created 203 charts with the EUD environment. 55 of these created visualizations were added to the dashboard. Most of the visualizations were created at the beginning and the end of the study.

Participants mentioned that they first used the EUD environment to play around with the data. They created charts, e.g. for temperature data, consumption data, etc., to get a feeling for smart home data and to explore possibilities for useful extensions for their dashboard. *"[At the beginning] I created some graphs, e.g. with the temperature curve, but they were not yet useful enough for us"* (H1, T2). After getting a feeling about the tool and its possibilities, the tool was used explicitly for individual use cases, e.g. for verification of configuration: *"I have created some [new widgets – saved to* *dashboard] [...] to check if rules work properly"* (H3, T2), the monitoring of specific devices in terms of energy consumption and temperature profiles: *"During a vacation, we could check if it was too hot for the cats at home."* (H1, T2). The visualizations of energy consumption data, especially, changed over the three-month usage. In most cases, the energy consumption visualization became more specific by displaying fewer devices in a chart, or it was removed completely after the first weeks. Another interesting usage scenario was that, for specific rooms participants sometimes created charts where they combined consumption data, temperature data, brightness data and event data to learn about what was going on in the room.

Additionally, participants used the creation tool to temporarily create visualizations to satisfy urgent questions and requirements or simply for "*looking into the data*". These visualizations were typically not added to the dashboard; only the preview was used to get the needed insights from the data. For example in the situation where something was considered as abnormal, participants looked into multiple data for the current day to find reasons. Another example was looking for changes in consumption behavior. If participants bought a new device or changed something in their smart home settings (e.g. cutting standby consumption off at night automatically) or their behavior, they created a time chart to compare current consumption levels with past consumption levels.

Overall, the participants stated that they liked being able to check and analyze their data spontaneously and flexibly. It allowed them to learn from the data and to continuously adjust their smart home. Yet, for some participants it was difficult for them to find any use cases themselves and especially for their set of sensors: "*I could not create any useful visualizations because we have not enough devices [sensors] installed.*" (H4, T2). The lack of ideas was also identified as a barrier for using the tool to explore data. The same household mentioned that "[…] *a source for ideas would be interesting*" (H4, T2).

8.6.3. Limitations

For the evaluation of our *open.DASH* interface, we used the sensors available in the households from the commercial system (see methodology section), which lead to a few limitations. The main use cases for these sensors are: energy consumption, temperature, brightness, motion, door/window status. The evaluation of our *open.DASH* interface was conducted during the summer months, where households mentioned that temperature and brightness are not that relevant when dealing with a smart home system. Therefore, we could not investigate all usage areas for our developed system. Additionally, some households had only a few sensors installed and, as a result, little data were collected. The households mentioned use cases that they would like to uncover but, because of the limited number of sensors available, the participants were unable to realize them in an appropriate and sense-giving manner.

8.7. Discussion and Implications

In this section, we discuss our results and provide implications that aim to support the design of future systems dealing with the visualization of smart home data.

8.7.1. Pre-Defined Visualizations vs. Visualization Creation Tool

We could see that pre-defined visualizations are important in allowing the participants to have a starting point in dealing with smart home data. The participants configured and used these pre-defined visualizations to gain awareness of the data and to get an overview of the current status of their (smart) home. Topic-based widgets with aggregated data, which can be selected and (re-)arranged on the dashboard freely, seem promising in this regard [116]. Additionally, when aggregating data, it is important to empower the user to select which sensors should be included in the calculation/aggregation process to exclude data from specific sensors that are (not) relevant for specific use cases.

The EUD environment enabled participants to get more detailed information about their smart home in a flexible manner. Particularly with regard to very individual requirements and use cases, the creation tool was helpful for the households as it allows non-programming users to query their data in an understandable way. Participants explored the tool and their data to get inspiration for new use cases or information within the data. The deployment of *open.DASH* in the Living Labs showed that the *combination of customizable pre-defined visualizations and creation tools for individual visualizations* could address different information needs and interests.

Based on our results, pre-defined visualizations therefore could be informed by existing research in special topics such as eco-feedback or AAL to extend the possible fields of application. As they are a good entry point, they should be designed to provide an overview on a specific topic, letting users check on the current status and whether further details are needed [326]. However, future systems should also enable users to create complementary visualizations that go beyond universal visualizations. These could take their individual interests more into account.

8.7.2. Supporting Short-Term and Long-Term Needs

We were able to identify that participants used *open.DASH* differently according to their changing interests over time. Users addressed specific long-term interests that occurred or were monitored regularly by creating new visualizations with the creation tool and afterwards saving them on the dashboard. In contrast, short-term interests were mainly realized by creating new mappings of data, but without saving them, and therefore allowing "on-demand" requests for temporal requirements.

Our findings suggest that smart home systems should allow users to quickly and easily map data to different kind of charts, text and symbols, thus fitting to users' different needs [325] and furthermore, enabling the user to create on demand visualization that are not permanently displayed on the dashboard. This separation in regard to the design of the dashboard also simplifies the overview page by reducing the risk of information overload on the first view.

It will be interesting to see how users deal with recurring short-term needs, e.g. checking energy consumption when a new bill arrives, and whether the creation tool is used in the same way every time. So far the system does not allow the history of self-created visualization to be stored, and users have to build the visualization from scratch every time.

8.7.3. Community and Sharing

Our participants had different knowledge about the potential of data. Some participants reported that they had several specific use cases at hand; others found it difficult to find new use cases or even one use case. During the workshops (where participants came together), we could see that there was considerable interest in finding out how other participants used their smart home. In the interviews (T2), the participants mentioned that it would be interesting to see what other households did with the visualization creation tool.

For the working context there is growing body of work that deals with the socially based tailoring of a flexible software systems to enable users to adapt the tools to achieve a specific work task [104, 362]. For private flexible smart home systems therefore, we argue for allowing creation tool configurations (e.g. for a visualization that showing the correlation of outside and inside temperature) to be shared, thus addressing both the inspiring of other participants and sharing the “how to” for creation of visualizations for specific use cases with an “over-the-shoulder-learning” approach [362]. Following the IFTTT approach could make it possible to share configurations for specific use cases on a platform that other users can configure and integrate into their interface.

8.7.4. (Flexible) Smart Home Data and Visualization Matters?

From our study, we learned that the participants had varying requirements regarding smart home data. Some requirements are superficial, some are very detailed, some demands overlap between participants, some are very specific and some participants are not very interested in smart home data. However, *open.DASH* gave us first insights of participants' usage and how they customize their dashboard.

Dynamic visualization tools allow people to create different views on domestic data which allow them to gain further insights into their (smart) home: "[Only after looking at the data did I] *realize what information the smart home collected"* (H7, T2). Especially, the flexibility enables the user to adapt the system according to changing needs. This is further supported by three participants who used a wall-mounted tablet as a public display where they used our *open.DASH* or other sites that were relevant for them. We agree with Mennicken et al. [241] that it would be promising to integrate smart home data into already used tools. But we could also identify that participants wanted to integrate other data into their smart home dashboard, for instance information from social media, timetable inquiries, activity and health data or the TV program. The design workshop, where some participants asked for a newsfeed to be integrated, showed that participants are interested in making the smart home interface a place where all interesting information is shown at a look.

In this vein, especially when dealing with multiple smart components and systems we argue that future private information systems should provide a single unified interface, similar to what Few [116] description for business dashboards. Scattered access points with their own login-mechanism and incoherence in styling and control present obstacles for current smart systems. On a middleware-level open source projects, such as openHAB [272], already enable unified control from different smart components. Currently, advanced approaches for visualization and monitoring are still largely neglected. As we have shown, however, the combination of smart home data enables new applications of smart home systems and additionally offers opportunities to tap into the full potential of exploring the own home. Going a step further, we believe that creating a user-centered information portal that combines all smart home data with other relevant information could be an interesting topic for future research.

8.8. Conclusion

While smart home enabling technology is continually developing and smart home configuration research is increasingly integrating the end-user with EUD rule editors or DIY hardware, research dealing with visualizing integrated smart home data is rare. As specific smart home use cases, eco-feedback and AAL research have shown that the user needs for, and interests in, domestic data differ, thus demanding more flexible tools to display sensor data. Our study shows that this view is also true for the integrated smart home case. We identified eight requirement categories that include overlapping and individual data-related use cases. To address these individuality of data demands, we developed a flexible dashboard system, including configurable pre-defined widgets and an EUD environment, allowing users to create data visualizations themselves. We tested our interface in 12 Living Lab households for three months to examine the usage and appropriation of such a flexible system. We found that participants configured and used the pre-defined widgets to get an overview of interesting topics (energy, comfort, safety, etc.). The EUD environment was used to create charts for specific use cases (e.g. temperature curve, consumption baseline) to extend dashboards individually. We also found that the EUD environment was used for urgent demands e.g. to obtain detailed information on anomalies. We think that such hybrid interfaces for smart home data visualizations are a promising approach to addressing the users' varying information demands and to supporting the development of consciousness through data exploration.

9. Beyond eco-feedback: Using room as a context to design new eco-support features at Home

In recent years research in Sustainable Interaction Design has put major efforts into understanding the potentials of saving energy in private households by providing energy consumption feedback. Trying to overcome pitfalls such as invisibility and immateriality, a great variety of designs with saving potentials from 5% - 15%, has emerged. However, feedback mechanisms are mostly reduced to a one-dimensional view on motivating energy savings. In this paper, we argue to take a broader view on eco-support, where eco-feedback should be used in combination with eco-control and eco-automation features. All these features have in common that they aim to reduce energy consumption in practice. From such a holistic understanding of eco-support, we demonstrate how design could benefit from ubiquitous- and context-aware computing approaches to enrich feedback, increase control and automatize cumbersome and boring routines. We use the presence of a user on room level as context information. Rooms present an essential domestic ordering system that structures daily routines at home. In this paper, we show that the usage of *room-as-a-context* has fundamental implications for the design of domestic indoor localization concepts. In addition, we show how the different types of eco-support systems benefit from it. We illustrate our consideration by presenting a prototype for Android based tablets, which was used to study the design concepts in the wild.

9.1. Introduction

Residential and commercial buildings are responsible for about 40% of the EU's total energy consumption [113]. However, conscious sustainable use of this limited resource is hampered by a lack of visibility and materiality of consumption [123]. One of the major challenges in Sustainable Interaction Design (SID) is to enable consumers to make informed decisions about energy consumption, thereby supporting the shift to or implementation of sustainable actions [31]. Technological innovations of smart metering allow a fine-grained consumption measuring, in turn paving the way for a rapid development of energy management systems.

Early systems were largely limited to simple displays providing information about the total energy consumption of the household (smart meter systems), such as 'eco-eye' [201] or the *Wattson Energy Monitor* [127]. More sophisticated energy management systems mostly based on real-time, disaggregated energy consumption data on device level [347] with various forms of visualization and approaches like goal-setting and gamification [181], conditioning [206] and comparison [286]. They are mostly realized as web-portals [111], smartphone applications [368] or ambient, artistic design approaches like the *Power-Aware Cord* [152] or *Watt-Lite* [190].

Modern home energy management systems (HEMS) further embrace different strategies into one holistic system [320] that includes features for consumption feedback, control, and automation.

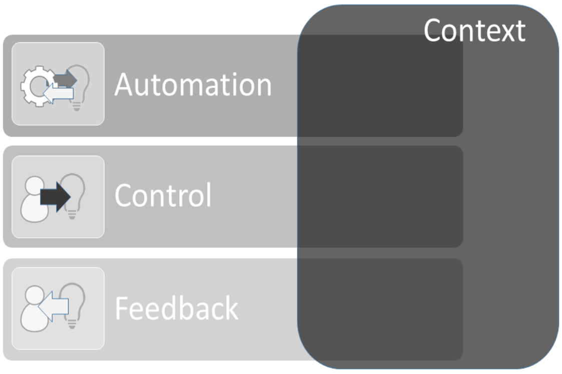

Figure 23. Context as a cross-cutting topic enhancing the various levels of eco-support

However, with the increasing volume of data, eco-support becomes more complex. To cope with this challenge current research focuses on how feedback can be made more informative and how the user can be supported to take action.

A promising approach in this topic is trying to support context awareness in enriching consumption data with personalized information. Context is a cross-cutting issue that could be used to enhance the various levels of eco-support (see Figure 23). The aim of this approach is to reduce information complexity, make control easy and to provide a rich context for interpretation to make data more meaningful for the user. By reducing the complexity of information and providing a rich context, context awareness enables the user to better interpret consumption data.

Contributing to this, we present the concept of room as context information, as rooms play an important role in structuring domestic routines, thus domestic energy consumption. We discuss implications for designing more meaningful interfaces with the regard to three different approaches that support a more sustainable behavior. Based on the concept [62], we additionally show an architecture for such a context-aware home energy management system and demonstrate a fully functional prototype for android-based tablets that illustrates how room information can be used to enrich feedback mechanisms and contextualize user interfaces of mobile home energy management systems (mHEMS).

9.2. Eco Support Systems

In literature a manifold of approaches for designing systems to support more sustainable behavior can be found. We subsume all these different approaches under the label of *eco support systems*.

Generally, eco-support systems are defined as measures to make behavior, habits, routines, and lifestyles more sustainable. In this paper, we focus on eco-support with regard to the private energy consumption. Here, we can roughly distinguish three categories of eco-support: *Eco-Feedback, Eco-*

Control, and *Eco-Automation* (see also Loviscach [232] for a similar taxonomy). All three are expected to increase energy efficiency as well as the energy sufficiency on the demand side. They are not mutual exclusive; in opposite: they complement and strengthen each other when included into a HEMS.

In the following we give a brief overview of these categories. In our discussion we show how additional context information contributes to the effectiveness and usefulness of these three categories (see Figure 23).

9.2.1. Eco-Feedback

Eco-Feedback is defined as providing people information about their consumption of natural resources (e.g. energy, water, etc.) with the aim to motivate and persuade them to reduce their environmental impact [135]. Today, all HEMS support at least some kind of eco-feedback.

The concept is shaped by rational behavior theories like Rational Choice, Expected Utility, or the Theory of Reasoned Action (TRA) [122] as well as corresponding motivational theories in Human-Computer-Interaction (HCI) like the Persuasion Theory (PT) [125]. Such theories interprets consumer's actions as an expression of their informed and conscious judgment aiming for utility maximization [178]. Wasteful behavior, in this view, is therefore caused by an information deficit. Hence, the major aim of eco-feedback is to bridge this gap by making the consumption behavior and its consequences visible.

The impact depends on many factors like whether the feedback is given at the right time, at the right place and if it is presented in the right form [123]. Concerning the representation issues like form, aesthetics, used metrics, frequency, granularity and comparison, optional user selections should be considered [123]. Also the feedback types vary from direct feedback (learning by looking) to inadvertent feedback (learning by association) [87].

However, just to feed back the consumption data is not enough, additional context information is needed so that users connect the rather abstract data to their domestic life [322]. For instance, more advanced eco-feedback could give advices about possible savings. Below, we want to show that room-context have a great potential to improve the eco-feedback at home.

9.2.2. Eco-Control

Eco-Control is defined as improving people's behavioral control of their consumption, making it easier to act pro-environmentally. It is shaped by the critique of rational choice theories and corresponding limitations of eco-feedback. A major critique of rational theories is that they neglect the bounded rationality of humans as well as that an intention behavior gap exists. In particular, studies shown that wasteful consumption often does not stem from a lack of knowledge or awareness, but turn the intention into action [88]. For instance, devices were not switched off, because the switches are difficult to reach and/or the process of switching off costs additional mental and physical power.

In reaction theoretical models like the Theory of Planned Behavior (TPB) [4] have been elaborated and extended in several ways e.g. by taking issues of perceived and actual control more seriously [88]. Perceived control is defined as the belief that one can influence the own environment to get desired outcomes. In contrast, actual control is defined as having the means within the situation to perform a task. In other words, perceived control presents a prerequisite, while actual control presents a necessity for action taken.

The substantial difference between eco-feedback and eco-control is that the former aims to motivate pro-environmental behavior, while the latter aims to make such behavior easy. In particular, the aim of eco-control is to increase the perceived and actual control of dwellers to cut down their consumption. While motivational factors addressed by eco-feedback have been relatively well-researched, only comparatively little reliable information is available on supporting control[5]. However, a general strategy is to provide and make aware of means to energy saving ready to hand. An example of a simple, but effective eco-control is a switchable multiple socket. Such a device makes it easier to switch off all devices e.g. when leaving the room or the house and thus fosters transition of this behavior into a sustainable habit.

In this paper we want to show that this kind of eco-control could be improved by mobile computing that provides direct, contextualized control options at the right time and place. Moreover, eco-feedback and eco-control could be improved, when both are united: While feedback increases the energy awareness and literacy hinting for potential savings, control options put the user in charge of managing the consumption in easy way [186].

9.2.3. Eco-Automation

Eco-Automation is defined as the computational control of devices and domestic consumers with the aim to reduce resource consumption. In the SID literature it is only rarely discussed, because at the first glance eco-automation seems to mean that humans are entirely left out of the loop. However, we argue that both the SID and Home Automation research would benefit, if we understood eco-automation as a part of an overall eco-support strategy.

For instance, one of the unsolved problems of eco-feedback and eco-control is that some kinds of eco-friendly behavior (like switching devices off to prevent stand-by consumption) called for investment of mental and physical efforts. In the case of everyday life, this often becomes boring and cumbersome, so that there is the risk that users revert to “bad” habits over time [363].

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[5] Also, persuasion theory [125] acknowledged that control is an important factor. However, and somehow surprisingly, persuasive eco-design mainly leaves the factor unattended.

Concerning this, studies show that eco-automation can lead to savings up to 30% [138]. In addition, they offer more comfort than unpleasant routines like switching the heating off when leaving the home, which could be delegated to the computer. Such delegation of disagreeable duties especially prevents a fallback into lazy habits, thus helping to sustain pro-environmental behavior. However, the challenge of eco-automation is not simply to just switch things off, but to do this when it makes sense [244].

Corollary, Mert and Tritthart found that consumers might fear losing control over automated devices [243]. Hence, automation should not be designed independently from feedback and the control mechanism. In particular, eco-automation should focus on those kinds of routines in which the users are in danger to revert to "bad" habits. Concerning this, the real skill in the design of eco-automation is to find a good mix of awareness mechanisms, user control and automation support to improve people's perceived control and self-efficacy [331].

In this paper, we want to show how this could be addressed by e.g. providing a rudimentary automation editor where the user could define rules that should be delegated to the computer. Here, room-context help to express automation rules that based on domestic activates (like switching the light and heating off, when leaving the home for more than 15 minutes).

9.2.4. Using Context in Eco Design

In general, context-aware computing is understood as the ability of an application "to discover and react to changes in the environment they are situated in" [318]. Dey et al. [92] distinguish between three kinds of context-aware systems: First, presenting context information and services to the user with the help of sensor information. For example, showing the user her current position through the placement of a marker on a map. Second, automatically executing services in reaction of a change of context. An example poses the car navigation system that calculates a new route when an exit has been missed. Third, attaching context information for later retrieval and use. Brown [43] also distinguishes three categories in a similar manner:

- Presenting information to the user
- Running a program
- Configuring the screen of the user

In Eco-design there are already a number of approaches to enrich consumption data with additional context information. For instance, Costanza et al. [75] have built an interactive feedback system, where users can add context-tags directly within the consumption feedback application. On the one side this allows a visual linkage of specific activities and energy consumption and on the other side new forms of visualizations are possible (e.g. event-centric/energy-centric forms of visualizations). Neustaedter et al. [260] use data from personal calendars to contextualize consumption data of users. Although many events and especially most of routine activities were not registered, it could be recognized that calendar entries can be used for the declaration of energy consumption (e.g. a house party explains high consumption, while eating in a restaurant would imply low consumption). Also, people's location at home helps to contextualize and individualize feedback. Jahn et al. [182] e.g. use the position of the user to present eco-information for the devices at hand. Guo et al. [150] use a RFID based check-in/check-out to get the position of dwellers to identify the individual consumption in a multi-person household.

9.3. Room as a context – a conceptual view

In previous empirical studies in a Living Lab we have explored how people make their energy consumption accountable and what kind of information they need for this [186, 321, 322]. In this research, we uncovered a need for flexibility as it became obvious that consumption and wasteful behavior have a high individual meaning for people. However, we also found common patterns regarding how such meaning was constructed e.g. by referring to domestic routines and actions as well as comparing devices, people and households. Especially room context (defined as users' presence in a specific room) turned out to be important information for the user to reconstruct activities in order to link consumption patterns to them. In the following, we conceptually outline how room context presentation can be used as useful resource in eco-support design.

9.3.1. Room as a domestic order for everyday activates

People live in homes and undertake activities and interact in this physical environment. Here, rooms have a special meaning when it comes to everyday-activities. Rooms often are decorated differently and serve a particular purpose. A room-structure specifies which activities are appropriate in it and what technology is available to carry them out [13]. For example, in the most cases cooking in the bedroom is unusual. Also, for architects, rooms are of central importance. The planning of electrical sockets is related to the intended use of the room and switches for lighting and heating are used to control devices on room-level. Additionally, switches for lights are usually attached next to the door such that when entering or leaving the room, one can switch on/off the required appliances.

In the 1990s, the concept of rooms gained high attention in the context of designing information and communication technology. In their investigation Harrison and Dourish [162] linked insights from architects and urban designers with their own studies to differentiate between space and place. Space, therefore, is a three-dimensional environment with objects and events that have relative positions and directions whereas places are spaces that are valued ("We are located in space, but we act in place" [162]).

9.3.2. Placing and spacing: A new view on domestic indoor location

The distinction between place- and space-oriented approaches leads to different requirements for locating in domestic environments. The major difference between common indoor localization solutions and room localization is that space-oriented approaches are relying on metric error measures, commonly defined by the distance between actual and estimated position. In opposite, place-oriented approaches rely on a quasi-topologic error measure defined by the ratio whether the actual room is estimated correctly or not. Figure 25 gives an example that good space accuracy does not necessarily imply good place accuracy. Yet, until we have specially optimized place-oriented localization techniques, existing space-oriented techniques could be used as a heuristic.

Concerning the various localization techniques, we principally can distinguish between four classes: The first group are so called beacon-based approaches that use proximity detection with short-range radio communication, for example RFID or NFC. Based on a globally unique identifier, e.g. a smartphone can look up the position of the beacon (e.g. [229]). But these approaches depend on additional hardware to locate the position of the user. The second group are geometry-based approaches estimating the position e.g. by triangulation and trilateration, determining positions from measurements of angle of arrival or distance between sender and receiver. The intersection of lines or radii respectively provides the current location (cf. [296]). One disadvantage is that conventional WiFi-routers are hardly suitable, because they either need special antennas allowing angle-measurement, or, for trilateration, a much more precise measure of distance that can be provided by electromagnetic waves. The third class of indoor-positioning approaches uses accelerometers and gyroscopes of a device to log the movement: speed and direction, starting from a given position to calculate a new position. Such dead reckoning techniques suffer from a fast increasing inaccuracy as small errors add up every step [345]. The fourth group is based on fingerprinting the signal strength of e.g. WiFi routers at different places. One disadvantage is that such a system must be trained beforehand [121]. Yet, it has the great advantage that existing router infrastructures in domestic settings could be reused for the positioning.

9.3.3. Understanding of energy consumption and energy wastage

The interplay between technology, places and activities can be used to classify energy consumption and thereby make wastage visible. Schwartz et al. [11] have demonstrated that dwellers distinguish energy consumption between consumption of background services (typically always-on devices like the refrigerator and freezer) and activity related consumption (like using a TV for watching television, light for reading, etc.). Generally, activity based consumption is closely related to the person's presence (respectively activities which in turn are related to places [13, 162]). Therefore, the actual place of habitants in their home is a strong indicator for energy being wasted (e.g. light in a room where no one is present is a waste of energy).

We use this heuristic by identifying the presence of users in the corresponding rooms to expand existing visualizations of eco-feedback systems and to create new forms of visualization to support the user in his sustainable practices. In the following sections we conceptually describe such a system.

9.3.4. Room-context aware feedback

We identified four, non-exhaustive, visualization categories where room-context information could help to make feedback more meaningful for the user:

- Analytic charts identifying spenders in the home
- Time series consumption graphs enriched by dwellers' presence information
- Person and domestic activity centered consumption visualization

- Domestic scoreboard systems

The room context information could therefore be used to identify spenders, which are defined as potential energy wasters. Analytic charts on device level allow making such spenders visible. For example, the device-level chart in Figure 24, left, shows that 21% are potential spending by splitting the overall consumption into consumption with presence and without. Such graphs help users to control their habit of switching devices off when not needed.

Further, presence information could be used to enrich time series consumption graphs in various ways. For instance, historic feedback graphs commonly show a curve of the device's consumption in a daily, weekly or monthly interval. Such graphs on a room level could be enriched by peoples' presence time in that room, e.g. by assigning a color to each dweller and coloring the graph's background accordingly for the time each person was in the room (see also in Figure 24 left, "week history"). Such graphs may make it easier for dwellers to identify consumption patterns and match them with their own behavior.

Figure 24. Using room-context information to enrich eco-feedback visualization (left) and to adapt home control interfaces (right)

The third improvment puts the focus on the user by showing the consumption of her immediate environment over time. For example, when walking through the apartment the user can see in which surrounding she has used the most energy. This person-centered visualization in combination with the previous one allows gaining new insights and surprising facts about one's own domestic energy practices. Last but not least, the room-context information could be used to define new indicators for domestic scoreboard systems like average room temperature when people are present and non-present. Further, this information could be used to personalize recommendations, tips, or statistics.

9.3.5. Room-context aware home control

In a further step, we explored, how room context information could be used to adapt home control panels. We have identified two categories, in which room-context can help to reduce the panel complexity and nudge people to switch off spenders:

- Adapt the control panel to the devices of the actual room
- Make aware about spenders outside the room

One of the current problems of control panels is the large number of switching options that can lead to a cluttered design. Architectures solve, for example, the problem of complex control panels by making use of rooms as a domestic order system: A room only includes the controls for the room. This is a smart choice as people most often are interested in controlling activity-related devices, which typically are in the person's current surrounding. Room context information helps to adopt this strategy by showing only controls of the actual room on the user interface. This radically simplifies the complexity of home control panels.

An exception to the rule above, are devices outside the room that have been forgotten to be switched off, e.g. because of laziness. To nudge people to switch off these devices, the control panel should make aware about these

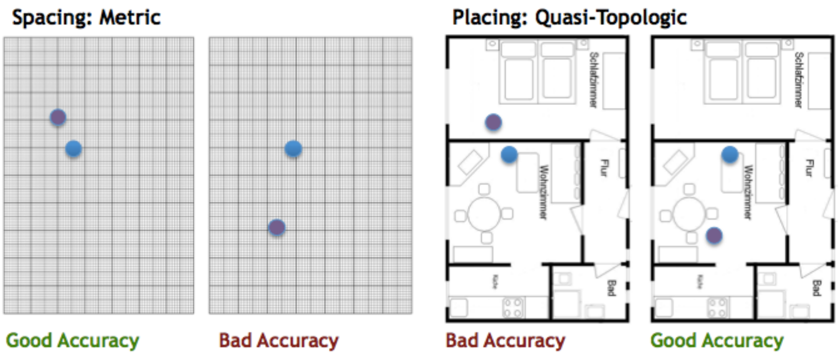

Figure 25. Difference between “space-oriented” and “place-oriented” localization

spending devices. Figure 24, right, presents our solution for this demand, where we split the control panel into two sections: The top section shows the controls in the current room. The bottom section shows the detected spenders outside the room. By focusing on the controls that are important in the current context, the panel is more structured and the number of switching options is greatly reduced.

9.3.6. Room-context aware home automation

As noted, some sort of consumption is linked to the presence of a person in a room, like the light in a room, the heating of a room or activity based consumption like watching TV or listening to the radio. In the previous section, we outlined how to use room-context to provide adapted control interface when people have forgotten to switch off such consumers when leaving the room. In addition to this, home automation could use this information to regulate and switch off these consumers directly without interrupting the user. The information could be used to create more sophisticated profiles of domestic behavior. Such patterns might be used by the heating regulation to decide which room should be heated and when.

However, because of the complexity of domestic life, one has to consider that the perceived control still remains at the dwellers. For example, by defining their own set of (room-context based) rules, such that users could decide which routines should be automatized and which ones should support contextualized feedback and control mechanisms.

9.4. Room as a context – realization of design implication

Based on our conceptual reflections, we have developed MyLocalEnergy, a fully functional prototype of a room-context aware home energy management system. Referring to eco-feedback, eco-control and eco-automation systems we demonstrate and discuss design implications, when using room as an additional contextual source.

Our prototype consists of a ZigBee-based multihop-measuring network (smart plugs) measuring consumption on socket (device) level, a raspberry pi running the energy middleware and an android device (cf. [321] for more details on this "traditional" part of our HEMS system).

The system was realized as a client-server architecture where the energy- and position-data is stored in a local database on the raspberry pi. The client was implemented as a native app for all kind of Android devices, however, it was optimized for Android Tablets.

The local architecture is further based on a three-tier layer concept with a data layer, a logic layer and a presentation layer (see Figure 26). The modularization allows that the representation of feedback can easily be changed and adapted to the context. In addition, the services provided by the logic layer could be used in other applications, as well. By the same token, the indoor positioning algorithm could be replaced with a better one without the need to change the presentation layer.

The data layer is responsible for storing all energy- and position-data in a database. The consumption data is linked with a timestamp to use it for direct feedback as well as for historic feedback and time series analysis.

As position data, the present room of the user is stored together with a timestamp. The positioning is mainly computed on the Android client, which tells the home server in which room the person actually is. We therefore use a fingerprinting approach based on available WiFi network signals as WiFi routers are available in most domestic environments and therefore no additional hardware is needed. Furthermore, a combination of multiple Received Signals Strengths (mRSS) provides relatively unique fingerprints.

Reducing the error rate can be handled by setting up additional WiFi AP. We also minimized the mentioned training problem by providing a user interface, where users iteratively can add, edit and delete multiple measurement points and assign them to a room. The users themselves can improve system accuracy by adding additional measurement points at places that are important from their perspective. We further implemented some filters that validate the results.

The logical layer mainly implements basic services concerning the actual and historic consumption as well as the actual and historic indoor position of the dwellers. It also provides an additional service to fuse or link both types of data, e.g. listing all devices in the current room, where the user is present. The location and the consumption services are independent from each other in order to ensure a good clarity and to be able to implement changes efficiently. The services of the logical layer are provided as web-services by a Tomcat webserver that runs on our low-power home server. The web-service allows that the presentation layer can run on the same home-server (e.g. as Java Server Pages) or remotely (implemented as native Android App).

This architecture allows the implementation of higher-level services for eco-feedback, control and automation as well as more sophisticated user interfaces. In the following we discuss this part of the HEMS in more detail.

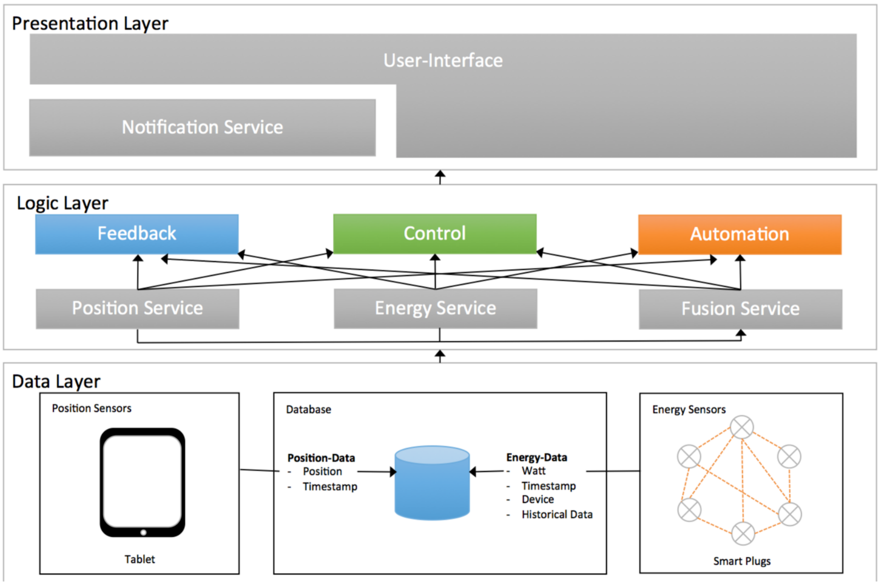

Figure 26. Simplified architecture of the context-HEMS system

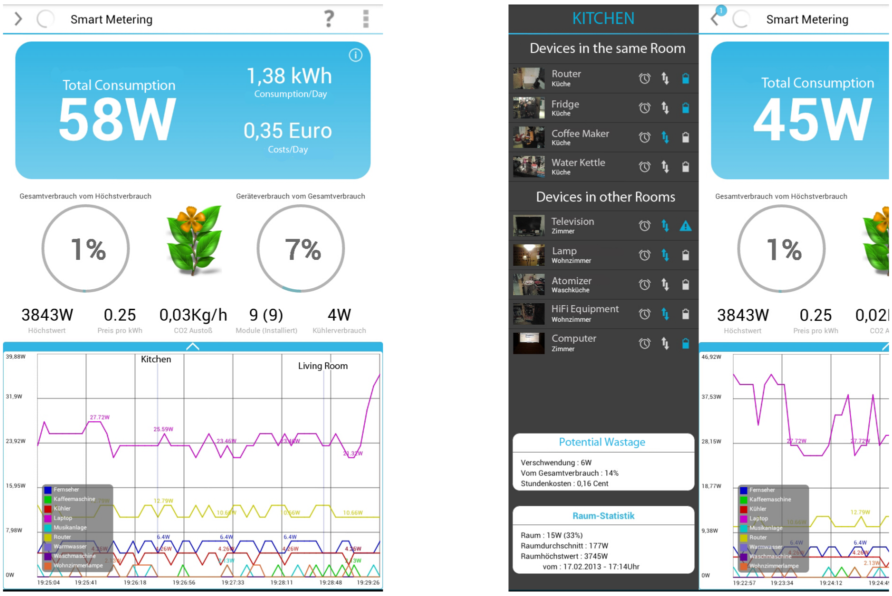

Figure 27. Visualization of the Prototype on an android tablet, partially translated (left: home screen, right: home screen with open control panel)

9.4.1. Contextualized Eco-Feedback

The most essential part of eco-feedback is to visualize the consumption so that it is meaningful and allows informed decision-making. Concerning this, we focused on how room-context helps to individualize and personalize the feedback. We further implemented various display options to address the heterogeneity among the users.

The main feedback element is a room-context aware time series consumption graph (see Figure 27 left) as a variant of the design concepts outlined above. The graph either displays current live consumption or historical values together with information about the users' presence. By default, the graph shows the live consumption of the devices defined in the system. Historical values, in a freely selectable period, can be shown in the graph as well. The graph helps to uncover relations between the personal behavior and the electricity consumption. E.g. the graph in Figure 27, left shows how the laptop of the user was awoken from sleep mode after he entered the room "Zimmer". As he was present in the room at the time of the consumption it can be assumed that this consumption is not "wastage".

We also use room context to adapt the screen of the user [43]. For instance, with information about the current room consumption, the share of total consumption, the average room consumption etc. The display also includes a room based "energy" flower as an ambient visualization, which changes the look depending on the consumption. It does not provide exact details, but provides emotionally perceived information [388].

9.4.2. Contextualized Eco-Control

We also realized some of the eco-control concepts. For instance, the system provides a context-adaptive display showing the home devices in two groups: The primary group includes all devices in the immediate environment of the user (room); the second includes all other devices (see Figure 27 right). This slightly differs from the concept outlined above as some of our users wanted to switch on devices in other rooms as well. This is why we decided to display more than the appliances in the room in this view. In addition to the names of the devices the list also includes additional information like the status (using/not using), remote-switch availability and some simple automation support. Users can switch devices on/off just by clicking on the corresponding item on the list. In particular, to ensure that users still get aware about spenders, they are marked with an extra symbol in the list. In addition, an Android application notification is sent to the user if a spender is detected. To persuade pro-environmental action, the notification includes a direct control element to switch the detected spender off.

9.4.3. Contextualize Eco-Automation

We also implement some rudimentary automation editor to define simple automation rules. Our goal was that malfunction (e.g. if position recognition is not accurate enough) does not lead to serious problems and users do not have the feeling that the perceived control is getting lost.

The editor allows the user to define which devices should be switched off when the house is left. This rule is executed only if the position service does not detect any room and the user was outside the range of his home wireless network. The additional condition was included to reduce the rate of false negatives (the system wrongly thinks that the user leaves the home) as they have more serious consequences than false positives.

In addition, a simple editor for a timer function is included, so that devices can be switched off at a particular time (e.g. switching off a VCR after recording the television program in order to save stand-by consumption).

9.5. Evaluation

We split our evaluation in a technical and a conceptual part concerning overall user experiences. For the technical evaluation of the position service we used a test routine asking the user at random selected points in time, whether the actual recognized room is correct or not. We have run this routine in two different households with three WiFi networks available and collected overall 29 measuring points in two days. We achieved a correctness of about 85%, which means that with an optimal establishment of the position service, a good accuracy could be achieved. The accuracy of the position determination, however, depends on the existing WiFi infrastructure and the structural conditions of the household. The WiFi networks should have sufficient signal strength and the routers should be placed in different corners and floors to get best results. The use of WiFi-extenders can distort the results, since in this case the distance to the router cannot be recognized. For the prototypical implementation, the position recognition is sufficiently accurate to examine the usefulness of the system in terms of supporting the user within a sustainable use of energy. We have not carried out a major technical evaluation, since the position determination is not the focus of this work.

We evaluated the user experience by conducting interviews and workshops with seven private living lab households [320] concerning the perceived usefulness and shortcomings using room-context to make the consumption feedback more meaningful and how such concepts should be realized. Overall, our participants appreciate the design concept and said that additional context information would help them to get a more profound understanding of their domestic consumption. Additionally, the participants agree, that their room-based position is an useful information, especially in the historical consideration of consumption data to inference on ineffective behavior. A further aspect that people regarded as practical was the better clarity provided by the distribution of the devices in the two categories in the control panel. Due to the fact that we measure up to 18 single devices for households, the usual control-panel becomes cluttered otherwise.

The people also noted that with an accurate detection of the position, some device could automatically be switched on or off, e.g. lamps. However, not all users wanted a system that would automatically switch devices on or off and “decrease” their control of an appliance. Another, point of criticism, among other detail improvements, was that participants could felt disturbed sometimes when they receive notifications after leaving a room with active devices to which they wanted to return soon again, e.g. when going to the kitchen to make a coffee.

People also expressed reservations concerning the opportunities to automatize particular routines by using context information. These reservations echoed the known control problem of home automation [243].

9.6. Discussion and Outlook

The first energy monitors simply fed back the more or less raw measured energy data. Today, real-time disaggregated consumption measurement is reality resulting to an explosion of data. Concerning this, major challenges in domestic settings regarding lowering the energy consumption are:

- How can we prevent an information overload given the vast amount of raw data?

- How can we make consumption feedback more meaningful for the users?

We contribute to this challenge by outlining the concept of room as a context and showing how it could be implemented. Studies on eco-feedback show that rooms have turned out to be useful for the user to support the detection of energy wastage. The aim of this paper was to demonstrate that this insight could be generalized by combining the concept of context-awareness [92] with the concept of eco-support concerning the different levels of feedback, control, and automation [232].

We think that room-context will not replace other approaches to contextualize eco-feedback in literature [75, 182, 260], but supplement them. For instance, room-context complements the device context and vice versa: When a user comes near a device, our room context-aware user interface could be adapted to a device context-aware one as outlined in [182].

In summary, this paper has outlined the potential of room-context aware HEMS. However, for the practical use several challenges have to be coped with, which we will address in our further research: Firstly, the practical value of the room-concept must be studied under realistic conditions with a larger sample and in long term. Secondly, while people most often take their smartphone and maybe their tablet with them when leaving home, they might leave devices on a desk, a sideboard, etc. when they being at home. Concerning this, future smartwatch based positioning services have great potential. Thirdly, we are aware that our solution is implicitly optimized for single households. Hence, in future we have to investigate how multi-person households adopt such design concepts and if, in which way the concepts must be extended

III. Research Outcome

10. Conclusion

As outlined at the beginning of this thesis, the IoT and the IIoT cover a wide range of application areas, ranging from smart homes to smart factories, and increasingly crossing established boundaries and contexts (such as those between work and home). This new technology is also characterized by exponential growth of data that is collected, networked, processed, and stored at both local and global levels. This exponential growth provides rich opportunities to increase personal and business intelligence. However, these heterogeneous, context- and boundary-spanning properties lead to challenges with regard to data maintenance, infrastructure management, data integration, and the like, where possibilities for fully automated analysis are limited. Therefore, it is a great challenge to empower end-users to extract valuable information from the mass of data without the help of expert data analysts [334].

This thesis contributes to HCI and CSCW research in the areas of data-centered IoT and IIoT technology appropriation and digital data work for end-users. In addition, it has shown how people make digital data accountable in their daily lives in different contexts (in the domestic context and in the industrial context). This thesis has also outlined a reference implementation of a system design for end-user data work in the context of IoT and IIoT systems that helps users to make use of their data by means of tailorable information visualizations and analysis.

Using a practice-based approach in both contexts, Part II.I (the industrial context) and Part II.II (the domestic context) helped to frame the design problem for a user-centered IoT and IIoT and to answer the research questions mentioned at the beginning of this thesis:

Q1) *IoT and IIoT in the wild: How do users set up, use, and appropriate current IoT and IIoT systems in different contexts and what are their data-driven needs?*

Q2) *Using digital data: What are the requirements for a data work environment and how can digital data be made accountable for end-users?*

Q3) *Designing for end-user data work for the IoT and IIoT: How may an end-user centered tool that enables end-user data work be conceived and designed?*

Regarding Q1, this thesis has identified several challenges, which, due to a far-reaching integration of new digital technology into everyday life, lead to increased complexity in the entire process, from setting up to use. In addition, the studies conducted reveal a great diversity of information needs, which depend on individual factors (own experiences, knowledge, and interests), contextual circumstances (personal and professional), and responsibilities (powers or roles), as well as volatility as needs change or only arise at short notice (see Subsections 10.1.1 and 10.1.2).

Regarding Q2, the studies conducted showed a number of requirements and best practices for the visualization of data and for the activities that play a role in (collaborative) data work. It was recognized that data work is not always a direct method for finding a solution and that it is also a process for explorative data analysis. This requires fast mapping to different forms of visual representation, integration into the personal contexts, and thus the adapting of one’s own understanding, as well as the possibility of sharing and jointly developing an understanding (see Subsections 10.1.3 and 10.1.4).

Regarding Q3, addressing Q1 and Q2 resulted in the collection of different content and functional requirements in order to take this complexity into account when designing end-user data work systems. From these insights, a concept was developed and implemented that focuses on end-user data work in the context of IoT and IIoT systems, thereby helping users to explore their data by means of tailorable information visualizations and analysis. Concepts from EUD were combined with approaches from the information visualization community to enable users without a technical background or a background in the field of data analysis to work intuitively and easily with their data (see Subsection 10.1.5).[6]

This thesis, therefore, contributes to the current state of research on the IoT and IIoT by showing that a central architectural requirement for digital tools is e.g. highly flexible data access layers that allow the integration of existing systems and (external) data sources. Furthermore, IoT tools require flexible modules that allow tailoring and the functionality to freely explore the available data and thereby support routine data work tasks as well as in-depth reasoning for nonexperts that takes users' mental model into account. Additionally, by adopting concepts of EUD and information visualization, this thesis contributes to these research areas by adapting best practices to the fields of the IoT and the IIoT in order to engage in end-user data work and thus for users to make better use of their IoT and IIoT systems.

10.1. Summary of Findings

The design case studies described in Chapters 4-9 led to a multiplicity of findings that can be summarized in five categories (which are partly inspired by the data work steps of Fischer et al. [120]): 1. installation and integration of IoT and IIoT technology; 2. individual information needs and contextual influence; 3. visualizing IoT and IIoT data; 4. requirements for a user-centered IoT and IIoT; and 5. developing tools for end-user data work with IoT and IIoT data.

10.1.1. Installation and integration of IoT and IIoT technology

A purely technical installation (which is also an important part of the new challenges [9, 168, 328]) focuses on technology, location, and/or network

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[6] The resulting tool was also published as open-source software on GitHub.

infrastructures. However, IoT and IIoT technology constitutes a socio-technical system that influences everyday life and practices [357] in both domestic and industrial contexts. Therefore, one can speak of integration [357] and appropriation [338] rather than pure (technical) installation.

For instance, this thesis has shown that the installation of sensors and the process of setting up IoT devices in the domestic context is not a trivial task (see Chapter 8). This had already been recognized in earlier studies [38, 355, 357]. In addition, the new promises of plug-and-play sensor technology remain challenging for users, and even experts have problems with the installation [355]. In the industrial context, the study presented identifies new challenges as well as familiar ones in the process of installation and setting up of digital IIoT sensors (see Chapter 4). Currently, there are no other existing studies that deal with these challenges for the industrial context in detail.

In both contexts (see Chapters 4 and 8), it could be seen that it is difficult for end-users to map future requirements to the necessary technology [259]. Mapping future requirements requires a combination of technological knowledge, technological understanding, and context knowledge, which end-users often do not have in their entirety. It has been shown that end-users can generally conceive of at least a sketchy idea of possible areas of application or of their motivations for using digital technology; however, they are then unable to implement their ideas, for example, due to the limits of existing sensors. Otherwise, data is often collected without a use-case or even a context, with the result that the data have no value for end-users [219].

In the domestic context, this thesis confirms previous findings [355] to the effect that, in the process of introducing digital technology, social aspects have to be taken into account. In the course of preparatory work, the various needs of all stakeholders should therefore be identified at an early stage so that the introduction of the digital technology can be planned and implemented accordingly.

Chapter 4 shows that this necessity holds in the industrial context too. Moreover, the thesis has shown that the social context is shaped by the organisational structure. Regarding this matter, possible use cases for a digital technology are quite different among employees and organizational units, which leads to different requirements for the necessary infrastructure.

The SmartLive projects has shown that the device aesthetic is an important factor within the domestic environment as the physical IoT infrastructure must fit with the domestic interior design. In contrast, in the industrial context, people do not emphasize aesthetics in the selection of sensors or in relation to their location; however, there is a stronger focus on integration with other systems.

Existing electrical and IT infrastructures, various defined processes and guidelines, as well as the partial local separation within a company make the installation and introduction of digital technology there much more complex than in domestic environments. This requires not only a purely technical understanding but also expertise in other areas (e.g. that concerning existing infrastructures and systems), which cannot be guaranteed by one person alone (see Chapter 4).

This socio-technical complexity requires more effort and greater requirements for the preparatory work than in the domestic context. In particular, communication between the various actors involved should be ensured at an early stage so that implementation is not viewed in isolation at each level (electrical, information technology, application technology; see Chapter 4).

10.1.2. Individual information needs and contextual influence

The design case studies uncovered various information and adaption needs of end-users, how they are motivated, how they change over time, and what circumstances influence the needs (see Chapters 4, 5, 6, 7, 8 and 9).

In general, this thesis has shown that information needs vary from user to user because they are often very personally motivated and arise from their knowledge and experience [46, 75, 165]. Hence, a one-size-fits-all approach does not work; solutions must be tailorable [249]. As pinpointed by the tailoring dilemma [103], not everything can be made tailorable, otherwise tailoring options would become too complex. Fortunately, the thesis has uncovered various patterns in the information needs and the practice of adaptation that provide a starting point for usable tailorability design. In the domestic context, the motivation was often to increase comfort (e.g. preheating the apartment), control (e.g. whether everything was switched off), or was economic (e.g. money savings by increasing energy efficiency). Here, people obtain a personal benefit from the information (see Chapters 7, 8 and 9). In the industrial context, information was often used to increase entrepreneurial success or to increase the efficiency of the company; therefore, information demands were mostly influenced by external factors [34]. The need for information typically depends on the role and position of the employee within the organization, but also on individual experience and knowledge. The studies (see Chapters 5 and 6) reveal that people in the same department may have very different needs but that these needs are strongly oriented to their working practices [384]. To make-use-of-data, the users need support in the parametrization of machines or as a first indicator of the quality of the produced goods (see Chapters 4, 5 and 6).

Another phenomenon that could be identified in both contexts was the change of information needs over time due to the increasing experience of users in the handling of their data. Initially, the main interest concerned learning and building trust in the procedures and gaining knowledge about the data and how it could be analyzed. Completely new requirements arose for new application areas or when existing requirements were no longer of interest because the information already gained may have been enough to have “solved” certain use cases in the long term. An example of this is the consideration of electricity consumption - after some time, users know how much electricity their television, for example, consumes, so that this information no longer needs to be constantly available to them (see Chapters 4 and 8).

A further aspect identified in the studies was the influence of the current environment and context on the requirements of the users. This is closely related to the different interests of people in different situations. For example, when on holiday, different information was important for users than when they were at home, for example, safety instead of comfort, or in terms of seasonal effects, where, for example, heating conditions are of greater interest in the winter months (see Chapter 8).

Another finding relating to data needs was the distinction between long-term needs and short-term needs. In the studies, it was recognized that there are requirements for long-term consideration (e.g. temperature curves or energy consumption), which are used, for example, for daily decisions. On the other hand, there are also one-time or short-term requirements, for example, if the energy bill or an audit is due, special data would be required (see Chapters 6 and 8).

In both contexts, several quite concrete data requirements and requirements for the handling and visualizing of the data were identified. A basic requirement for example in both contexts were to check whether values fell below a certain limit or exceeded a certain limit (i.e. threshold control), in addition to the change of values over time (see Chapters 5 and 8). The linking of different data was another general requirement of the users. It was also recognized that linking data (especially with context data) can produce new information to actively support the user to make informed decisions (see Chapter 9). Especially due to the novelty of the technology and its potential influence on everyday activities, a certain plausibility or functional check was also of interest. Therefore, it would be of interest to ascertain whether the system still worked and whether the data that were provided were valid and correct (see Chapters 4 and 8).

The requirements identified in the studies have shown that there are many overlaps between the two contexts (industrial and domestic), particularly with regard to the handling of digital data and the operations to be applied to the data. This reveals that EUD data work could benefit from a common basis, independent of context, to enable users to work with their digital data. Concrete needs can then be determined by the environment, tasks, practices, processes, and situations.

10.1.3. How to visualize IoT and IIoT data

The visualization of data is quite a complex matter. This complexity is increased by the fact that information needs constantly change, as has been shown in this thesis. In the studies conducted (see Chapters 4, 5, 6, 7, 8 and 9), various procedures for selecting appropriate visualizations and for the design of these visualizations were identified and evaluated.

Several approaches exist within the literature for the visualization of digital data. Chapter 7 shows in an exemplary manner how the data for eco-feedback can be systematically prepared and visualized for the domestic context. Based on a literature survey, a design taxonomy was developed. This taxonomy consists of five factors: study goal, design strategies, data source, output media, and visual forms. The literature survey (see Chapters 7) and the other studies conducted have shown that these dimensions influence how data should be presented. Especially the study goal, which should be attained by means of the visualization, has a strong influence on the way data should be presented. Line and bar charts are often used for monitoring time-based data because they represent an exact temporal pattern. For playful or ambient approaches, where the focus is not on the exact data, an abstract representation is suitable. Comparisons are often represented by means of simple numerical values as these require little interpretation effort.

Therefore, the most important factors are the task to be solved by the data and the characteristics of the data (see Chapters 6 and 7). There are already a large number of concrete process models for selecting suitable visualizations by using data and tasks, for example, by Aigner et al. [3]. Here the data characteristics are defined by different questions (e.g. whether seasonalities are present in the data or whether the data are quantifiable). This ensures that data are correctly visualized later and that no blurred representations occur. For defining the task, the task model of Andrienko and Andrienko [7] is well suited because it is a low-level task model focusing on data tasks. Here, a distinction is made between concrete data-related questions (e.g. the exploration of data or finding patterns and trends). By means of these factors' exact characteristics for the necessary visualization can be determined and thus a suitable selection can be made (see Chapter 6). This allows the determining, on the one hand, of what the focus should be (e.g. spatial factors, seasonal factors, or trends) and, on the other, which visualizations can correctly display the data.

Once a suitable visualization of the digital data has been identified (e.g. charts, key performance indicators, maps or tables), it must still be appropriately designed. At first, the general design guidelines from the literature apply, such as the information visualization mantra: "overview first, zoom and filter, then details on demand" [326]; this was also identified in the studies (see Chapters 5, 6, 7 and 8). In addition, further design requirements could be identified. The time between information processing and subsequent action, for example, determines the information density of the visualization (e.g. in operational activities in companies, simpler visualizations are needed and in the strategic area, where there is more time for interpretation, more information can be provided in one visualization; see Chapter 6). A special aspect that is mainly a result of the constant development of IoT and IIoT technology, especially the continuous and near real-time acquisition of digital data, is the display of live data. Here, the understanding of a "normal" state [42], which is sometimes very subjective, should be able to be grasped quickly. Otherwise, this necessitates further analysis. In addition, only changes should be made visible in order to attract attention in the event of deviations.

10.1.4. System requirements for a user-centered IoT and IIoT

In spite of all the differences (between the industural and domestic context) in relation to skills, motivation, social context, tools, and technologies, general requirements for an EUD infrastructure could be identified to support the data work of end-users.

First of all, a system is needed that lets users customize and tailor it to focus on the data of greatest interest. Furthermore, it is necessary to let users quickly and easily change the focus of the data (see Chapters 6 and 8). The studies also identified various functional needs that are necessary for users to be able to undertake all data work tasks using the tool and thus harness the full potential of the data.

For instance, in both contexts, the studies show that end-users need support for explorative, playful data work that often leads to surprising insights, helping to build trust in the system and gaining knowledge on how the system works. In the exploration of the data, it became clear that users make use of their local knowledge and experience for the purpose of analysis. In this regard, the studies have shown that there is a great need to map data to different visual representations, for example, on a line chart, on a heatmap, or on a spider chart to find links between working practices and the data. Here, users compared data from different sensors, systems, or from different periods. This was especially relevant in the industrial context in which users tried to understand complex (production) processes. For this purpose, the various data had to be displayed flexibly and had to be comparable. This means that both flexible time views and statistical methods had to be available at an aggregated as well as at a fine-grained level [14, 325] (see Chapters 6 and 8).

In addition, as a part of the sense-making process, users adjust pre-defined visualizations to the personal meanings. Users have their own, and often very personal, understanding of their situated practices and their context (see Chapters 4 and 8). While, technically, sensors are devices in their own right, from a user's point-of-view, sensors serve as a medium to monitor an object-of-interest. For example, the consumption sensor, which is used to measure the electricity consumption of the television, is not understood as an extra device. Instead, users linked the sensor data directly to the television, so that the data was not sourced from the sensor but from the television. In the interviews, they also referred to the data as the television data. The requirements that arise here are the consideration of this individual understanding for the design of such a system. Users should be able to map their understanding in the system so that the designations also correspond to their practices and personal points of view (see Chapters 6 and 8).

Concerning data visualization, the studies have shown that mobile devices have become an important factor for viewing digital data. Considering the situations in which mobile devices are used, it could be seen that they are often used on the road and especially in situations in which the persona is waiting (see Chapter 7 and [209]). This implies that visualization frameworks should consider also mobile devices with small displays and the particular information needs relating to the different mobile contexts (see Chapter 8).

As shown in the literature, sense-making of digital data is also a very collaborative process, for example, between users and experts [119] or between users themselves [282]. This result is confirmed in this thesis (see Chapter 6). In addition, the case studies uncovered practices of peer-learning that are related to the one described by Draxler et al. [104]: Experienced users were familiar with the use of digital data and used the systems more efficiently and were furthermore able to quickly identify new use-cases (see Chapter 8) and less techy-safe users adopted the ideas and solutions of the more experienced ones. Especially in workshops, where different users meet, approaches such as over-the-shoulder learning [362] could be identified - inexperienced users observed how experienced users proceed and work with the data (see Chapter 8). In addition, there were situations where the data acted as a “ticket-to-talk” [349] (see Chapter 6). Overall, data and data views were often used as a basis for discussion or as a tool to explain states of affairs, to form a common consensus, or as a tool to support common work.

These processes should be supported so that people can also use these factors in their work.

Another important requirement identified in both contexts was the integration of data from different sources in order to link and compare them (see Chapters 5, 6, 7, 8 and 9). This allows the user to identify and understand relationships between different data (e.g. the relationship between the temperature outside and product quality - see Chapter 5). In particular, the integration of contextual information may provide additional information in relation to other data (see Chapter 9). One approach to support these practices is single unified interfaces, especially dashboards, in which different data are combined in one system [116]. In addition to the dashboard approach, where the data is shown in different charts, end-users should be able to visualize the data as different layers in one chart.

10.1.5. Developing a tool for end-user data work

Based on the findings of the various studies in both contexts, a flexible and highly customizable design framework was developed as a proof of concept for analyzing and visualizing IoT and IIoT data (see Chapters 6 and 8). The framework is called open.DASH and it is a web-based open source project. The goal of open.DASH is to support end-user data work and data appropriation in different contexts.

It based on a dashboard metaphor that allows people to freely adjust their view (by quickly moving, resizing, adding, and deleting widgets). In addition, it is possible for a user to create different dashboards (see Chapters 6 and 8); the selection of the current dashboard is stored in the local storage of the browser. This makes it possible for mobile devices, such as smartphones or tablets, to create own data views, which are automatically opened again after a one-time setup.

(i) Allowing consolidation of data across system boundaries

open.DASH was developed using current web technologies so as to lower the burden for end-users to install it. In addition, end-users can access their data and the implemented functionalities independent of the device.

The software architecture was based on mobile code concept: Dev-ops have only to maintain one central server, where the code is hosted, though the code is executed in the browser of the end-user and thus the computing power of the client computer is used. Since the data queries are also performed by the client, additional security mechanisms can be implemented in the backend to guarantee that the user can only query the data he or she is allowed to see.

Although open.DASH is a pure frontend application, it also has a three-layer architecture consisting of model, view, and controller in order to be able to address all acquisition, abstract and processing requirements. This offers the possibility of implementing one's own data adapter layers, which allows the integration of different (web-based) data sources and the consolidation of the data into a uniform format. Thus, it can be used as a system of systems, uniting different IoT and IIoT technologies in a uniform interface (in the sense of Few [116]) (see Chapters 6 and 8).

open.DASH additionally has an abstraction layer to connect to a user management system in order to manage access rights and access permissions. In combination with a user backend, further functions are also possible (see Chapter 6).

(ii) Consider the contextual understanding of the user and fit the data for the user's needs

As mentioned above, it is important that users understand what data came from which source to make sense of it. The system supports this mapping as it allows users to inspect the context of the data and the metadata provided by the data source (see Chapter 6). Therefore, the initial metadata of IoT/IIoT sensors, which is often based on a technical vocabulary, can be changed to match users' understanding. In addition, there are often context-specific vocabularies that are important for the end-user, for example, whether it is the living room television or the one in the bedroom. As those vocabularies may be different for each user, even when they are talking about the same device, it is important that users can give data sources a name that is meaningful to them.

Another issue relates to the level of aggregation. Sensors often output data at intervals that are not appropriate for the purposes of the user. Particularly in the industrial context, there are different requirements for aggregation and the way in which aggregation is calculated (see Chapters 4, 5 and 6). At the operational level, for example, fine-grained data are required for some tasks and, at the strategic level, more aggregated data are needed.

To obtain the necessary data in the right form or at the right level, open.DASH introduces the concept of "virtual sensors." This concept allows end-users to apply a set of arithmetic operations to the raw data and thus create a new "virtual" sensor or data source. Thus, it is possible to change data, for example, to a temporarily higher aggregation level (e.g. data become summed to hourly values or only an average value per 15 minutes is given). In addition, values can also be linked in order to form key performance indicators directly, if necessary, so that users can work with their data in any form they need.

(iii) Support data visualizations

One of the most important tasks of data workers is to specify how data points are mapped to visual representations. As it was seen in the studies, there is no general way to fit all user needs in the right data visualization. Therefore, open.DASH uses a dual approach where low-level overview widgets exist (as pre-defined widgets), and there is an assistant to provide users with the option of creating their own personal visualizations in an EUD manner. Due to the resulting flexibility, it is possible to address individual requirements even when they change as well as one-time demands. Using the virtual sensors presented, completely individual new content can be created and adapted to the context of use.

Pre-defined visualizations

Pre-defined widgets can be dynamically added from a widget catalogue. In the first draft of open.DASH, multiple generic widgets that were inspired by information visualization literature for standard data work requirements as well as for use cases from the conducted studies (see Chapters 6 and 8) were included. This included for example the exploration of data (e.g. historical line charts), the analysis of data (e.g. seasonal effects in a heatmap) and validation through data (e.g. pattern recognition in overlapping lines). Additionally, special display formats were developed for typical applications in the smart home (see Chapter 8) or energy management (see Chapter 6) areas. The development of the pre-defined visualizations was steered by the visual information-seeking mantra [326] to first provide an overview of the related topics and then filtering and details on demand.

The main goal of these pre-defined visualizations is to provide a first insight into different sensor values to obtain a first impression and an overview to ascertain whether everything is "normal." The pre-defined visualizations include live-monitoring charts for the real-time observation of value changes; widgets for building key performance indicators, such as for a timely comparison of sensor values; and widgets for identifying irregular data patterns or for finding seasonal effects in data. In a next step, end-users can then configure the pre-defined visualizations for different data sources and time periods and customize these to suit their individual preferences.

End-user development visualization tool

For individual questions and because of the need for simple possibilities to freely explore and map data [326], an EUD environment was integrated to create custom visualizations. Based on best practices from the literature, a guided step-by-step creation mechanism was realized that provides simple click/touch interactions instead of more complex operations such as drag and drop [90]. This assistant is integrated into the dashboard in order to decrease the cognitive load between using and adapting [223].

Following the visualization pipeline by Card [52], the visualization creation process consists of five-steps: 1. selecting the data (data analysis), 2. selecting the time (filtering), 3. selecting the chart, 4. configuration (mapping), and 5. adaption (rendering).

The first step is to select which data should be visualized. The user can choose one or many devices and sensors from the list of included data sources. As a second step, the user can choose between an absolute timespan (e.g. for the exploration of a specific billing period) or a relative timespan (e.g. the last four months). As a next step, the user can select how the data should be visualized. A pre-selection is automatically made regarding which visualizations are suitable for the selection. The fourth step allows the configuration for the selected chart type, for example, whether data should be mapped on lines, points, and so forth on a timeline chart. Following these steps, the user receives a preview of the chart where interactions such as zooming, selecting, or hovering over points to access a tooltip with information is possible. This step mainly supports task-driven adjustments, for example, for localizing or identifying data [358]. Then the user can configure the interaction or layout of the chart (e.g. changing animation settings and allowing/disallowing zoom) and decide whether the chart should be added to the dashboard.

(iv) Supporting sharing context

As the studies have shown, joint sense-making and collaborative work are of great importance, especially for knowledge-sharing (see Chapters 6 and 8). Users can create shared dashboards so that multiple people can jointly create their own data views and visualizations. This can serve as a basis for developing a common understanding [104] or new users can benefit from the experiences of expert users [376], in the sense of "over-the-shoulder" learning [362].

It is also possible to share the configurations of individual visualizations or entire dashboard compilations. Thus, for example, experienced users can help new users to implement possible requirements [104] or provide solutions for general tasks, which can then be applied by each user to his or her own database.

Since anomalies detected in the data often served as a "ticket-to-talk" [349], the option to comment on and share screenshots of created visualizations was also implemented. These can also be used as examples for the training of new employees in order to show, in an exemplary manner, which characteristics require attention in the data courses.

10.2. Outlook and Conclusion

This thesis has shown that there is the potential to support end-user data work, but also that the complexity and the diversity of contexts, knowledge, experience, and logical skills are challenging. Several findings of this thesis confirm findings from the related literature and draw new connections between different research areas, such as data work, EUD, information visualization, sustainable interaction design, smart home research, human-computer interaction and computer-supported cooperative work. Such synthesis is promising for understanding and designing data work in the wild.

Nevertheless, the aim of this thesis was not to provide a general solution or a general concept, but rather to examine the possibilities to integrate people into the IoT and the IIoT and support them with tools to use and work with data within their daily life. Concepts such as EUD and data work do not replace data science experts, but nonprofessional data workers certainly bring their *own* expertise and unique domain knowledge to the process. Here, EUD aims to empower non- and semiprofessional users to transform IoT and IIoT data into information that is meaningful for them in their specific context.

As lessons learned, the following implications for design can be derived:

- Allow users to define their own abstraction of raw data: Users should be able to add their own contextual understanding to the system in order to be able to use their knowledge optimally in an understandable environment.
- Give users tools, not solutions: Data systems should not be static but must allow users to work freely with data in order to discover unanticipated potential for their daily live and to increase

transparency. Therefore, the system should serve as a toolbox rather than a fixed solution.

- Support distributed cognition and peer-learning via sharing: In order to promote collaborative data work, knowledge transfer, and common context understanding, sharing concepts must be provided through which users can share content, analyses, and configurations to create the basis for a common understanding and exchange.
- Bring together data and contextual expertise: Systems need to allow domain experts to easily and freely combine data and analytical tools as certain insights become visible only through continuous data work with background knowledge on how and why the data were generated.

This insight is not the end but is rather the beginning of research on end-user data work. In particular, there is minimal knowledge of the impact of end-user data work in practice. Hence, further long-term studies should be conducted focusing on the impact on habits, activities, and practice.

In future, it will be necessary also to explore other IoT and IIoT contexts, such as smart cars, smart health, or smart supply chains to validate the presented findings. Such research will allow even further insights into the impact of increasing digitalization of everyday life and work. Furthermore, the developed prototype, open.DASH, can be used as the basis for research through design activities in other areas. This will allow researchers to feed back opportunities for this technology and for the consideration of wicked problems [396].

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