Designing Data Interactions for Sustainable Consumption

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DOI (link to publication from Publisher):
10.54337/aau617105772

Publication date:
2023

Document Version
Publisher's PDF, also known as Version of record

DESIGNING DATA INTERACTIONS FOR SUSTAINABLE CONSUMPTION

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DISSERTATION SUBMITTED 2023

AALBORG UNIVERSITY
DENMARK

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UNIVERSITY

Dissertation Submitted September 2023

Dissertation submitted: August 2023

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Department: Department of Computer Science

ISSN (online): 2446-1628
ISBN (online): 978-87-7573-642-3

Published by:
Aalborg University Press
Kroghstræde 3
DK – 9220 Aalborg Ø
Phone: +45 99407140
aauf@forlag.aau.dk
forlag.aau.dk

Printed in Denmark by Stibo Complete, 2023

ENGLISH SUMMARY

When we think about sustainability and sustainability issues, we most often think with and through data. To a large degree, data is used to steer consumption and production patterns towards more sustainable patterns. In Human-Computer Interaction (HCI) research, the most common approach to achieving this has been through eco-feedback and persuasive technology. However, the acknowledgement that people are not rational agents who change their behaviour in predictable ways, has led to calls for alternative approaches. I present an approach that seeks to *represent data with people* in order to foster sense-making about, and engagement in, sustainable consumption.

This dissertation has provided empirical understandings and design considerations for researchers and designers of data interactions for sustainable consumption based on a collection of six research papers. In addition to six paper contributions, the dissertation contributes a framework for characterising data interactions for sustainable consumption in HCI. On the basis of investigations, the dissertation presents three main findings.

First, understanding sustainable consumption from a data interaction perspective is a process of sense-making that can be supported by active engagement. Instead of seeking to remove ambiguity in sustainability data, I argue that fostering ways to engage in this ambiguity can result in more meaningful understandings of data and sustainability issues.

Second, the form of data (i.e., digital or physical) plays a large role in how people use the data in sense-making processes. Digital data for sustainable consumption is often more precise and exhaustive than data in physical form; however, it does not foster engagement as it is often represented through interfaces with low operationality and ambiguity tends to be hidden through interfaces that represent digital data. Physical data interactions, on the other hand, can be an alternative to digital data interactions for sense-making processes as they allow people to 'stay in the interactions'.

Third, traditional data representation can benefit from complementary approaches that focus on embodying and reifying of data through physicality. Embodied data interactions has been shown to bring forth affective and relational stances to sustainability issues. I highlight two design considerations for embodied data interactions: (1) the use of material narratives in data and (2) finding ways to bring future trouble of sustainability issues into the present. Reifying data through physicalisation has been shown to support sense-making towards understanding and/or changing consumption patterns. I present three design considerations that can support the reification of data: (1) making physical data representations interactive so that people can grapple with data, (2) allowing for active perception, e.g. movement around physical data representations, and (3) facilitating participation in data.

DANSK RESUME

Når vi tænker på bæredygtighed og bæredygtighedsproblemer, tænker vi for det meste med data. Data bruges i stor udstrækning til at styre forbrug og produktion henimod mere bæredygtighed. Inden for Human-Computer-Interaction (HCI) forskning er den mest almindelige tilgang til dette eco-feedback og persuasive technology. Dog har erkendelsen af, at mennesker ikke er rationelle væsener, der ændrer adfærd på forudsigelige måder, medført opfordringer om alternative tilgange. Jeg præsenterer en tilgang, der *repræsenterer data med mennesker* for at fremme meningsskabelse omkring og engagement i bæredygtigt forbrug.

Denne afhandling har resulteret i empiriske forståelser og designovervejelser for forskere og designere af data-interaktioner for bæredygtigt forbrug baseret på en samling af seks forskningsartikler. Ud over de seks artikler bidrager afhandlingen med et framework, der karakteriserer data-interaktioner for bæredygtigt forbrug inden for HCI. På baggrund af de empiriske undersøgelser præsenterer afhandlingen tre primære fund.

Forståelse af bæredygtigt forbrug, fra et data-interaktionsperspektiv, er en meningsskabelsesproces, der kan understøttes af aktivt engagement. I stedet for at forsøge at fjerne usikkerhed og tvetydighed i data, så argumenterer jeg for at skabe måder at engagere folk i disse, da det kan skabe mere meningsfulde forståelser af data og bæredygtighedsproblemer.

Hvorvidt data optræder i digital eller fysisk form, spiller en stor rolle i hvordan folk bruger disse data i meningsskabelsesprocesser. Digital data for bæredygtigt forbrug er ofte mere præcise og omfattende end data i fysisk form; men digital data fordrer ikke engagement, da det ofte er repræsenteret i brugergrænseflader med lav operationalitet, og tvetydigheden i dataen er ofte gemt i brugergrænseflader, der repræsenterer data i digital form. På den anden side kan fysiske data-interaktioner være et alternativ til digitale data-interaktioner med henblik på meningsskabelse, da de medvirker til at man kan 'blive i interaktionen'.

Traditionel data-repræsentation kan drage fordel af tilgange, der fokuserer på legemliggørelse og tingsliggørelse af data gennem fysisk form. Legemliggørelse af data har vist sig at frembringe følelsesmæssige og relationelle standpunkter til bæredygtighedsproblemer. Jeg fremhæver to designovervejelser for legemliggørelse af data: (1) brugen af materielle narrativer omkring data og (2) at finde måder at bringe fremtidige bæredygtighedsproblemer ind i nutiden. Tingsliggørelse af data gennem fysisk repræsentation har vist at støtte meningsskabelse for at forstå og/eller ændre forbrugsmønstre. Jeg præsenterer tre designovervejelser, der kan støtte tingsliggørelsen af data: (1) at gøre fysiske data repræsentationer interaktive, så folk kan arbejde med data, (2) at tillade aktiv perception, f.eks. bevægelse omkring fysiske data repræsentationer og (3) at facilitere deltagelse i data repræsentationer.

ACKNOWLEDGEMENTS

Although the resulting text from my three years of work only has one name on it, there are a lot of people who have contributed to making this accomplishment possible, insightful and joyful.

First, I want to thank my fiance, Martina, for always being there, lifting me up and keeping me grounded. You have listened to so many of my rants during these three years and always remained curious and supportive. I am so happy that I have you to bounce off ideas, share important moments, and process difficulties with.

I would also like to thank my family, my mother and my brother, and my friends for your continued support. Especially, my two dear friends, Lasse and Ida, for being there when support was most needed towards the end of the one and a half year lockdown.

Thank you to the HCC group! To my supervisors for giving me the opportunity to form my research in ways that I found interesting and relevant. To Eike for the awesome times at the office and after work — team silverbacks! To Joel for bringing fun to the office and for letting me borrow your apartment in Stockholm. To Rune for making your team (i.e. me) look good when playing fussball. To Rikke, my conference buddy when the world allowed for travelling again. To Niels for being very considerate and always being up for socialising.

Thank you Sara, Steffen, Andreas, Aysegül and Peter – my PhD netværk – for creating a space where we can talk about both good and bad elements in a PhD in a lightweight environment. A special shout out to Peter and Aysegül for making our road trip to Stevns absolutely amazing.

Thank you Rob for inviting me to KTH Royale Institute of Technology and also thank you Elina, Aksel and Arjun for making the stay memorable and insightful. You really did a great job at making Stockholm my second home. Rob, thank you for all the great talks about research and about life.

DISSERTATION DETAILS

Dissertation name: Designing Data Interactions for Sustainable Consumption

PhD student: Martin Valdemar Anker Lindrup, Aalborg University

PhD supervisors: Professor Mikael B. Skov, Aalborg University; Associate Professor Dimitrios Raptis, Aalborg University

The following six papers are incorporated into the dissertation and can be found in the Appendix:

1. **Martin Lindrup**, EunJeong Cheon, Mikael B Skov, and Dimitrios Raptis. One Byte at a Time: Insights about Meaningful Data for Sustainable Food Consumption Practices. In *Proceedings of the 2021 ACM Conference on Designing Interactive Systems*, pages 683–696, Virtual Event, USA, 2021. ACM.

2. **Martin Lindrup**, Mikael B. Skov, and Dimitrios Raptis. Between Egoism and Altruism: A Mixed-Methods Study of Reflections about Energy Use in the Life Cycle of High Preference Grocery Products. In *Proceedings of the 2022 Nordic ACM Conference on Human-Computer Interaction*, pages 1–10, Aarhus, Denmark, 2022. ACM.

3. **Martin Lindrup**, EunJeong Cheon, Mikael B. Skov, Dimitrios Raptis, and Rob Comber. Sustainable Foodtures: Exploring Roles of Future Technology in Sustainable Food Shopping. In *Proceedings of the 2022 Nordic ACM Conference on Human-Computer Interaction*, pages 1–12, Aarhus, Denmark, 2022. ACM.

4. **Martin Lindrup**, Arjun Rajendran Menon, and Aksel Biørn-Hansen. Carbon Scales: Collective Sense-making of Carbon Emissions from Food Production through Physical Data Representation. In *Proceedings of the 2023 ACM Conference on Designing Interactive Systems*, pages 1515–1530, Pittsburgh, PA, USA, 2023. ACM.

5. Aksel Biørn-Hansen, **Martin Lindrup**, Elina Eriksson, Daniel Pargman, and Jarmo Laaksolahti. Invitation to action: physicalisation and materialisation of carbon emissions to engage people with the climate impact of academic flying. Submitted to *the 2024 ACM Conference on Tangible and Embedded Interaction*, Cork, Ireland, 2024. ACM. In review.

6. **Martin Lindrup**, Jakob Tholander, Chiara Rossitto, Rob Comber, and Mattias Jacobsson. Designing for Digital Environmental Stewardship in Waste Management. In *Proceedings of the 2023 ACM Conference on Designing Interactive Systems*, pages 1581–1594, Pittsburgh, PA, USA, 2023. ACM.

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1 INTRODUCTION

In recent years, the role of data as a material of computer technology has become increasingly central in society due to advances in storage and processing, together with data collection and representation. This has resulted in the emergence of concepts such as Big Data and Data-Driven Society [35, 82]. Through the use of data-driven technologies, it is possible to obtain and represent data on almost every aspect of our existence from smartwatches collecting data on our heartbeats to interstellar satellites collecting data on the formation of the universe. Data plays a central part in every area of modern life, from politics, environment, health, economics, etc. [82]; such a central part that it has been coined the 'oil' of modern day society [135]. Data shapes our ideas and the kinds of questions we can ask about the world. It forms us as humans and makes us relate to the world in certain ways [35]. However, data has always had a central role in human lives. For example, ancient Egyptians recorded the position of celestial bodies and visualised these data points to make maps that would aid in navigation [44] and Upper Palaeolithic humans engraved signs into cave walls to pair animal sightings with calendar information and, thus, determine the seasonal behaviour of their prey [7].

Broadly, data can be understood as an abstraction of any phenomenon through observation, recording, and representation [82]. Let us picture how data come to be in the above two examples. First, people would *observe* either celestial bodies on the night sky or animals in a nearby field. The observations are *recorded* into a mental idea of the distance between these heavenly bodies or the number of animals. To crystallise the observations for further use and to communicate them to others, they could be *represented* by drawing lines in the sand that corresponded to the distance between celestial bodies, or by engraving signs in walls that capture the number of animals spotted. Although the phenomena described in the above two examples are simple data representations, the representations do not manage to capture the wholeness of the phenomena which makes them into *abstractions*. These abstractions, while not capturing the complete phenomena they depict, can be used to support people in transforming their understanding of the phenomena.

A central part of our lives that we seek to understand is our environment, as the well-being of our environment is paramount for human existence. With the Brundtland report, it became clear that the planet is greatly impacted by human activities to such a degree that it cannot sustain itself [19]. The conclusions from the Brundtland report and other literature detailing the state of the planet are based on measurements of temperatures, sea-levels, concentrations of pollutants and more. The acknowledgement of global sustainability problems (e.g. rising sea-levels, pollution, accelerating temperature increases) can therefore be seen to be a result of a vast variety and quantity of environmental data, enabled through modern sen-

sor technology and advances in computation. The datafication of our planet has also led to the acknowledgement that household consumption is a major contributor to sustainability problems. Household consumption represents about 60% of the world's total carbon, land, material and water footprint [75]. The major consumption pillars are housing (e.g. electricity, water consumption), mobility (e.g. air, water, land transport), and food consumption (e.g. refrigeration, preparation, disposal) [75].

Data and environmental sustainability, especially within the above-mentioned areas of housing, mobility and food consumption, have been of increasing interest to Human-Computer Interaction (HCI) research. As a response to the 2007 paper on Sustainable Interaction Design (SID) [15] and the 2010 landscape paper [32], more and more HCI research began to grapple with sustainability problem and the research area of Sustainable HCI (SHCI)[1] emerged. Most of the early SHCI research focused on behaviour change through eco-feedback technologies [32]. Examples of early technological interventions include: Power-Aware Cord for the awareness of energy consumption [55]; Waterbot to motivate change in water consumption behaviour when using the sink [5]; an augmented shopping trolley handle for changing behaviour towards food products with less food miles [80, 81]; monitors that display water consumption to affect household dynamics [46]; living plant displays for changing recycling behaviour [66]; and GreenScanner to help engage individuals in environmentally preferable purchasing [121] (see also Figure 1.1). These examples use different techniques, such as aggregating data on graphical user interfaces, ambient displays, ubiquitous computing and shape-changing displays. Common to these examples is that they adopt a persuasive technology strategy [42] to change individuals' behaviour towards, and/or increasing knowledge about, sustainable practices through representing data to people, i.e. eco-feedback [45].

The persuasive technology strategy for sustainability change comes primarily from work on Persuasive Design [42] that aims, as the concept suggests, to persuade people to change behaviour in prescriptive manners through technology that strengthens intrinsic and extrinsic motivational factors. Eco-feedback technology adopts this strategy by using technology to give people feedback in order to support better management of their consumption [45]. This strategy has been criticised from within SHCI for its prescriptive nature and for framing sustainability problems too narrowly [20], which can lead to rebound effects that counteract the purposes of the interventions (e.g. the efficiency paradox [28]). It is well known that there is a gap between knowledge and behaviour [84]; people do not necessarily act rationally towards sustainability when knowledge of their consumption increases [84, 116, 117]. Brynjarsdóttir et al. [20, p. 954] argue that *"Modernism provides a seductive role for HCI: it proposes technical solutions to social problems. Ironically, a key aspect of our critique is that most persuasive sustainability research is not producing solutions"*. The focus on techno-solutionism and technology that 'shout at people' to change [104] has been challenged by research that proposes collectively engaging

[1] SHCI will be used throughout the dissertation as an overarching term that also encompasses SID

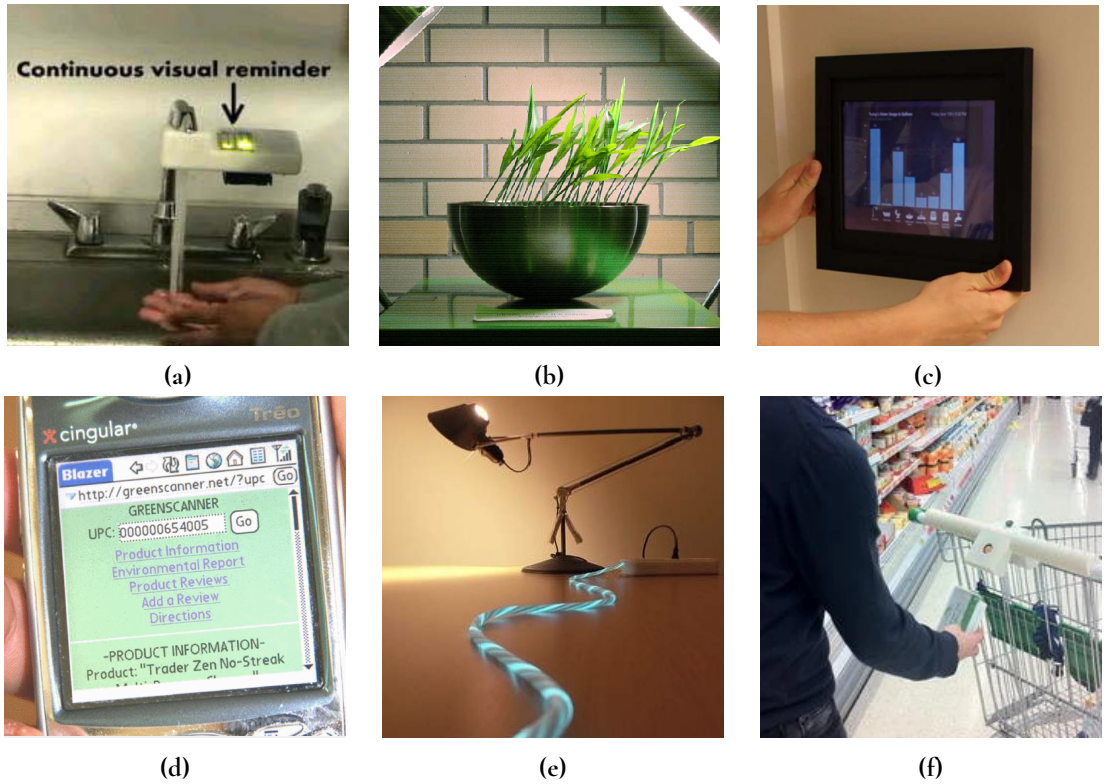

Figure 1.1: A selection of early design examples for sustainable consumption. a) Waterbot [5], b) living display [66], c) water consumption display [46], d) GreenScanner [121], e) Power Aware Cord [55], e) ambient trolley handle [80].

people in their consumption and with the environment [14, 56, 68, 104, 109, 128].

Through their work on materialising energy, Pierce and Paulos [104, p. 121] argued that *"Energy Engagement could be a powerful way of transforming our relationships with energy in more meaningful and sustainable ways"*. Fostering engagement is not only relevant for transforming our relationship with energy consumption; it is just as important for every other aspect of our lives that has become disconnected due to abundance, and which has a large impact on our planet (e.g. water consumption). To implement sustainable changes in addition to things such as regulation and infrastructure, there is a need to support people in creating meaningful relationships with the environment, as this has a positive impact on values towards, and engagement in, sustainability [128]. Moreover, since data has such a large impact on how people understand sustainability issues today, I see a need to take the data out of passive and controlled expert environments, and to invite non-experts, who are impacting and impacted by the data and the events that the data depicts, to participate actively in sense-making processes around data.

Through acknowledgement that people are not rational agents who process data only using their brain and eyes (i.e. in a strictly cognitive manner), we can develop new perspectives

on data representation that also take into account our bodily, relational and situated knowledge, and use these multi-sensory and situated aspects to foster meaningful relationships with data and the environment. I therefore suggest a complementary research agenda to previous SHCI, which focuses on data interactions for sustainable consumption that goes beyond *representing data to people* and instead seeks to *represent data with people* to foster engagement and action.

To guide the investigation of data interactions for sustainable consumption, three research questions have been formulated. Each of the research questions addresses an aspect necessary to the understanding of the problem as well as contributing new knowledge.

Research question 1: What characterises data interactions for sustainable consumption?

With the accumulating quantity and variety of types of data available to signify the sustainability of products and services, research question 1 contributes characterisations of data that people use in their daily lives.

Research question 2: How do people use data to make sense of sustainable consumption?

Research question 2 investigates what kind of sense-making processes are enabled through interactions with data in different forms (i.e. digital and physical) for sustainable consumption.

Research question 3: How can we foster sense-making and engagement in sustainable consumption through data interactions?

Research question 3 provides insight into how data interactions for sustainable consumption can be designed to emphasise sense-making and engagement towards action for more sustainable consumption.

2 BACKGROUND

In this chapter, I outline related research on data interactions for sustainable consumption. First, the chapter describes characteristics of sustainability and how sustainability has been researched in HCI throughout the last two decades. Second, it lays out different perspectives on what data is and gives an overview of different types of interactions with data. Third, the chapter describes combinations of sustainability and data research in HCI to situate my research focus.

2.1 What is sustainability?

In history, sustainability meant environmental sustainability, i.e., balancing the use and production of natural resources. The origin of the term dates back to around 1600 where it was used to describe 'lasting-ness' of, for example, forest or farmland [130]. Taking the example of farmland, we know that farmland consists of organic material (i.e., nutrients, soil, seeds, and water). Seeds draw nutrients and water out of the soil to grow into plants for consumption. This process is strenuous for the soil, which needs, for example, worms and insects to regain nutrients. This process can take many years. When we talk about sustainability, we talk about cycles of taking and giving. Although the farmland example is focused on food production and consumption, the general notions translate to many similar (e.g., forestry, fishing, mining) and diverse (e.g., labour, governance) processes. This early conceptualisation of sustainability had a local focus; with increasingly globalised systems of production and consumption, the focus of sustainability has also broadened in scope.

In the late 1900s, the Brundtland Commission published a report called Our Common Future [19], which is one of the first works to articulate the global focus of sustainability, *"In the middle of the 20th century, we saw our planet from space for the first time. [...] From space, we see a small and fragile ball dominated not by human activity and edifice but by a pattern of clouds, oceans, greenery, and soils. Humanity's inability to fit its activities into that pattern is changing planetary systems, fundamentally. Many such changes are accompanied by life threatening hazards. This new reality, from which there is no escape, must be recognized - and managed"* [19, p. 13]. The so-called Brundtland report conceptualised sustainability with a development component as 'sustainable development' and defined sustainable development as *"meet[ing] the needs of the present without compromising the ability of future generations to meet their own needs"* [19, p. 16]. At this point in time, Brundtland's conceptualisation of sustainable development focused primarily on environmental aspects of sustainability. In recent years, the United Nations (UN) has expanded the concept of sustainable development to also include economic and social aspects [124] that echo previous research on the so-called triple bottom line [37]. While

acknowledging the triple bottom line of sustainability, this project focuses mainly on environmental sustainability to make a more in-depth contribution. Having the development component, the modern conceptualisation of sustainability concerns growth (i.e. environmental, social and economic growth) and limits to growth, which are both on local and global levels. Multiple measures have been developed to capture the state of the world; for example, the ecological footprint [52] and average global temperatures [10]. These measures are used to communicate the impact of sustainability issues. Examples of data-enabled communication of sustainability issues are 'Earth Overshoot Day' [53] and carbon footprints on products and services [133]. Sustainability issues are, to a large extent, understood through data about the world and its inhabitants. Acting on sustainability issues is complex, as it involves changing orientation, i.e. from self-interested to self-transcending values [41, 83], and relies on action from multiple levels on both local and global scales [93]. A wealth of research traditions have sought to bring their views on how to move towards more sustainable living. One of these is HCI, which seeks to employ technology in different ways to understand and change (un)sustainable tendencies in society. In the next section, I will present the research carried out within HCI on sustainability[1].

2.2 Sustainable consumption in HCI research

Within HCI research, a special interest group on sustainability (SHCI) has been developing ever since the formal introduction of Sustainable Interaction Design at the 2007 ACM CHI conference [15]. SHCI outlines, both implicitly and explicitly, two main efforts with research: (1) *increasing understanding* about (un)sustainable consumption and (2) *changing* unsustainable consumption patterns. Authors do not use precisely these terms; 'understanding' is occasionally referred to as, for example, awareness, reflection or knowledge and 'changing' as action or transformation. For example, Disalvo et al. [31, p. 388], discussing the implications of previous SHCI work, note that *"The thrust of this work, and related projects, is to raise awareness and ideally change behavior"* and Silberman et al. [111, p. 67] explain that the SHCI community has a *"[...] commitment to translating knowledge into action"*. Although the use of various terms often describes the different scales at which understanding and change occur (e.g. individual, group, institutional), the essence of the terms remains. Understanding can be seen as describing an increase/decrease in capacity to grasp a phenomenon, and change can be seen as describing increase/decrease in capacity to mobilise towards or away from a phenomenon. The two efforts are also in line with previous research on environmental psychology which states that environmentally sustainable consumption is about *"[...] the possession of environmental knowledge and environmental awareness, and displaying pro-environmental behavior"* [84, p. 240]. Knowledge and awareness about sustainable consumption is something

[1] I limit the scope of sustainability in this dissertation to sustainable consumption as it will make for a more coherent contribution.

that a person can possess and/or express — an understanding — and behaviour is something that can be displayed — a change that happens. Therefore, based on these examples and multiple others (e.g. [55, 80, 97, 109]), I choose to adopt the terms *understanding* and *changing* in the following to describe the two efforts that I see present in SHCI research.

In early SHCI research, a central focus was on changing behaviour in predetermined ways, based mainly on cognitive understanding, towards more sustainable consumption (i.e. passively observing a representation of consumption patterns and adjusting according to set values for sustainable consumption), and most often through eco-feedback technology (e.g. [5, 46, 78, 80, 92, 121, 136]). For example, Froehlich et al. [46] designed and evaluated a water usage display for individual household members. The prototype was developed to steer behaviour in predetermined ways by influencing the members of the household's cognitive understanding of water usage with an assumption that change will follow. Two central limitations in the study are that it does not consider the long-term effects of the behaviour change intervention and it considers all water consumption as equally avoidable, which can be seen as a limited view of household water consumption and consumption in general [46].

The strict focus on behaviour change in early SHCI sparked criticism from the research community (e.g. [20, 34, 116, 117]). In particular, Brynjardóttir and colleagues [20] wanted peers to see that sustainability is not a technical problem that can be solved and that people are not rational agents that perform predictable activities based on a technical prompt. This resulted in a shift in focus on increasing understanding and making changes, which manifested itself in work on practices and open-ended reflection and negotiations about (un)sustainable practices (e.g. [2, 22, 25, 26, 47, 48, 56, 77, 79, 120]). An example is Ganglbauer and colleagues [47] who studied food waste practices using FridgeCam — a system that takes images of refrigerator inventories and sends these to a digital application — which allowed participants to gain insights about the current inventory and the changes made to it. Although at first glance this study looks like a behaviour change intervention to reduce food waste, the authors unfold the complexity of wasting, which is not limited to the relationship between the refrigerator and the rubbish bin. They seek to influence the multitude of factors that go into wasting as a dispersed practice, that is, a practice *"[...] interwoven into other practices and itself arises from multiple other moments of consumption across multiple other practices [...]"* [47, p. 21]. From this, it can be seen that the practice turn in SHCI does not aim to deploy behaviour change techniques to foster sustainable consumption. Instead, it aims to understand meaningful and meaningless consumption patterns within larger constellations to foster the conditions for change to happen.

Recently, the focus of SHCI research has expanded to encompass future orientation (e.g. imaginaries and speculations) [11, 112, 113, 114], more-than-human focus on sustainability [33, 65, 122, 134], and exploring new ways of engaging with environmental data (e.g. through

narrations [13, 89, 94], combining data and subjective experiences [22, 23, 27, 64, 94], embodiment [11, 96], and physicalisation [109, 115]). Rossitto et al. [106] outline the contemporary focus of SHCI research by stating that there is a need to *"[...] move towards an ethics of sustainability that not only engages the moral responsibility to act, but also the value of making meaning (not only finding solutions) in the practices of sustainable living"* [106, p. 4]. There is a need to move beyond the ingrained focus on cognitive understandings and behaviour change. Instead, SHCI should design for promoting our material and relational stances towards the environment through engagement [104,106]. For example, Pierce and Paulos [104], drawing on the work of Borgmann [17], argue for designing for focal engagement with everyday sustainable consumption and technology. In addition, with the recent focus on data as proxies for environmental sustainability both locally and globally, and the increased possibilities for collecting and representing data in general and on the environment specifically [105], it becomes relevant to investigate how focal engagement in sustainable consumption can be fostered by drawing on techniques for interacting with data (see section 2.4 for elaboration).

2.3 Interactions with data

Humans make sense of phenomena in the world through their senses. To crystallise and communicate their understanding, a process of abstracting the phenomenon takes place. This process involves observation, recording and representation [82]. The phenomenon is turned into data points that each capture bits of the whole. Since data in itself is an abstract understanding, data is represented[2] in graphs, maps, plots, charts, etc. to make the abstract more comprehensible.

What is data?

Traditionally, the term 'data' was seen as *"a fact given or granted"* [29]. This definition of data has changed over the years to *"numerical facts collected for future reference"* [29]. Later, when computer technology started to make its mark, data was thought of as *"transmittable and storable information by which computer operations are performed"* [29]. From the above, and also evident in scholarly readings (e.g. [51, 82, 95]), data has traditionally been seen as factual entities, in numerical form, and often used in computers. Bellinger et al. [8, p. 1] stress that *"[Data] simply exists and has no significance beyond its existence (in and of itself)"*. In addition, as Ackoff argued [1, p. 1], there is a linear relation between data and information: *"An ounce of information is worth a pound of data. An ounce of knowledge is worth a pound of information. An ounce of understanding is worth a pound of knowledge"*. The relation is also apparent in the data, information, knowledge and wisdom hierarchy (i.e. wisdom hierarchy) [107], in which data

[2]Representation is here defined as the data-enabled portraying of a phenomenon in a particular manner [100].

is represented at the bottom of the hierarchy as symbols with no meaning or value. Moving up the hierarchy, information is seen as data that has been processed so that it is meaningful to a recipient [107]. This understanding that data is objective, and the linear connection from data to information, has recently been challenged, especially by scholars within Science, Technology and Society Studies (STS). Gitelman [51] argues that it can seem apparent that data acts as a starting point for what we know, who we are, and how we communicate. They continues to state that this can lead to the assumption that data is transparent and the fundamental stuff of truth itself [51]. However, this objective truth is situated and historically specific, Gitelman argues. It comes from somewhere and is the result of ongoing material, social and ethical conditions of enquiry. In other words, data can be seen as cooked by the circumstances of its collection, storage and transmission, making the term 'raw data' an oxymoron [51]. This view is shared by multiple scholars (e.g. [30, 36, 95, 98]). For example, Manovich [98] states that *"data does not just exist - it has to be generated"* and Loukissas [95] argues that the collection, usage and representation of data is bound to local circumstances and must be treated in that way [95]. Data is a product of various processes with physical and technical constraints, and with that, Loukissas stresses the importance of understanding what lies behind the data with which we are presented [95].

For this dissertation, I adopt a broad understanding of data as the abstraction of any phenomenon through observation, recording and representation [82]. This broad understanding enables an investigation of the role of data in our lives as products of various processes (e.g. technical, political) and the exploration of data in different forms (i.e. digital and physical). This is an attempt to provide an alternative to traditional understandings of data as mere facts that objective experts can obtain through observation and representation (i.e. [8]). The broad understanding of data allows me to study the layers of sense-making that are enabled through interactions with data and how engagement in data might be a step towards more sustainable consumption (see also limitations section, section 6.4, for more reflections on this).

Data representation

Data representation draws on multiple research traditions, such as computer science, mathematics, linguistics, psychology, and sociology among others and has deep historical roots [3, 44]. The introduction of computer technology made way for interactive and dynamic digital representations of data. Furthermore, in the same period, more emphasis was placed on the cognitive and perceptual benefits of representing data [44]. In order to convey their message, data representations use shapes, colours, numerical values etc. — so-called data mapping rules [125]. The elements can be attributed to gestalt psychology's principles of visual perception [132] and visual cognitive sciences [131]. There are two primary ways of representing data that greatly influence interaction possibilities: data in *digital* form and in *physical* form [73].

For clarification, when using the terms 'interactions with data' or 'data interactions', I refer to interactions with data representations which are made possible through physical or digital means. In the following, I will describe similarities and differences between these two ways of representing data.

Digital data representation

Digital data representation encompasses the design, development and application of computer-generated graphical representations of data [108]. This type of data representation has been the most common since the field of data visualisation emerged in the mid 1980s [125]. Vande Moere [125] describes the main attributes of digital data representations as effectiveness, accuracy and completeness. Digital data representations have advantages as a form of communication, as they increase the amount of information delivered, while at the same time decreasing the cognitive and intellectual burden of interpretation [103]. However, the challenge with communicating through digital data representation, especially to non-experts, is that these representations are often static, detached and controlled by experts [125].

Physical data representation

Physical data representation encompasses the design, development and application of physical representations of data, which includes the materialisation of data into physical artefacts [118, 125]. The move towards more physical ways of representing data has been accelerating in parallel with research on tangible user interfaces (TUIs). A landmark paper that has guided the development of physical data representation is Ishii and Ullmer [74, p. 234] who developed the vision 'Tangible Bits' as a way of designing user interfaces that would allow for direct manipulation of computational bits, by coupling these with everyday physical objects. This example has led to a number of studies that have focused on bringing data into the world by physicalising it in various ways (e.g. [43, 73, 119, 125]). Vande Moere [125] outlines a conceptual spectrum of physical data representation that includes displays (i.e. ambient displays, pixel sculpture and data sculptures), the augmentation of data into everyday objects, and the embodiment of data using wearables together with alternative modalities (e.g. sound, touch). Researchers in physical data representation have highlighted possible benefits of physical data representations: they can leverage perceptual exploration skills by enabling active and depth perception; support embodied cognition; they bring data into the world; and engage people in the data and the phenomenon that the data represents in more comprehensible ways [76].

2.4 Data representations in SHCI

As mentioned previously, early SHCI research focused primarily on behaviour change using eco-feedback data representations. There are multiple examples of eco-feedback data representations for sustainable consumption (e.g. [5, 46, 80, 136]). Zapico et al. [136] developed a web application that shows, through the use of eco-feedback visualisations, the share of organic food that people buy in the store. Although the authors state that the central premise of eco-feedback is to adjust future behaviour based on real-time data, they recognise that this does not always work on its own and that other means may be necessary to implement changes in consumption patterns [136, p. 7]. Common to eco-feedback strategies for sustainable consumption is that they assume people are rational agents that make sustainable decisions if provided with the right data; however, this has been shown to be untrue multiple times [20, 116, 117]. Instead, researchers have begun to recognise that data is shaped by human activities (i.e. data collection, processing and representation) [51] and data shapes the kinds of questions we can ask about the world [35]. With this in mind, they have sought to broaden the scope for interaction with data both in general and in relation to sustainability. In addition, due to the ever-increasing amount of data that is collected about the state of the environment and the fact that data is not only accessible in expert environments, there are also calls for improving the comprehensibility of the data to non-experts since they are the ones both impacted by and impacting what the data depicts [112].

Researchers have sought to challenge the objective and definitive understanding of data by juxtaposing it with subjective experiences. In an attempt to make air quality data more meaningful to residents of a geographical area, Liu and colleagues [94] had participants draw their own subjective experiences of geographical areas on air quality heat maps. The authors argue that *"[...] reductive measures fail to capture the contours of personal experiences [...]"* and as a result *"[...] environmental data needs to be situated and narrated to have meaning"* [94, p. 1320]. Similarly, reports from a thermal comfort project in a workplace environment (i.e. [22, 23]) show that environmental data coupled with data on personal experiences of comfort can be used for social negotiation between workers and management to facilitate a common ground. In Clear et al. [22, p. 2459], the authors stress the potential of data-mediated negotiations, and further, argue for making the incompleteness of data a driver for change. Drawing from these previous studies, it becomes clear that environmental data can be made more engaging to non-experts by situating it, embedding it in narratives and fostering negotiations around it.

Gaver et al. [50] designed Datacatcher, an artefact that represents data about the local environment to people as they move. The artefact sparked engagement in, and critical reflection about, the sorts of data that we encounter on a day-to-day basis and the inherent uncertainties in this data. Additionally, De Greve et al. [27] drew on the notion of critical engagement

as a component for reactivating environmental data into matters of concern as opposed to matters of fact. Drawing on both art and science, Soden et al. [113] held a Disaster and Climate Change Artathon to provide critical reframings of climate data. They suggested that designers could leverage artistic data visualisations to bring forth the affective and relational elements of data that are rarely explicated in statistics, maps and charts.

Environmental data representation endeavours also include research that seeks to materialise or physicalise data in an attempt to make it concrete for non-experts and/or make it more comprehensible (e.g. [6,68,109]). Sauve et al. [109] worked with data physicalisations of CO2 emissions of dietary choices through the design and evaluation of Econundrum. They found that the data physicalisation made CO2 emissions more comprehensible for individuals as well as groups of people. In addition, Houben et al. [68] designed and evaluated Physikit, a data physicalisation that allowed for environmental data to be displayed in physical form using different modalities (i.e. light, vibration, movement, air flow). The authors showed that the Physikit cubes allowed social exploration and reflection about environmental data as well as marking a step towards democratisation of data [68, p. 1617]. In the context of energy consumption, Asgeirsdottir and Comber [6] take a soma-aesthetic design perspective in an attempt at 'making energy matter'. Their critique is that sustainability has for too long been a cognitive concept and they suggest that material engagement with energy and energy data can lead to more ethical and sustainable relations. This is consistent with Biggs and Desjardins' [11] research on embodied data experiences. Biggs and Desjardins designed and evaluated a prototype that allowed for bodily experiences of sea-level rise in an urban area in an attempt to spark conversations about future ways of living. By bringing environmental data out of cognitive frames and into the world, more sustainable consumption patterns can be nourished through engagement.

The above outlines several directions for fostering engagement in non-experts around data towards sustainable consumption. The following will introduce a research framework that characterises the intersection between interactions with data and sustainable consumption in order to contribute knowledge about the different dimensions hereof.

2.5 Research framework: data interactions for sustainability

The related research on data and sustainable consumption from an HCI perspective described in the previous sections, provides the foundation and informs the construction of a framework for characterising data interactions for sustainable consumption. The framework displays two dimensions of interactions with data for sustainable consumption (see Figure 2.1). The horizontal dimension *sustainable consumption* consists of *understanding* (un)sustainable consumption and *changing* consumption patterns. As I have outlined earlier, sustainable consumption research uses a wide vocabulary to describe its purposes; however, they

all revolve around two central purposes, which are to increase understanding and/or make changes. Therefore, I choose to adopt these two terms (i.e. understanding and changing) as they encompass the core purposes of sustainability research. The vertical dimension *interactions with data* is separated into interactions with *digital* and *physical* data representations. These two forms of data are extracted from HCI research which characterises data from an interaction perspective as either digital (i.e. data embedded into a computational artefact and represented digitally) or physical (i.e. data embedded into a physical artefact and represented physically) [123]. The dimensions will be elaborated in the following.

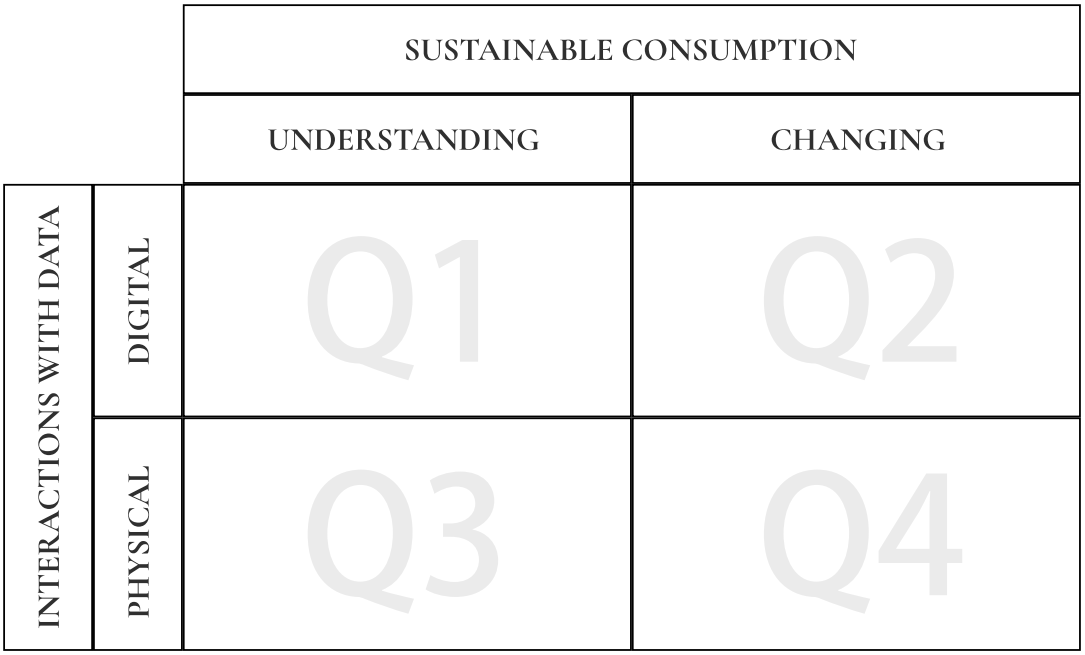

Figure 2.1: Framework for characterising data interactions for sustainable consumption. Quadrants are referred to as Q1-4.

The horizontal dimension outlines sustainable consumption. As noted above, previous research uses a variety of different terms to characterise the process of increasing understanding of (un)sustainable consumption and/or enacting changes in consumption patterns. To organise these, I adopt the terms 'understanding' and 'changing' based on the terminology used in previous environmental psychology and SHCI literature (e.g. [32, 84, 111]). That being said, I do acknowledge that words matter — using the term 'behaviour change' as opposed to 'transitioning' carries valuable meaning about the scale on which the change is supposed to happen. To avoid misunderstandings, I have carefully chosen 'understanding' and 'changing' as they describe generic processes of building an intellectual and bodily capacity (understanding) and moving toward a desirable goal (changing). When using understanding and changing, I am sensitive to the issues of e.g. scale and purpose and also that the two terms, while distinct, characterise interconnected efforts.

The vertical dimension outlines interactions with data. Based on research (i.e. [73, 123]), I choose to divide interactions with data in two: interaction with digital data representations and interaction with physical data representations. Drawing on Ishii [73, p. 21], the central difference between data representations relates to the form it takes — whether it is physical or digital. When referring to interactions with data in digital form, I adopt Ishii's understanding of interaction with digital information: *"Interactions with digital information are now largely confined to Graphical User Interfaces (GUIs). [...] GUIs represent information (bits) with pixels on a bitmapped display"* [73, p. 15]. Interactions with digital data involve interactions with data that is represented through computational and graphical means. The understanding of physical data interactions that will be used in this dissertation is also adopted from Ishii [73, p. 16] who conceptualises physical data as being *"[..] directly manipulatable with our hands, and perceptible through our peripheral senses by physically embodying it"*. When referring to a physical data representation, I refer to a representation that is made from one or more physical objects whose purpose is to display a dataset in ways that can be perceived through our senses and which may or may not be directly manipulable. The reason that I do not adopt the idea that physical data has to be directly manipulable is that I also see data sculptures (e.g. [125]) as physical data representations, although they are not necessarily interactive. This definition of physical data representations also includes embodied data representations (e.g. [11]) that can be perceived through on-body experiences. Embodied data interactions are included due to the fact that although there might be digital or cyber-physical input, the output is physical.

3 RESEARCH DESIGN

In this chapter, I outline the research design for the dissertation to bridge between the proposed area of research on data interactions for sustainable consumption and the paper contributions that investigate the dimensions of this research area. The chapter is divided into the ontology and methodology that constitute my research design.

3.1 Ontology

The ontology of this research is (post-)phenomenological[1] in nature. Phenomenology is the study of phenomena as they occur in an observers' world [69]. Unlike positivism, which seeks to understand the world as an objective entity [54], phenomenology seeks to understand the world as it is experienced by people [61]. Phenomenology has guided me both in terms of research logic (i.e. how I seek to produce knowledge) and research design (i.e. how questions and methods support this production of knowledge). Drawing on traditional phenomenology is post-phenomenology, which views relations between humans and the lifeworld as mediated by technology. Verbeek [126], drawing on post-phenomenologist Ihde's work (i.e., [71]), outlines four technology relations that capture mediations that happen between humans and the world.

- Alterity relation: human → technology (- world)
- Background relation: human (technology - world)
- Hermeneutic relation: human → (technology - world)
- Embodiment relation: (human - technology) → world

I will not go into detail with each of the technology relations (see Verbeek [126]); however, I want to highlight the implications that this understanding has on my worldview, how I produce knowledge and, more specifically, how I analyse interactions with technology. All four technology relations illustrate that interaction does not happen in isolation between a person and a technological artefact. There is a world surrounding the interactions that impacts and is impacted by these. In addition, interactions with technology, from a post-phenomenological perspective, are formed not only by input and output modalities but by our 'being-in-the-world' [61] including our prior experiences and physical capabilities.

Using a post-phenomenological lens, since interactions between humans and world happen

[1] While I draw explicitly on post-phenomenology when analysing specific interactions with technology, the underlying considerations are based on readings from Heidegger's phenomenology of things [61] and Merleau-Ponty's phenomenology of perception [99].

through technology, data can be seen as embedded into and generated through technology — technology in a broad perspective as the artefacts and/or processes that enable or disable certain actions. Returning to the earlier example with the cave engraving (see Chapter 1), technology can be seen as both the tools (e.g. hammer and chisel 'things'[2]) and the techniques that were employed to generate the data representations of animal sightings. Data in and of itself is an abstract concept; it needs representation to be perceived. Ihde [71] uses the example of how the microscope opens up a magnified world when we look through it but when we step back from it, we can see it magnifies only a specific part of the world. They argues that representation is inseparable from perception but can be produced through different mediations with technology and the world. Data can, for example, be represented using digital or analogue technology that shapes how it mediates between humans and world [126]. Since representation, from a post-phenomenological point of view, can be seen as inseparable from perception, it becomes necessary to reflect on how data is represented both from a perceptual and an ethical perspective.

So why am I drawing on phenomenology and post-phenomenology in my research? Studying interactions with data that go beyond traditional computational data representations, calls for an understanding of interactions with data and of the contextual elements that shape interaction and experiences — the lifeworld. Although, data and lifeworld, from a post-phenomenological perspective, should not be seen as separate entities; interactions with data mediate between us and the lifeworld. They shape the way we experience the world. Take, for example, the step counter. This data-driven technology, as its name implies, counts steps whenever a person moves. However, it might also alter the qualitative experience of a walk in the park to a quantitative measure towards a certain step goal. The investigation of this mediating relationship between human, technology (data) and world is at the core of the post-phenomenological ontology [126].

I argue that (post-)phenomenology fits well with interaction design in this dissertation as it embraces both the explicit and tacit understandings that people might express when interacting with technology; however, it does not necessarily provide a generative dimension, which is why I have turned to design research (i.e. [137]). I use design research in combination with phenomenology to address the generative dimensions of designing for sustainability without losing the deep connection between human, technology and world. Studying how to design for sustainable consumption practices brings unique challenges since these practices may not be apparent yet or may be at a tentative beginning stage — designing for sustainability becomes designing for futures [9]. Bendor [9] uses the term 'futurescaping' to describe the activities that occur when designing technological artefacts for sustainability: *"[...] to design an artifact, service, or interaction is to foreshadow a future where the artifact, service, or interaction will be used to accomplish something or be meaningful for someone"* [9, p. 206]. While it can be argued

[2] I draw on the Heideggerian understanding of 'things' as 'something in order to' [61, p. 97].

the case for all design work, the context of sustainability challenges design as it emphasises radical rather than an incremental change-making. In interaction design for sustainability, 'the future' — the future we fear, the future we desire, the future we long for — is constantly present [9]. From a post-phenomenological perspective, Bendor's idea of futurescaping supports reflection about how we, in the future, will experience and make sense of the world and how data can transform these experiences. While experiences are bound up with our being in the world and thereby in the present, the exploration of possible futurescapes can allow a move closer to the experiences of others in the future.

3.2 Methodology

With the challenges that sustainability poses for design work, it is essential to account for this in the methodology and the choice of concrete methods. I have chosen a probe-driven Research through Design (RtD) [137] approach for addressing the challenges that come with designing for sustainability. The following elaborates on the methodology and concrete methods and how my research ontology has informed the choice of methods.

Probe-driven Research through Design

Research through Design (RtD) is an approach that employs methods, practices and processes of design to generate scientific knowledge [137]. The emphasis in RtD is to *"[...] investigate the speculative future, probing on what the world could and should be"* [137, p. 168], which is done by continuously reinterpreting and reframing a problematic situation through designing artefacts, and then evaluating and critiquing them against the problem at hand. Unlike design work in general, RtD is an approach to research that means the outcomes are not a design that works and can be implemented but instead knowledge *for* design. In other words, it generates knowledge about the social situation that a design has to function in, and knowledge *into* the design process; for example, knowledge about how to tailor a design process to achieve a certain goal [137]. My RtD approach was built around different probing techniques (i.e. [49, 70, 129]).

I designed probes to address specific research questions. For instance, one of the questions that emerged at the beginning of the PhD project was how people evaluate the sustainability of food products based on available data (see [87] for more details). For this, a cultural probe was designed that allowed participants to place stickers on food products and write their evaluation criteria on a sheet, in order for them to reflect on their assumptions about sustainable food products (see figure 3.1). This resulted in valuable insights about the characteristics of data for sustainable consumption (i.e., Research question 1).

Other examples of the use of probing to address emerging research questions is the work

Figure 3.1: Cultural probe consisting of stickers and reflection sheet for evaluating food sustainability.

with the EnergyFetcher [90] and Sensing Climate Change [88] probes. In the EnergyFetcher study, the research question was how preference for specific food products could change values from altruistic to egoistic during food shopping [90]. The EnergyFetcher probe pack involved a technology probe, EnergyFetcher, and a digital survey in the form of a chatbot that prompted participants to reflect on their food shopping on a regular basis (see figure 3.2). In addition, the Sensing Climate Change study had the purpose of investigating how embodied interactions with data alter people's stance towards the environment. This was investigated by deploying a technology probe that invited sensing climate change based on slow adjustments to body temperature (see figure 3.3). Therefore, the two studies provided insights for Research question 2 about how people use data to make sense of sustainable consumption and Research question 3 about how to foster sense-making and engagement in sustainable consumption through design.

Figure 3.2: Technology probe, EnergyFetcher, consisting of a web application for mobile devices and an online survey.

The aim with a probe, as opposed to a prototype, is to be a vehicle for data collection and refinement of research questions [70]. I used probing techniques not for the purpose of advancing towards a potential product but for refining the questions that can be raised for the social setting where the design would be situated. This is especially important in the con-

text of sustainable consumption where social settings are often imaginative and, therefore, difficult to experience firsthand [9].

Figure 3.3: Technology probes, Sensing Climate Change and Connecting Stakeholders, consisting of a sleeve that regulates body temperature and a web application for tablet devices that allows communication with stakeholders in food stores.

Probing into possible future scenarios gives an opportunity to reflect on these futures in the context of the present. In addition, probes are great at challenging what we know, as shown in the work with Carbon Scales [89], a data physicalisation for sense-making about CO2 emissions in food production (see Figure 3.4). Carbon Scales invited people to make sense of CO2 emissions from food production by physically moving Carbon Bits. This process tapped into the assumptions people have about where their food comes from and how it is produced. So, although the work with Carbon Scales did not result in a more elaborate prototype, it helped answer questions about what we do and do not know about the globalised food system. Hence, it acted as a probe for conversations about the food system at large and the changes that need to happen. The probing techniques facilitated a form of futurescaping [9] by establishing future scenarios where data-enabled decision-making and sense-making for sustainable consumption are possible.

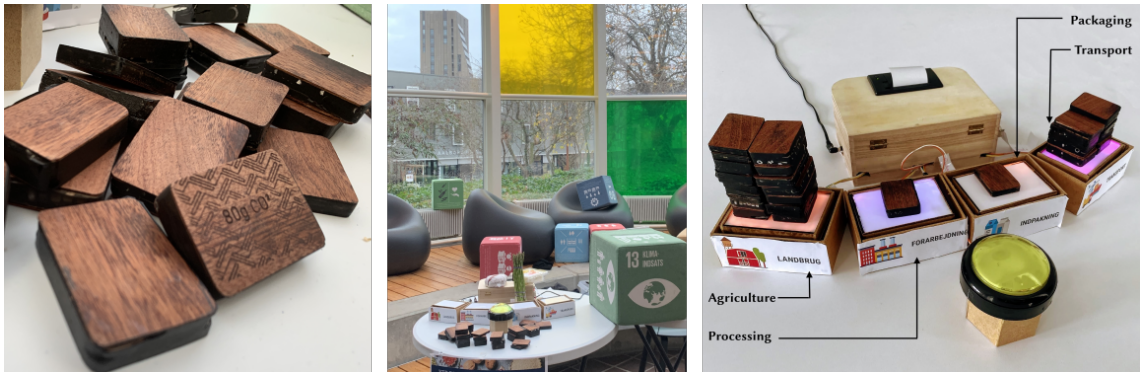

Figure 3.4: Technology probe, Carbon Scales, consisting of physical blocks (Carbon Bits) and four platforms that can be used to weigh carbon emissions from food production.

Studying probes

I deployed a variety of different methods to study the designed probes. The phenomenological ontology outlined above guided the choice of methods, as phenomenology recognises that knowledge is produced at the intersection between being and the life world, as forming and reforming experiences [61]. People use artefacts as mediators between themselves and their surroundings to transform their understanding of the world as they experience it; for example, the microscope allows for a transformative understanding of the composition of a leaf [126]. Without these artefacts, the understanding of a given phenomenon would have been different or perhaps lost. When providing people with artefacts (probes), they start developing a language to communicate about, and agency to experience, the world in a new way. It is these tacit and explicit aspects of the mediation between person and world through artefact that need to be captured in order to gain a rich understanding of the phenomenon that is unfolding. In analysing these mediations, post-phenomenology provides concepts and structures that support in-depth understanding of these phenomena. During the project, the application of post-phenomenology fostered rich understandings of people's experiences from interacting with data represented in digital and physical form. It also guided how to intervene with probes and how to gather data from interactions with the probes. Regarding interventions, the project used field studies, enactments, workshops and public installations, and with regard to data collection methods, the approach was primarily qualitative with concrete methods such as interviews and observations (see each of the attached papers for further details on methods and data analysis processes). The project also drew on the quantitative methods of online surveys and data logging — mainly to support the qualitative insights.

Interventions

Two primary types of interventions that I call *contextual intervention* and *staged intervention* were chosen for the project.

Contextual interventions include field deployments and enactments (see [87, 88, 90]). For the field deployments, the participants were provided with the probe with minimal instructions on how to use it, in order to encourage reinterpretations of the probe. Hutchinson et al. [70, p. 19] argue that this type of flexibility is a core strength of probes as opposed to prototypes, *"[probes] should be designed to be open-ended with respect to use, and users should be encouraged to reinterpret them and use them in unexpected ways. [Compared to probes,] prototypes are generally more focused as to purpose and expected manner of use"*. Field deployment also allowed for more contextually embedded understandings of how the probe integrates into everyday life. This is also true for the enactments. Enactments with probes (see [88]) also sought to capture the contextual aspects of interactions with the probes; however, due to the more future-

orientated nature of the probes, enactments were chosen above field deployments to provide participants with slightly more guidance for use, as these probes were not close to the usual practices of the participants and the probes required technical assistance to function properly. Common to both field deployments and enactments is that the probes were situated in the participants' everyday context (e.g. food planning and shopping) and participants reported back on their experiences from interacting with the probes. Observations were also used to capture tacit knowledge from interactions. As I touched upon earlier, capturing tacit knowledge has been very important for the purpose of this project, as it seeks not only to gain insights into how people reason about data but also how their multi-sensory experiences guide reasoning and actions.

Staged interventions include workshops and public installations (see [13,89,91]). For the workshops, the probes were staged for a short period of time, and the context of use was limited. The strength of the workshop format, I would argue, is that participants can negotiate their opinions and experiences of the probes in a shared environment. Similarly to the workshop format, the public installation probe deployment also limits the context of use to some degree; however, it allows for long-term deployment where interactions happen multiple times over a longer period of time. I found that staged interventions were beneficial for studying probes that are not necessarily bound up with any everyday practice, such as the case with Carbon Scales [89] where participants weighed a food product up against the CO2 that had been emitted during its production.

4 PAPER CONTRIBUTIONS

During the project, I participated in various research activities, resulting in six papers. The findings from the papers contribute new perspectives and designs for data interactions that move beyond the dominant focus on eco-feedback and static displays for individual behaviour change. The papers comprise the empirical research contribution of the dissertation. I have placed each of the papers into the research framework that was introduced in Section 2.5 according to the primary contribution in relation to sustainable consumption and data interactions (see Figure 4.1).

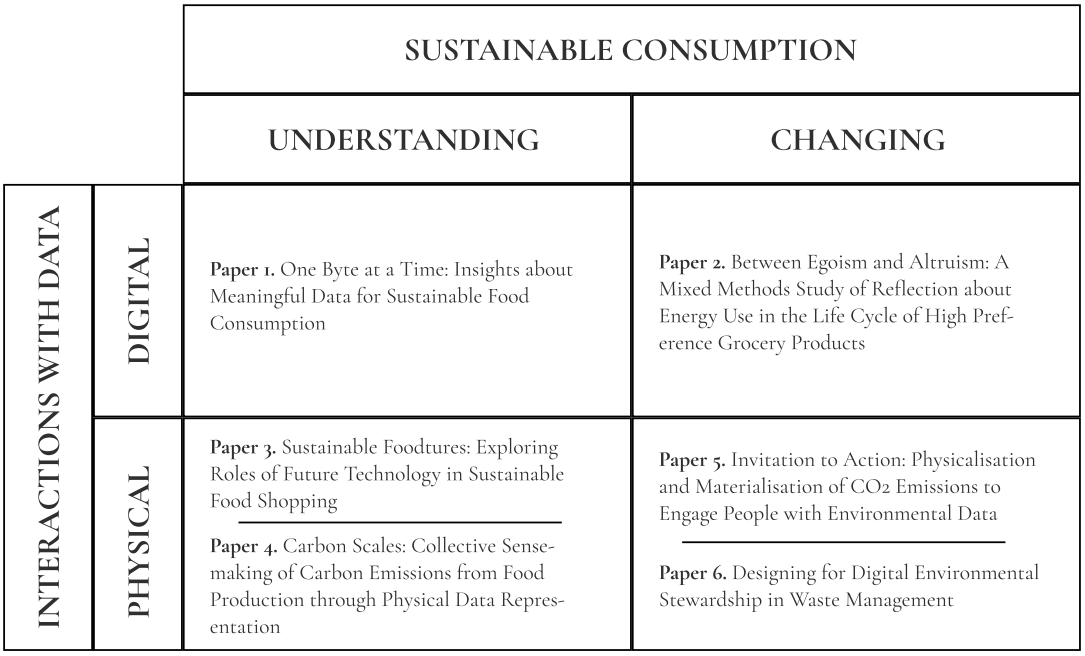

Figure 4.1: The six research papers placed on the framework to outline their individual focus.

The six papers can be found in the Appendix:

1. **Martin Lindrup**, EunJeong Cheon, Mikael B Skov, and Dimitrios Raptis. One Byte at a Time: Insights about Meaningful Data for Sustainable Food Consumption Practices. In *Proceedings of the 2021 ACM Conference on Designing Interactive Systems*, pages 683–696, Virtual Event, USA, 2021. ACM.

2. **Martin Lindrup**, Mikael B. Skov, and Dimitrios Raptis. Between Egoism and Altruism: A Mixed-Methods Study of Reflections about Energy Use in the Life Cycle of High Preference Grocery Products. In *Proceedings of the 2022 Nordic ACM Conference on*

Human-Computer Interaction, pages 1–10, Aarhus, Denmark, 2022. ACM.

3. **Martin Lindrup**, EunJeong Cheon, Mikael B. Skov, Dimitrios Raptis, and Rob Comber. Sustainable Foodtures: Exploring Roles of Future Technology in Sustainable Food Shopping. In *Proceedings of the 2022 Nordic ACM Conference on Human-Computer Interaction*, pages 1–12, Aarhus, Denmark, 2022. ACM.

4. **Martin Lindrup**, Arjun Rajendran Menon, and Aksel Biørn-Hansen. Carbon Scales: Collective Sense-making of Carbon Emissions from Food Production through Physical Data Representation. In *Proceedings of the 2023 ACM Conference on Designing Interactive Systems*, pages 1515–1530, Pittsburgh, PA, USA, 2023. ACM.

5. Aksel Biørn-Hansen, **Martin Lindrup**, Elina Eriksson, Daniel Pargman, and Jarmo Laaksolahti. Invitation to action: physicalisation and materialisation of carbon emissions to engage people with the climate impact of academic flying. Submitted to *the 2024 ACM Conference on Tangible and Embedded Interaction*, Cork, Ireland, 2024. ACM. In review.

6. **Martin Lindrup**, Jakob Tholander, Chiara Rossitto, Rob Comber, and Mattias Jacobsson. Designing for Digital Environmental Stewardship in Waste Management. In *Proceedings of the 2023 ACM Conference on Designing Interactive Systems*, pages 1581–1594, Pittsburgh, PA, USA, 2023. ACM.

4.1 Digital data for understanding (un)sustainable consumption

Paper 1

Martin Lindrup, EunJeong Cheon, Mikael B Skov, and Dimitrios Raptis. One Byte at a Time: Insights about Meaningful Data for Sustainable Food Consumption Practices. In *Proceedings of the 2021 ACM Conference on Designing Interactive Systems*, pages 683–696, Virtual Event, USA, 2021. ACM.

Data on sustainability plays an increasingly central role in everyday consumption [105]; however, we have little knowledge about which data is meaningful for evaluating food sustainability [24]. Using food consumption as a case, this paper investigates how people use digital data to gain an understanding of the sustainability of food and how to make this data more meaningful by drawing on principles from critical data studies [95]. The paper is placed in *Q1* as it shows how people understand sustainability through the use of digital data.

Decisions about food choices are influenced by a number of external and internal factors [16] and food shopping is largely a dispersed activity [47] that is intertwined in a complex network of related activities, such as coming home from work or visiting family. To capture the richness of these decisions, we chose an interview and cultural probe study. First, exploratory interviews were conducted with each of the participants to gain insight into their food shopping practices and decision making about data that goes into sustainable food shopping. Second, a probe pack was sent to the participants. The probe invited participants to place stickers with traffic light colours on newly bought food items based on how sustainable they believed the item to be and elaborate on this with a reflection sheet in order to tap into the everyday practices of making decisions about food sustainability. Third, follow-up interviews aimed to capture participants' reflections on meaningful data based on their experiences.

The paper highlights four findings for understanding sustainability through digital data: (1) people use diverse and sometimes conflicting data for evaluating the sustainability of products; (2) decisions about products are negotiations of values that take into account accumulated local knowledge and data cultures; (3) people need to be equipped with the resources to access, interpret and take action on data by being provided an 'operational context' [95] that bridges environmental data and subjective experiences of sustainability; and (4) 'data artefacts' [95] have the possibility of informing more actionable and critical readings of environmental data. The paper's findings inform *Q1* of the research framework by identifying the main sources of data that are used to understand the sustainability of food products, i.e. food miles, carbon emissions, organicity and water consumption. In addition, digital data shows partial realities, and is often experienced as ambiguous and opaque. Therefore, it is used mainly as part of negotiation processes [87].

4.2 Designing digital data interactions for sustainable consumption

Paper 2

Martin Lindrup, Mikael B. Skov, and Dimitrios Raptis. Between Egoism and Altruism: A Mixed-Methods Study of Reflections about Energy Use in the Life Cycle of High Preference Grocery Products. In *Proceedings of the 2022 Nordic ACM Conference on Human-Computer Interaction*, pages 1–10, Aarhus, Denmark, 2022. ACM.

While eco-feedback technologies in general have been criticised for having a low impact on behaviour change, few have conducted empirical studies of the impact (e.g. [136]). In addition, no research has investigated how product preferences interact with sustainable change strategies such as eco-feedback. Using the case of food shopping, therefore, this paper investigates how food preferences in concert with eco-feedback technology impact sustainable food choices. The paper is placed in *Q2* as it researches how digital data interactions can be used as a design strategy for sustainable change-making.

To study this, a technology probe was developed that provided data on energy production related to food products. The probe was deployed for eight weeks, where participants interacted with it 1-3 times a week. During deployment, participants completed an online survey each week that tapped into their usage patterns, use experience and impact of using the probe. Before and after deployment, interviews were held with each participant to gain insight into their knowledge and behaviour in relation to sustainable consumption and their experiences with using the probe.

The findings show that, while being provided with the data did not change participants' immediate behaviour, the data interfered with their relationship to specific products which sometimes led to conflicting values [90]. It was seen that the participants' altruistic values (e.g. toward the climate crisis) and egoistic values (e.g. toward their own health or pleasure) were conflicting in ways that were incommensurable when presented with environmental data on their food [90]. Also, it became evident that values are highly fluid which means that a food product that was regarded as high preference could go from being affected by egoistic values of taste and appearance, to altruistic values, dependent on, for example, the frequency of consumption. This observed value plurality [72] complicated change-making. Presenting environmental data to people using principles from eco-feedback affects their relationship with food and sustainability; however, this does not necessarily lead to actions toward more sustainable living, as it mainly emphasises our cognitive capacities at arm's length, and usually creates a passive stance towards the data [90]. The findings of the paper inform *Q2* of the research framework by confirming that eco-feedback strategies to change-making have limited impact and extending research by showing that food preferences complicate this even more, as preferences can change altruistic values to egoistic values and vice versa.

4.3 Understanding (un)sustainable consumption through physical data

Paper 3

Martin Lindrup, EunJeong Cheon, Mikael B. Skov, Dimitrios Raptis, and Rob Comber. Sustainable Foodtures: Exploring Roles of Future Technology in Sustainable Food Shopping. In *Proceedings of the 2022 Nordic ACM Conference on Human-Computer Interaction*, pages 1–12, Aarhus, Denmark, 2022. ACM.

As previous attempts to improve understanding of sustainable consumption have been dominated by eco-feedback technology [20, 32], a motivation for this paper was to broaden the design space for data-driven technology for sustainable consumption by departing from the insights from *Paper 1* about how to make data meaningful [87]. Using food shopping as a case, the paper explores how future physical data interactions can support people in understanding the environmental impact of food products and is therefore placed in *Q3*.

The study consisted of co-design workshops and speculative enactments [38] to capture multiple perspectives (i.e. tell, make and enact principles [18]) of people's expectations and experiences of future physical data interactions. The participants were a mix of sustainable food consumers and stakeholders. In the workshops, the participants reflected on what makes data meaningful (tell) and created collages of future data-driven technology that would support their sustainable food shopping (make). The collages were translated into two technology probes; one that allowed for traditional eco-feedback interactions and one that allowed for embodied interactions with data. Participants were invited to explore these in-situ through speculative enactments (enact).

The paper finds that physical data interactions connect to peoples bodies in, and bodily relations towards, the world and toward food in ways that might be difficult to achieve through eco-feedback visualisations [88]. The probe allowed for slow adjustments to body temperature based on which product was picked up, which let the participants stay with their bodily experiences and the relation between the experiences and environmental crises. Although the granularity of data is rather low when translating numeric values into electronic pulses that cause temperature changes on the skin, the embodied data interaction brings another quality — *"It connects data to our bodies and imagination in order to bring forth the affective and ethical aspects of the unsustainable food system"* [88, p. 8]. This allowed for an understanding of the impact of food choices that was grounded in both cognitive and bodily experiences. The paper's findings inform *Q3* of the research framework by showing that physical data interactions can increase understanding of sustainable consumption in ways that are rooted in both bodily and cognitive reflections. Furthermore, although the granularity of the data is low for the physical data interaction, the impact of feeling the environmental impact of food products is high.

4.4 Physical data interactions for understanding (un)sustainable consumption

Paper 4

Martin Lindrup, Arjun Rajendran Menon, and Aksel Biørn-Hansen. Carbon Scales: Collective Sense-making of Carbon Emissions from Food Production through Physical Data Representation. In *Proceedings of the 2023 ACM Conference on Designing Interactive Systems*, pages 1515–1530, Pittsburgh, PA, USA, 2023. ACM.

Carbon emissions related to the production of items can be difficult to understand. This might have to do with their immaterial presence in people's day-to-day lives [104] and the fact that they are ephemeral in nature and often emitted far away from where the products are purchased and used. Using food production and consumption as a case, this paper investigates how materialisation and physicalisation of carbon emissions can support a greater understanding of the environmental impact of food production. The paper, thus, informs *Q3* of the framework.

For this study, carbon emissions data was materialised into physical blocks. In addition, a data physicalisation was designed to be part of a public installation. The data physicalisation consisted of 100g blocks, *Carbon Bits*, and four platforms, *Carbon Scales*, which each represented one of four main phases of food production: agriculture, processing, packaging and transport [89]. People interacted with the data physicalisation in groups of 1-3 with the goal of collectively making sense of where and how much CO2 is emitted in the different phases of food production. Interactions with the data physicalisation were logged and, after interacting with it, the participants shared their experiences from the interactions in a follow-up interview.

The paper finds that physical interactions with carbon emissions data not only made the data more comprehensible and engaging; it also triggered affective stances as it influenced people's senses and expectations about what the data represented, which in turn might create more meaningful relationships with sustainability [104]. In particular, the high interactivity of the data physicalisation made the physical data interactions engaging for the participants. Additionally, embedding weight into *Carbon Bits* that was consistent with how much the CO2 in the atmosphere would weigh if we could capture, enclose and weigh it, helped people form a relationship with the effort it takes to produce various food products — connecting their felt experiences with the realities of the global food system [89]. The paper's findings inform *Q3* of the research framework. It suggests that physical data interactions can foster sense-making processes if they allow people to 'stay in the interaction'. Furthermore, this kind of sense-making results in increased understanding of (un)sustainable consumption [89].

4.5 Designing physical data interactions for sustainable consumption

Paper 5

Aksel Biørn-Hansen, **Martin Lindrup**, Elina Eriksson, Daniel Pargman, and Jarmo Laaksolahti. Invitation to action: physicalisation and materialisation of carbon emissions to engage people with the climate impact of academic flying. Submitted to *the 2024 ACM Conference on Tangible and Embedded Interaction*, Cork, Ireland, 2024. ACM. In review.

For academics, air travel has become an established way of disseminating knowledge, e.g. at conferences all over the world [85]. This leads to academics producing a large carbon footprint [102]. Using academic flying as a case, this paper investigates a design strategy for changing academic flying patterns through physical data interactions. The paper is placed in *Q4* as it investigates how data in physical form can support changing consumption patterns.

For the study, a low-tech and interactive data physicalisation was created that represented a department, the individuals in the department, their flights, and the CO2 emissions connected to their flights. Each individual in the department was presented with a 10x10 cm paper sheet and their flights, together with the accompanying CO2 emissions which were presented using different coloured poker chips. The data physicalisation was brought to four workshops where participants (i.e. scientific staff, political decision-makers and administrative staff) interacted with it in order to reflect upon and/or change current practices.

The paper's findings show that it is possible to foster reflections about when flying is meaningful and which kinds of actions needs to be taken to change current flying patterns [13]. Here, the interactivity of the data physicalisation together with the fact that it was placed in the middle of the room — in the middle of the conversations — supported both sense-making and negotiation processes on multiple levels within the organisation (i.e. departmental, individual, political). Through investigations of data in physical form, we learnt that taking data out of digital structures and bringing it into physical and tangible situations makes the data more actionable, due to material (e.g. using physical tokens to represent CO2 emissions in a physical form) and interactive qualities (e.g. multiple people can engage with the data representation simultaneously; taking individual data points and replacing them to explore different perspectives). The paper informs *Q4* by illustrating that physical data interactions support reflections about current flight patterns and how to change them. For collective change-making purposes in organisational settings, data physicalisation can be a feasible design strategy.

4.6 Changing consumption through physical data interactions

Paper 6

Martin Lindrup, Jakob Tholander, Chiara Rossitto, Rob Comber, and Mattias Jacobsson. Designing for Digital Environmental Stewardship in Waste Management. In *Proceedings of the 2023 ACM Conference on Designing Interactive Systems*, pages 1581–1594, Pittsburgh, PA, USA, 2023. ACM.

As opposed to early SHCI strategies for designing for sustainability (e.g. individual behaviour change [32]), Digital Environmental Stewardship (DES) has a long-term, ecological perspective on design [106]. Using household waste management as a case, this paper investigates how physical data interactions can support changing household waste management practices through a DES design lens. The paper is placed in *Q4* as it investigates a strategy for change that is supported by physical data interactions.

To study this, a series of workshops were held with the residents and management of an apartment complex. In addition, post-cards were collected that tapped into people's issues with collective waste management. Lastly, log data from when people enter one of the four recycling rooms was collected and used as a capacity in the design process. The data, both in aggregated form (i.e. displayed in data visualisations) and in non-aggregated form (i.e. spreadsheets printed on paper), was brought to the workshops as data intermediaries [91].

The paper highlights that data in physical form fosters discussions based on local knowledge from people using the recycling rooms and digitally captured knowledge (i.e. log data) about the area. The physical data interactions resulted in an understanding of the residents' experiences of room use, responsibilities, issues of care, etc. — the actions that are needed and who needs to be part of this change-making toward better recyclable waste management [91]. While there has been a tradition in modern times for data representations to be static, polished and controlled by a single person [125], this paper argues for an approach which emphasises very tangible work with incomplete and small data (i.e. data that is gathered locally by and/or from the people the data concerns [40]). This paper suggests using this as 'data intermediaries' to explore conflicting positions and gain new insights about possible ways to make changes towards more sustainable waste management [91]. The paper informs *Q4* through strengthening the findings from *Paper 5* regarding the value of physical data interactions for collective change-making and expanding the findings of *Paper 5* by suggesting data intermediaries as an approach to physical data interactions in sustainable consumption.

5 DISCUSSION

This dissertation has outlined a research framework for characterising data interactions for sustainable consumption and provided empirical findings in six papers that investigate each quadrant of the framework (see Figure 5.1). In this chapter, I will reflect on the research that was carried out and present design considerations based on my research.

		SUSTAINABLE CONSUMPTION	
		UNDERSTANDING	CHANGING
INTERACTIONS WITH DATA	DIGITAL	• People use digital data such as carbon footprints and transport length to understand sustainable consumption and use these together with their accumulated knowledge to make choices (Paper 1) • Digital data is perceived as opaque and ambiguous (Paper 1)	• Eco-feedback technology has limited impact on changing consumption patterns (Paper 2) • Individual preferences complicates changing consumption due to value conflict (Paper 2)
	PHYSICAL	• Physical data interactions that invite bodily and cognitive reflections can increase understanding of sustainable consumption and are often perceived as engaging (Paper 3 and Paper 4) • Interactions that allow people to 'stay in the interaction' supports sense-making (Paper 4)	• Physical data interactions can support reflections about consumption patterns and how to change them. Especially for collective change-making purposes (Paper 5 and Paper 6) • Data intermediaries can be a favorable approach for doing physical data interactions for sustainable consumption (Paper 6)

Figure 5.1: Overview of the empirical findings from the six papers plotted into each quadrant of the research framework.

5.1 HCI for sustainable consumption

Supporting sustainable consumption through technological means is no straight forward task [59]. People do not act rationally towards a single sustainability definition when provided with data on their consumption patterns which was the general belief from the early SHCI research (i.e. [20, 117]). This does not mean that data provision does not play a role in supporting sustainable consumption; it means that we need to rethink how we do it so that data becomes engaging and meaningful. I approached the need for rethinking how to make data on sustainability matters engaging and meaningful, by turning to embodiment and physicalisation. Notably, it is not my intention to reject previous work on data representation for sustainable consumption altogether but instead outline a complementary agenda for researchers and designers of data interactions for sustainability, focusing on engagement as a means to make data more meaningful for non-experts.

As my research has been divided into understanding (un)sustainable consumption and changing consumption patterns, the following sections will deal with each of these in turn.

Understanding (un)sustainable consumption

In this section, I will reflect on the first vertical axis of the research framework, i.e. understanding consumption through digital and physical data interactions. Throughout my research, I found that two aspects in particular characterise the current landscape of data interactions for understanding (un)sustainable consumption: (1) an inherent ambiguity and (2) low levels of operationality in the available data.

People experience a sense of ambiguity when interacting with technological artefacts that represent data on sustainability products (e.g. carbon footprint calculators), which can be caused by abstractions of the data [87]. However, it is not necessarily the abstractions, since all data is an abstraction of a phenomenon, but the missing opportunity to engage with the data, that creates a sense of ambiguity. In *Paper 1*, I observed that participants experienced ambiguity in especially digital representations of carbon footprints (understanding/digital quadrant). For example, the carbon footprint on a ready-made pizza dough was the same as for a ready-made pizza, although the latter contained both animal protein and vegetables. The interfaces for gaining an understanding of the sustainability of products did not allow further investigations into why, for example, two carbon footprints may be similar for very differnt products. From a post-phenomenlogical perspective, this type of interface generates a hermeneutic relation [126] in which the data mediates a certain understanding of the world in which two different products can have the same characteristics. This will, however, conflict with the knowledge that people may have about carbon footprints and thus renders these technological artefacts meaningless for enacting sustainable consumption [87]. I identified a need for developing an operational context [95] in which people could grapple with and explore the data [87], turning the hermeneutic relation into an alterity relation [126]. An alterity relation with data would involve finding ways to enable people to engage in the ambiguity. This echoes previous research that has argued for making the incompleteness of data a strength [23]. To establish the operational context, I turned to physical data interactions (understanding/physical quadrant), as previous research has outlined multiple benefits with physical data interactions to support understanding through engagement (e.g. [76,104]). My physical data interaction efforts to support understanding (un)sustainable consumption, draw especially on two aspects for making data more meaningful and engaging: embodiment and reification of data.

I found that embodied data interactions allow for encounters with the future trouble of climate change, which results in a relational stance towards the environment that is perceived as meaningful for fostering understandings of sustainable consumption. An example of this

is the work with embodiment in *Paper 3*, where participants were sensing climate change through on-skin sensations of heat or cold based on which product they picked up in a store. Additionally, my work with Carbon Bits in *Paper 4* also drew on embodiment by allowing participants to weigh carbon emissions from food production using physical blocks. This work resonates with previous HCI research that draws on art and science and finds that bringing forth affective aspects of crisis provides more compelling and engaging encounters with these crises through environmental data [112,113]. I showed that researchers and designers can engage non-experts in environmental data in ways that are meaningful by drawing on embodiment in physical data interactions [88, 89].

In addition, I found that data physicalisation allows people to 'stay in the interaction' and makes data engaging — two aspects of data interactions that greatly support sense-making processes [13,89]. An example is the work with the physicalisation of academic flight data (i.e. *Paper 5*), where we invited participants to collectively make sense of their flying by engaging them in data about their flight patterns. The idea of staying in the interactions with data draws from prior work on slow technology [57] and reflective design [110], by suggesting that interactions with the environment through data should invite reflection, thus addressing SHCI critism of eco-feedback systems for sustainable consumption [20]. One important consideration for fostering reflections based on slow interactions is how to reify data. This will be discussed in more detail in Section 5.2.

My research shows that inviting people to make sense of data and the environment engages them in the sustainability problems that are emerging, and increases their understanding about the relation between consumption and sustainability problems [13, 88, 89]. These two aspects of interactions (i.e. sense-making and engagement) are, in my view, valuable for creating meaningful relations with the environment. Prior technological interventions have aimed to present sustainability issues *to* people in an effort to change their behaviour, instead of *with* people, which could very well be a more engaging and meaningful way of building understanding of sustainable consumption. In Section 5.2, I will lay out my suggestions to designers of data interactions to go beyond presenting data *to* people and instead present data *with* people in an effort to promote more sustainable consumption.

Changing consumption patterns

In this section, I will reflect on the second vertical axis of the research framework, i.e. changing consumption through digital and physical data interactions. In my studies, I observed that there is a clash between egoistic and altruistic values that complicates sustainable change-making (changing/digital quadrant). For example, in *Paper 2*, EnergyFetcher failed to induce radical changes in people's food purchases [90]. However, I saw accounts of value plurality [72] where people carry their choices with them and use them to reflect on future choices.

This was also seen in the other studies on changing consumption patterns through physical data interactions (changing/physical quadrant). Changing consumption patterns is a complex process that takes place over a prolonged period of time and is the result of a multitude of actions. This is an issue that has been highlighted in previous literature (e.g. [20, 60]). I am unable to see whether this line of research actually leads to long-term changes. The move from understanding (un)sustainable consumption patterns to changing them has been a central issue in the SHCI literature for decades (i.e. knowledge-action gap [84, 127, 128]). While I am unable to provide suggestions for changing consumption patterns based directly on my empirical findings, I have identified several considerations that can support the move from understanding to changing.

Based on my research, I would argue that technology should not be viewed in terms of solutions to sustainable problems. Instead, technology should rather be seen as supportive tools that might help illuminate parts of the different roads towards sustainable consumption. There is no single way to live sustainably and, therefore, in turning towards technology, designers and researchers should acknowledge the various ways of enacting sustainable consumption. In this view, technology could instead be seen as 'transition tools' [12], each with their own supportive capabilities for increasing understanding or enacting changes but also their own prescriptive purposes. As designers, we should invite people to carefully reflect on their values concerning sustainable consumption and choose the tools (if any) that support their unique transition. This understanding of technology is also apparent in the phenomenological literature on 'the question of technology' [62]. Rather than seeing technology as the answer to sustainability problems, it should instead be seen as a lens for understanding the world [62]. Turning to post-phenomenology can help us reflect on the technological lenses that we develop and the kind of relation they mediate [126]. Thereby, helping us understand how technology, and hereunder data, shapes us as humans.

Additionally, since all action is embedded in the social sphere, SHCI researchers and designers should engage more deliberately with multi-scales of actions in order to make lasting sustainable changes [111]. During my research, I have sought to engage different stakeholders in sustainability issues using data. My work with placing data in between different stakeholders and their object of focus has resulted in a preliminary understanding of data-enabled negotiations of view points and conflicting understandings towards environmental action. I have coined these constellations of people, data and environmental action 'data intermediaries' (see [91]). I conceptualise data intermediaries as multi-stakeholder interactions with data enabled through, for example, workshops or similar formats that allow people to negotiate between the digitally captured knowledge (the data) and their subjective experiences of the phenomenon that the data depicts (e.g. [13, 91]). This shifting focus between data and the world, i.e. alterity relation, can foster negotiations about the meaning of the data and the collective and personal actions needed based on the data [22, 23]. By drawing attention to its

own presence and the surroundings, the data mediates between collectives of people and the issues that are at hand. Combined with data physicalisation principles, data intermediaries make data engaging and actionable for non-experts, which may very well lead to sustained changes in current practices.

In my research, I have studied interactions on individual and collective levels; yet, only so many changes can be enacted on these levels. Since individuals are entangled in infrastructural and political realities, I believe that research also needs to engage more with these realities to make significant changes (cf. [34]).

5.2 Design considerations

Based on my studies, I have identified two considerations for designing data interactions for non-experts that are complementary to eco-feedback strategies. The considerations concern embodied data interactions and reifying data. These should not necessarily be seen as an alternatives to the more traditional eco-feedback approaches to interacting with data; instead, they should be seen as complementary approaches for data representation that foster engagement. In addition, the considerations are based on my work and do not present an exhaustive list of possible considerations for designing data interactions for sustainable consumption. Nonetheless, I lay them out to support designers of data interactions for sustainable consumption based on my experiences from studying this research area.

Embodied data interactions

In my research, I investigated embodying data into our actions to change our relationship with the environment [88, 89]. I developed interventions to interweave people in environmental issues in ways that let them explore them in new ways — the data acted as a subtle extension of their sensory capabilities (i.e. [61]).

An example is Sensing Climate Change (see *Paper 3*) which simulated, through a personal air-conditioning device, global warming or cooling by regulating body temperature based on the climate footprint of products picked up in a store. Reaching for a product in the store, the capabilities of feeling the environment were enhanced through placing data in-between and in the interaction of the person and the product: *"[…] technology we might create to be worn on our bodies or to respond to our movements would also change our capacity for certain experiences, as well as our practices and our understanding of our own bodies"* [67, p. 13]. Embodied data interactions connect to both our bodies in, and bodily relations with, the world in ways that are difficult to achieve through eco-feedback visualisations [88]. The idea with the embodied data experiences are not for people to make more efficient decisions — which is one of the reasons for using weight and temperature as modalities for the interaction. This allowed people to stay

with their bodily-, aesthetically- and intellectually-rooted reflections about the experiences and the mediation between the experience with the probes and the environmental crises. So, although there is little granularity in the data when translating numeric values into e.g. electronic pulses that cause temperature changes on the skin, the embodied data brings a different quality to the interaction — the entanglement with the experience of future trouble [58]. While it might not be a 'nice' experience to visit our thoughts about a potential, yet dystopian, future, we have a moral and practical need for doing so to foster discussions about how we adapt to potential future scenarios. In soma-aesthetic design, it is a central principle that designing *"[...] harmonize with the pleasures and displeasures, beats, rhythms, and richness of the living, felt, bodily subjectivity — our human condition"* [67, p. 22]. Although we may want to shield ourselves from thinking about the consequences of today's environmental issues, foregrounding them can foster a sense of connectedness with and responsibility for others and the environment, since we all share the same human conditions [4].

The research on Carbon Scales and Carbon Bits (i.e. *Paper 4*) showed how embodied experiences of climate impact can be triggered through the use of weight and narratives around physical blocks. Carbon Bits were designed to draw attention to themselves through their weight and to be used as tangible data points that participants could use in their discussions. The tangible and embodied experiences of carbon emissions allowed people to 'stay in the interactions' which was valuable in fostering sense-making [89]. Furthermore, the Carbon Bits were ascribed a narrative — as captured carbon dioxide from the atmosphere compressed into a block form. Drawing on Dourish and Cruz' [36] concept of data narratives, the narrative supported the imagining of culturally embedded tropes that shape or are shaped by the data and/or the phenomena that the data represents. With the combination of physical weight and the narrative surrounding the Carbon Bits, the experiences facilitated affective engagement in the efforts it takes from the food system to produce fresh food [89]; thus, involving people in sustainability issues in ways that are non-prescriptive cf. calls from research (e.g. [11, 20, 21, 110]). Extending the concept of data narratives [36], I want to argue for material data narratives, as the combination of materiality and narratives activates an affective engagement in the issues that are depicted by data.

Through my research on embodied data interactions, I want to highlight opportunities that embodiment has in relation to sustainable consumption. I found that embodied data interactions can engage people in the future trouble of sustainability issues in a present day context and make an exploratory and safe space for reflecting about the potential crisis that lies ahead of us [88, 89]. The embodied data interactions *"[...] connects data to our bodies and imagination in order to bring forth the affective and ethical aspects of the unsustainable food system"* [88, p. 8]. Although embodiment has less focus on data granularity, the impact of making data-driven technologies an extension of our sensory 'system was very visible in the ability to connect to our ethics in movement [39]. In addition, introducing materiality and narratives into the

embodied data interactions, such as the global temperature change narrative from *Paper 3* or the condensed CO2 narrative from *Paper 4*, also supports affective engagement. Therefore, I want to highlight two aspects that designers should consider when designing embodied data interactions for sustainable consumption.

Bringing trouble to the present: bringing future sustainability issues into a present-day scale using embodiment gives people ways of relating to the environment through a sensory connection with data.

Weaving material narratives into data: the combination of materiality in and narratives around data supports affective engagement in the issues depicted by the data.

Reifying data through physicality

In my research, I also gained insight into reifying data through the process of materialising data in physical form and the impacts of doing so on interactivity and engagement. People tend to focus primarily on 'visible' manifestations of e.g. CO2 emissions such as smoke from the chimney of a local factory, while 'invisible' emissions are neglected, not necessarily because of their impact on the environment, but because of their abstract form and distance from our daily practices [104]. Translating these abstract concepts into tangible ones through the process of materialisation and physicalisation can make the otherwise invisible and ephemeral elements of our everyday lives, such as carbon emissions, interactive and engaging for people who are impacting and/or impacted by carbon concentrations in the atmosphere [13, 89].

Data physicalisation in the area of sustainable consumption has proven beneficial in the past for communicating e.g. the impact of dietary choices [109] and air quality in home settings [68]. However, these data physicalisations have most often been static in nature — so-called data sculptures [125]. In my research, I have sought to design highly interactive data physicalisations in order to promote engagement in the data. In *Paper 5*, this was achieved using poker chips to display individual flights for each employee and the carbon emissions associated with each flight. People could thereby engage with the data physicalisation by lifting up the chips, counting them, replacing them, and in other ways using them actively in their discussions. Similarly, in *Paper 4*, people were able to pick-up and place Carbon Bits and also weigh them in their hands to gain a bodily understanding of the impact of food production. In the two papers, it was clear that making physical data representations interactive, supported sense-making about sustainability issues. Data in physical form produced a material and sensory anchoring in the phenomena that helped people relate to otherwise abstract concepts of e.g. kilograms or tonnes of CO2.

Another distinct quality of physicalising data concerns our active perception. Heidegger [63,

p. 15] provided an analogy of how movement guides perception: "*Today I am in all clarity at a place from which my entire previous literary output [...] has become alien to me. Alien like a path brought to an impasse, a path overgrown with grass and vegetation - a path which yet retains the fact that it leads to Da-sein as temporality*". It is through our temporal and spatial being-in-the-world [61] that an object of focus is explored. Drawing from this analogy, it becomes evident that data represented in a two-dimensional digital environment and three-dimensional physical environment afford different explorations of the data that not only concern the added z-axis. Although both data representations are within our temporal and spatial present, the physical representation allows for a particular kind of movement that affords new explorations of the data, where people gradually unfold the object of focus through careful examination. This active examination of data was found to be beneficial as it facilitated explorations of the data [13, 89].

Additionally, due to the nature of the data physicalisations, i.e. that they are displayed in a spatial environment where no one person has control over them, I observed that people, both through their movement around, and discussions based on, the data physicalisations, claimed individual and collective ownership of the data and the issues that the data depicted [13]. In *Paper 5* in particular, it was evident that the vast majority of people actively participated in discussions around the data physicalisation which might be due to the fact that no single person was in control. This finding suggests that data physicalisations might be useful in situations where participation is key for sustainable action. Physicalising data, having people actively interact with it (e.g. as data intermediaries) and engaging in discussions around the data in spatial environments, fosters ownership and participation from diverse stakeholders which can be seen as a step towards 'democratising data' [13, 86].

Based on my research, I found that the process of materialising data in physical form and making interactive physicalisations of environmental data can be fruitful for sustainable consumption. There are three key aspects that I want to highlight which support reifying data for non-experts: interactivity, active perception and participation in representation. Designing data physicalisations to be highly interactive and allowing people to actively move around and perceive data physicalisations in various ways, promotes exploration and supports engagement. Also, data physicalisations provide the opportunity to foster a sense of ownership and participation [13]. Therefore, I want to outline the following for designers and researchers who seek to reify data for sustainable consumption purposes:

Supporting engagement through interactivity: data in a physical form has the benefit of being highly interactive (e.g. stackable, manipulative) which supports engagement with sustainable consumption.

Active perception for exploration: moving around, feeling and seeing data from different angles is a way of utilising our active perception, which supports exploration of sustainability

issues.

Participation in representation: allowing for participation in data representations can support individual and collective ownership of sustainability issues.

5. DISCUSSION

6 CONCLUSION

In this dissertation, I have argued for the need to deepen our understanding of the role that data plays in sustainable consumption through a Human-Computer Interaction perspective. Based on empirical investigations in six papers employing probing techniques and qualitative research methods, I have gained insight into this area. In addition to the six paper contributions, this dissertation also contributed a framework for characterising data interactions for sustainable consumption in HCI. The dissertation has provided empirical understandings and design considerations for researchers and designers of data interactions for sustainable consumption based on a collection of research papers. The following chapter concludes the dissertation by answering the three research questions.

6.1 What characterises data interactions for sustainable consumption?

Data interactions for sustainable consumption can be characterised in two dimensions. The first dimension is *sustainable consumption* in which research can be seen to be motivated by two core purposes: *understanding* (un)sustainable consumption and *changing* unsustainable consumption patterns. The second dimension is *interactions with data* (or data interactions for short) which, as I have argued, can be separated into interactions with *digital* and *physical* data representations.

The dissertation contributes a framework that characterises data interactions for sustainable consumption by juxtaposing the two dimensions and their underlying concepts (see Figure 2.1 in Section 2.5). The characteristics of sustainable consumption are based on terminology from previous environmental psychology and SHCI research that highlights two main purposes in transitioning to more sustainable consumption. These purposes are to understand (un)sustainable consumption patterns and to change these patterns to more sustainable ones. It should be noted that understanding and changing in this context refer to the intentions that an intervention can have, e.g. changing waste management practices so more waste is recycled, and not necessarily the outcome hereof. Interactions with data in relation to sustainable consumption can be characterised as either digital or physical on the basis of the representative form of the data.

The framework supported structuring the empirical investigations into four quadrants, each with a distinct albeit interconnected focus (see Figure 5.1). Reflecting on the findings gained from applying the framework, I argue that understanding sustainable consumption from a data interaction perspective, is a process of sense-making that can be supported by active engagement and discouraged through ambiguity and low levels of operational data. However, instead of seeking to remove ambiguity in sustainability data, I argue that fostering ways to

engage in this ambiguity, using the incompleteness of data as a strength, can result in a more meaningful understanding of data and sustainability issues.

6.2 How do people use data to make sense of sustainable consumption?

The six paper contributions in this dissertation detail how people, both individually and collectively, make sense of data on sustainable consumption when interacting with digital and physical data representations. Several factors come into play when people make sense of data for sustainable consumption. *Paper 1* and *Paper 6* detail that data partakes in individual and collective negotiation processes together with accumulated knowledge that people might have built up over time. Two papers (*Paper 4* and *Paper 5*) highlight that the impact of data interactions are connected to our perceptual frames. For example, by moving around a physical data representation and taking up and replacing physical data pieces, people explored aspects of the data that were otherwise hidden. In *Paper 3* and *Paper 4*, in particular, the impact of modality in interacting with data was explored through embodiment and tangibility. The papers show that introducing multiple modalities in data interactions can support sense-making in ways that are highly engaging for non-experts. *Paper 2* and *Paper 5* highlight the importance of making data relative so that people can relate the data to known phenomena. I found that the form of the data (i.e. digital or physical) plays a large role in how people use the data in sense-making processes. Digital data for sustainable consumption is often more precise and exhaustive than data in physical form; however, it does not foster engagement as it is often represented through interfaces with low operationality, and ambiguity tends to be hidden through interfaces that represent digital data. Physical data interactions, on the other hand, can be an alternative to digital data interactions for sense-making processes as they allow people to stay in the interactions with both the data itself and the issues that the data depicts in ways that are highly engaging. However, interactions with data in physical form might require more physical space and more effort to create.

6.3 How can we foster sense-making and engagement in sustainable consumption through data interactions?

In addition to gaining an understanding of the constituents of sense-making processes, the six papers also provide considerations for how to design data interactions that support sense-making and engagement for non-expert audiences. I show the value of complementing traditional data representation techniques, such as eco-feedback, with two less explored modes of data interactions, which involve embodiment and reifying data through physicality.

Embodiment has been shown to bring forth affective and relational stances to sustainabil-

ity issues through data interactions towards understanding and/or changing consumption patterns. I want to highlight two design considerations in particular for embodied data interactions: (1) the use of material narratives around data and (2) finding ways to bring future trouble from sustainability issues into the present.

My research on physical data interactions has also led to considerations on how to reify data, as a means to support sense-making towards understanding and/or changing consumption patterns. Here, I present three design considerations that can support reifying data for non-experts: (1) making physical data representations interactive so that people can grapple with the data, (2) allowing for active perception by giving the opportunity for movement around the physical data representations, and (3) facilitating participation in the data, which to a large degree connects to the first two considerations and to the format that physical data interactions can partake in where no one person is in control of the data representations.

6.4 Limitations

There are some limitations with this dissertation that I will reflect on in the following. The limitations concern the understanding of the term 'data', the understanding of sustainable consumption concepts, and the experience that participants had when it came to interacting with data.

First, in the context of this dissertation, I have chosen to adopt a broad understanding of the term 'data' as an abstraction of any phenomenon through observation, recording and representation [82]. For decades, in various research communities there have been multiple and sometimes conflicting understandings of when something can be understood as data and when it should be understood as information. Had I chosen to adopt a narrower understanding of data (e.g. [8]), then most of my uses of the term 'data' should have been changed to 'information'. This would have led to theories and concepts from, e.g. information studies and possibly different results in my studies. By adopting a broad understanding of the term data, I want to emphasise the 'strangeness' and 'unsettledness' of the phenomenon that the data depicts (i.e. [95]). This, I would argue, fits well with the exploratory approach I have taken to design work in the dissertation.

Second, a central interest in the dissertation is sustainable consumption, which has been divided into two underlying concepts of understanding and changing. While I have explored design strategies to support understandings and changes towards sustainable consumption, I cannot document long-term changes to consumption patterns with this dissertation. This would have entailed a different set of theories and methods. What I can say is that the designed interventions that were studied in this dissertation have potential for changing consumption patterns based on parameters that are characteristic to changes in consumption

such as engagement and care [84, 101]. When adopting the concepts of understanding and changing, I refer to design strategies aimed at either increasing understanding or enacting changes in consumption patterns towards more sustainable ones.

Third, the focus on non-experts in relation to interactions with data, i.e. individuals who have not received comprehensive training in understanding and manipulating data representations, has limited the findings in certain ways. It would have been valuable to compare similarities and differences in the perception of data between experts and non-experts; however, this would have resulted in a different kind of dissertation. The reason for limiting the scope of this work to non-experts is that the increasing amount of data that is becoming available is to a large degree impacting non-experts and these non-experts are also impacting the issues that the data represents (e.g. global temperature changes).

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APPENDIX

This chapter contains the following six papers constituting the primary contribution of this dissertation.

1. **Martin Lindrup**, EunJeong Cheon, Mikael B Skov, and Dimitrios Raptis. One Byte at a Time: Insights about Meaningful Data for Sustainable Food Consumption Practices. In *Proceedings of the 2021 ACM Conference on Designing Interactive Systems*, pages 683–696, Virtual Event, USA, 2021. ACM.

2. **Martin Lindrup**, Mikael B. Skov, and Dimitrios Raptis. Between Egoism and Altruism: A Mixed-Methods Study of Reflections about Energy Use in the Life Cycle of High Preference Grocery Products. In *Proceedings of the 2022 Nordic ACM Conference on Human-Computer Interaction*, pages 1–10, Aarhus, Denmark, 2022. ACM.

3. **Martin Lindrup**, EunJeong Cheon, Mikael B. Skov, Dimitrios Raptis, and Rob Comber. Sustainable Foodtures: Exploring Roles of Future Technology in Sustainable Food Shopping. In *Proceedings of the 2022 Nordic ACM Conference on Human-Computer Interaction*, pages 1–12, Aarhus, Denmark, 2022. ACM.

4. **Martin Lindrup**, Arjun Rajendran Menon, and Aksel Biørn-Hansen. Carbon Scales: Collective Sense-making of Carbon Emissions from Food Production through Physical Data Representation. In *Proceedings of the 2023 ACM Conference on Designing Interactive Systems*, pages 1515–1530, Pittsburgh, PA, USA, 2023. ACM.

5. Aksel Biørn-Hansen, **Martin Lindrup**, Elina Eriksson, Daniel Pargman, and Jarmo Laaksolahti. Invitation to action: physicalisation and materialisation of carbon emissions to engage people with the climate impact of academic flying. Submitted to *the 2024 ACM Conference on Tangible and Embedded Interaction*, Cork, Ireland, 2024. ACM. In review.

6. **Martin Lindrup**, Jakob Tholander, Chiara Rossitto, Rob Comber, and Mattias Jacobsson. Designing for Digital Environmental Stewardship in Waste Management. In *Proceedings of the 2023 ACM Conference on Designing Interactive Systems*, pages 1581–1594, Pittsburgh, PA, USA, 2023. ACM.

Each paper will be preceded by a page presenting the title, abstract, and publication information, followed by the paper. The digitally available version of this dissertation is redacted and contains only each paper's title, abstract, and publication information.

Paper 1

One Byte at a Time: Insights about Meaningful Data for Sustainable Food Consumption Practices

Abstract

Data have played an extensive role in sustainable HCI research by informing the impacts of our behavior on the environment and helping us make better environmental choices. However, in the area of sustainable food consumption and sustainable HCI, there is little investigation on the roles of food data for the design of technology. This paper presents findings from a qualitative study of sustainable-conscious individuals' food data seeking experiences. Our results show the way in which the current food data is challenging our understanding of its environmental impacts, which concern data of availability, data representations, and data cultures. Drawing from Loukissas' six critical data principles, we discuss how "locality" and "place" could cast a new insight on food and its sustainability. We also offer possible design directions for sustainable HCI technologies utilizing food data.

Martin Lindrup, EunJeong Cheon, Mikael B Skov, and Dimitrios Raptis. One Byte at a Time: Insights about Meaningful Data for Sustainable Food Consumption Practices. In *Proceedings of the 2021 ACM Conference on Designing Interactive Systems*, pages 683–696, Virtual Event, USA, 2021. ACM.

Paper 2

Between Egoism and Altruism: A Mixed-Methods Study of Reflections about Energy Use in the Life Cycle of High Preference Grocery Products

Abstract

The global food system is a major contributor to environmental unsustainability partly due to the immense amount of energy that is consumed in product life cycles. Our endeavour with the present study was to gain insights about how people experience and reflect upon energy use embedded in the life cycle of grocery products. Based on a two-month mixed-methods study that encompassed interviews, technology probe deployment, and continuous surveys with eight participants, we identified characteristics of choices for high and low preference foods on sustainability; impacts of various abstractions of information; and challenges and opportunities for digital technology in grocery shopping. We discuss the findings in relation to the notion of value plurality and present design implications for food assistance systems in Sustainable HCI.

Martin Lindrup, Mikael B. Skov, and Dimitrios Raptis. Between Egoism and Altruism: A Mixed-Methods Study of Reflections about Energy Use in the Life Cycle of High Preference Grocery Products. In *Proceedings of the 2022 Nordic ACM Conference on Human-Computer Interaction*, pages 1–10, Aarhus, Denmark, 2022. ACM.

Paper 3

Sustainable Foodtures: Exploring Roles of Future Technology in Sustainable Food Shopping

Abstract

Several efforts have been made to use technology to encourage people to buy more environmentally sustainable food. However, only a small amount of research has attempted to understand the roles of technology in food shopping by incorporating perspectives from various stakeholders. We aimed to explore how the design space for future technology in sustainable food shopping is negotiated among sustainability-aware individuals, sustainability professionals, and designers through co-design workshops and speculative enactments. We identify three roles of technology in sustainable food shopping: technology as guidance, technology as mediator, and technology for reflection. Additional insights are provided regarding how parts of these roles for future technology are rejected, adopted, or adjusted when enacted in everyday food shopping. We discuss design implications for the roles of sustainability technology in terms of data accuracy and transparency, as well as embodied data experiences. Furthermore, we provide methodological considerations for speculative enactments in SHCI.

Martin Lindrup, EunJeong Cheon, Mikael B. Skov, Dimitrios Raptis, and Rob Comber. Sustainable Foodtures: Exploring Roles of Future Technology in Sustainable Food Shopping. In *Proceedings of the 2022 Nordic ACM Conference on Human-Computer Interaction*, pages 1–12, Aarhus, Denmark, 2022. ACM.

Paper 4

Carbon Scales: Collective sense-making of carbon emissions from food production through physical data representation

Abstract

The climate impact of our food consumption is a key issue to sustainability. Yet understanding the food system and the impact it has can be difficult given its abstract nature. In this paper, we report on a Research through Design project aimed at designing and evaluating a data physicalization for supporting collective sense-making of the climate impact of food. Throughout the design process, we have explored the materiality of CO2 emissions and ways to design through less resource use. Our findings show that collective sense-making can be enabled through interactive data physicalizations and that this can lead to carbon literacy. We expand on a) sustainability through design by arguing for the value of artifacts that let people *stay in the interaction* as this can support collective sense-making, and b) sustainability in design by showcasing the value of designing with an *interaction-first and materials-second* mindset.

Martin Lindrup, Arjun Rajendran Menon, and Aksel Biørn-Hansen. Carbon Scales: Collective Sense-making of Carbon Emissions from Food Production through Physical Data Representation. In *Proceedings of the 2023 ACM Conference on Designing Interactive Systems*, pages 1515–1530, Pittsburgh, PA, USA, 2023. ACM.

Paper 5

Invitation to action: physicalisation and materialisation of CO2 emissions to engage people with environmental data

Abstract

Today there is a wealth of data available detailing the climate impact of our actions, including the CO2 emissions and climate impact of academic flying. Despite this, such data is hard to engage with in the abstract, leading to little practical action. We argue that we need new ways of making environmental data such as CO2 emissions more engaging, meaningful, and actionable. Drawing on the results of a series of four workshops where we created and evaluated a low-tech data physicalisation of flight data with students and staff at a research-intensive university, this paper outlines three sets of methodological considerations for data physicalisations aimed at supporting new conversations and actions toward sustainability. We conclude the paper with reflections and a discussion of this work and its implications.

Aksel Biørn-Hansen, **Martin Lindrup**, Elina Eriksson, Daniel Pargman, and Jarmo Laaksolahti. Invitation to action: physicalisation and materialisation of carbon emissions to engage people with the climate impact of academic flying. Submitted to *the 2024 ACM Conference on Tangible and Embedded Interaction*, Cork, Ireland, 2024. ACM. In review.

Paper 6

Designing for Digital Environmental Stewardship in Waste Management

Abstract

Waste management in urban areas is a complex process, encompassing a variety of activities, actors (e.g., single individuals, waste collectors, condominium associations), and capacities (e.g., from household recycling stations to physical infrastructures such as recycling and sorting facilities). Whereas previous HCI Design research has tackled problems with waste management from an individual, behavioral change perspective, we approach this design space through a feminist ecological design perspective of Digital Environmental Stewardship. Through a combination of qualitative empirical data and materials generated at design workshops, we outline challenges related to waste management in a complex of five multi-apartment buildings. We propose a number of design explorations addressing such challenges, and reflect on the generative role of the DES framework in framing design from a collective and ecological perspective.

Martin Lindrup, Jakob Tholander, Chiara Rossitto, Rob Comber, and Mattias Jacobsson. Designing for Digital Environmental Stewardship in Waste Management. In *Proceedings of the 2023 ACM Conference on Designing Interactive Systems*, pages 1581–1594, Pittsburgh, PA, USA, 2023. ACM.

ISSN (online): 2446-1628
ISBN (online): 978-87-7573-642-3

AALBORG UNIVERSITY PRESS