Computational Environmental Ethnography: Combining Collective Sensing and Ethnographic Inquiries to Advance Means for Reducing Environmental Footprints

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ABSTRACT

We lack an understanding of human values, motivations and behavior in regards to new means for changing people's behavior towards more sustainable choices in their everyday life. Previous anthropological and sociological studies have identified these objects of study to be quite complex and to require new methods to be unfolded further. Especially behavior within the privacy of people's homes has proven challenging to uncover through the use of traditional qualitative and quantitative social scientific methods (e.g. interviews, participatory observations and questionnaires). Furthermore, many research experiments are attempting to motivate environmental improvements through feedback via, e.g., room displays, web pages or smart phones, based on (smart) metering of energy usage, or for saving energy by automatic control of, e.g., heating, lighting or appliances. However, existing evaluation methods are primarily unilateral by opting for either a quantitative or a qualitative method or for a simple combination—and therefore do not provide detailed insight into the potentials and impacts of such solutions. This paper therefore proposes a combined quantitative and qualitative collective sensing and anthropologic investigation methodology we term Computational Environmental Ethnography, which provides quantitative sensing data that document behavior while facilitating qualitative investigations to link the data to explanations and ideas for further sensing. We propose this methodology to include the establishment of base lines, comparative experimental feedback, traceable sensor data with respect for different privacy levels, visualization of sensor data, qualitative explanations of recurrent and exceptional patterns in sensor data, taking place as part of an innovative process and in an iterative interplay among complementing disciplines, potentially including also partners from industry. Experiences from using the methodology in a zero-emission home setting, as well as an ongoing case investigating transportation habits are discussed.

Categories and Subject Descriptors

H5.m. Information interfaces and presentation

General Terms: Measurement, Design, Human Factors.

Keywords: Evaluation methods, anthropology, environmental behavior, collective sensing, eco-feedback, smart control

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1. INTRODUCTION

Climate change and other environmental concerns have led the European Union to decide that by 2020 developed countries should collectively reduce their greenhouse gas emissions by 20% [18]. This requires that companies, cities, and society at large are mobilized and engaged to take collective action towards a sustainable future.

To help reach such goals, research is exploring methods to help companies, cities and the society at large to decrease their environmental impact. Two of the methods considered in connection with computing technologies are: 1) increasing awareness: changing people's behavior with computing technologies encouraging more environmentally friendly behavior, e.g. using eco-feedback technologies for water or electricity [27]; 2) infrastructure improvements: optimize or redesign the infrastructure in buildings and cities using computing technologies to decrease the environmental footprint of human behavior, e.g., through automation [19]. Both methods have advantages and drawbacks, and active research is assessing their respective effectiveness. However, in either case, whether developing a new incentive for changing behavior, or optimizing infrastructure, the respective initiative should be grounded in an understanding of everyday life of humans [26, 41] and afterwards be evaluated to assess its impact and to understand problems and prospects. This complex of design and evaluation calls for a combination of qualitative and quantitative investigations.

Much existing work has approached such evaluations solely from the perspective of computer science: E.g., Barker et al. [11] present a quantitative evaluation of a system for flattening peak energy consumption, and Erickson et al. [7] present a quantitative and qualitative evaluation of an eco-feedback technology for water consumption. Furthermore, often when quantitative and qualitative methods are used together they are applied in a disconnected fashion in independent phases, and qualitative methods are limited to pre- and post-interviews. Furthermore, current approaches that combine quantitative and qualitative methods are primarily retrospective and developed and applied to generate knowledge for academic use alone—instead of being part of an innovation process, as proposed here, where the main purpose is to generate shared knowledge across academic disciplines and with industry and public sector parties in order to develop future innovative and effective solutions. An amplification of the single scientific perspective on the domain is given by Froehlich et al. [20] who compare work in different disciplines and argue for more interaction among the disciplines.

The emerging domain of environmental ethnography concerning energy consumption [28] within anthropology intends to study human behaviors and values relating to environmental issues with

an aim of understanding these in their social and cultural context [49]. As such, environmental ethnography offers to provide new contextual insights and a better understanding of human motivations, barriers and values in the context of evaluating means for eco-footprint reduction.

The objects of study and the theories applied for understanding these objects are overlapping with environmental sociology, but there is a difference in methodology: Where sociology in comparison leans towards quantitative methods such as questionnaires and/or structured interviews [42, 44], environmental ethnography will take a more qualitative approach applying methods such as participatory observation and in-depth semi-structured interviews in its evaluation [25][46][47][48]. The objects of study also overlap with research on sustainability within environmental psychology, which focuses on the internal psychological mechanisms involved in human behavior, assuming the systematic use of information and consistent behavior based on specific intentions [53]; over the years several models [26][45] have been proposed that explain the factors impacting human pro-environmental behavior. In contrast, environmental ethnography views behavior in a social and cultural context, and explores how this context affects behavior, values, and motivation.

Another recent trend is the use of increasingly widespread sensing technologies and computational techniques and models to quantify and model environmental related human behavior. This we capture in the concept of collective sensing, which encompasses the use of both mobile and stationary sensors available in the users' environment, and which can be utilized to quantify user behavior that is relevant to environmental impact. Collective sensing creates new opportunities for mapping human behavior at different scales from individuals to societies, see, e.g., [29][2][3]. We argue for including such methods in the evaluation of new means for reducing environmental footprints. To do so, we propose an inter-disciplinary methodology of *Computational Environmental Ethnography (CEE)* that combines methods from the disciplines of computer science / engineering and anthropology. The methodology enables evaluations that not only quantify the environmental impact but also provide an understanding of the mechanisms behind the impact, such as human motivations, on the basis of both qualitative and quantitative technical investigations. The methodology furthermore allows us to evaluate the experienced human value, such as comfort, health, etc. With its systemized methodology and incorporation of anthropological data, CEE thus goes beyond the combination of consumption data and survey study, as conducted by researchers within environmental sociology [42]. The combination and interplay of different disciplines and types of data give evaluators access to additional and novel insights, which are not obtainable through the use of either qualitative or quantitative/technical studies alone. But it is important to stress that this new knowledge does not only arise because of additional or more diverse data, but that the mentioned interplay of disciplines and types of data provides a valuable synergy effect: The inter-disciplinary methodology facilitates that new types of questions may be asked, and therefore new types of knowledge be generated, and it ensures a more challenged and thus valid interpretations and understanding of the different types of data.

In this paper, we introduce CEE as an inter-disciplinary and combined quantitative and qualitative methodology, and we illustrate its usage in several case studies, focusing on a case for smart home controls for reducing footprints at home. Additionally, we present and discuss how CEE can enable more insightful evaluations in an ongoing case exploring transportation habits.

2. RELATED WORK

In this section we review existing method usage for studying means to reduce environmental footprints in regards to human behavior, barriers, motivations and values; e.g., for studying smart control systems, eco-feedback technologies, or for studying existing technologies or practices. As listed in Table 1 we classify work according to: the used research method; the involved research domains: computer science (CS), engineering (Eng), environmental ethnography (Env. Ethno.), environmental psychology (Env. Psyc.), environmental sociology (Env. Socio.), and architecture (Arch); the application area; the main research contributions; and how the research methods were applied.

The reviewed articles include work targeting consumption of water, gas, electricity, heating, ventilation and air conditioning in the home and public buildings as well as transportation. Most of the reviewed articles use quantitative methods (10), many a combination (8), and three articles use solely qualitative methods. In the articles that combine quantitative and qualitative methods, the methods are used in independent steps, and the qualitative method used is pre- or post-interviews. Furthermore, only one article involves several research domains. With a single disciplinary perspective the work closest to ours are the ones of Gram et al. [42] and Bates et al. [1]. In both cases input data is sensed (here, regarding electricity usage) as well as gathered in interviews with participants and then combined in analysis. In contrast to our work, though, their processes are i) not evolving, but only assess a status quo by selective data gatherings, ii) use a short evaluation period, and iii) do not utilize the method of participatory observations. In comparison, the methodology described in this paper proposes an inter-disciplinary methodology involving anthropology, engineering, and computer science, and utilizes both several qualitative and quantitative methods to gather more holistic findings. This, we argue, is valuable in order to make an actual impact on the environmental challenges ahead.

3. COMPUTATIONAL ENVIRONMENTAL ETHNOGRAPHY

CEE represents an iterative methodology combining primarily quantitative collective sensing with qualitative ethnographic inquires. The methodology is applicable in foremost two use scenarios: 1) in an explorative manner in a study of existing practices or in a development process with relatively few participants to ground a design process; 2) as an evaluation methodology when an environmental control/feedback system has been implemented or an environmental campaign has been initiated.

Figure 1 shows the interplay between the two inquiry disciplines. On the one hand, collective sensing analysis may inspire the ethnographic inquires to ask certain questions. Furthermore, if privacy restrictions allow, the collective sensing data concerning individual participants may be analyzed and used as basis for qualitative inquiries about their behavioral patterns.

On the other hand, the ethnographic inquiries may generate hypotheses for collective sensing data collection and also suggest indicators for verifying user claims about behavior in the qualitative interviews. The above items are just examples of the potential interplays between the inquiring disciplines. We propose to arrange the process of Computational Environmental Ethnographic data gathering and analysis in a lifecycle, structured by a set of stages, where in all but the final stage, the process is governed by either collective sensing or ethnographic inquires. We will provide more thorough explanations of such a lifecycle in Section 3.3 and the subsequent sections.

Table 1 – research methods, research domains and application areas for existing work.

Authors	Research Methods	Research Domains	Area	Research Contributions	Research Method usage
Srikantha et al. [15]	Quantitative	CS / Eng.	City	Methods for lowering peak power consumption using appliance elasticity	Quantitative method evaluations on data sets of sensor data
Gram-Hanssen et al. [42]	Quantitative/Qualitative	Env. Socio.	Home	Methods for identifying patterns of domestic electricity use and explanations for variations	Quantitative method evaluations on data sets of sensor data compared with variables from questionnaires and interviews.
Gram-Hanssen [43]	Qualitative	Env. Socio.	Home	The inter-relatedness of water consumption and cleanliness practices	Qualitative analysis
Bartiaux [41]	Quantitative/Qualitative	Env. Socio.	Home	Research on residential energy consumption challenging conception of consumer rationality	Quantitative survey and qualitative in-depth interviews
Rahayu et al. [14]	Quantitative	CS	Home	Methods for disaggregating individual usage events from electricity data	Quantitative method evaluations on data sets of sensor data
Froehlich et al. [2]	Quantitative	CS / Eng.	Home	Single point methods for disaggregating usage from water, gas and electricity data	Quantitative method evaluations on collected data sets of sensor data
Bates et al. [1]	Quantitative / Qualitative	CS	Home	Service-oriented analysis and sensing of resource usage	Quantitative analysis of collected sensor data and qualitative follow-up interviews.
Brush et al. [5]	Qualitative	CS	Home	Study results in regards to living with existing home automation systems	Qualitative methods including home tour and semi-structured interviews
Erickson et al. [7]	Qualitative / Quantitative	CS	Home	Eco-feedback technology for water consumption using smart water meters	Quantitative methods for analysis of log data and surveys and qualitative interviews
Kjeldskov et al. [8]	Qualitative / Quantitative	CS	Home	Eco-feedback tool for understanding and reducing electricity usage	Quantitative methods for analyzing tool logs and usage data and qualitative interviews
Costanza et al. [6]	Qualitative / Quantitative	CS	Home	Interactive energy annotation systems focusing on activities	Quantitative methods for analyzing usage logs of usage and qualitative semi structured interviews
Barker et al. [11]	Quantitative	CS	Home	Method for flattening electricity demand by scheduling background loads.	Quantitative method evaluations on collected data sets of sensor data
Scott et al. [12]	Quantitative	CS	Home	System for smarter scheduling of heating using occupancy prediction	Quantitative system evaluation in deployments and with collected data.
Lu et al. [13]	Quantitative	Arch. / CS	Home	Methods for smarter scheduling of HVAC using occupancy sensing	Quantitative method evaluation with collected data.
Winett et al. [50]	Quantitative	Env. Psyc.	Home	Assessment of the effect of monetary rebates and eco-feedback on household electricity consumption.	Controlled experiment of rebates and eco-feedback. Quantitative questionnaires combined with electricity meter readings.
Kuznetsov et al. [10]	Qualitative / Quantitative	CS	Home / Public	Design implications for persuasive water-conservations displays	Qualitative interviews and quantitative performance evaluations
Kim et al. [16]	Quantitative	CS / Eng.	Home / Public	Vibration-based water flow rate monitoring system and findings	Quantitative method evaluations on data sets of sensor data
Aswani et al. [17]	Quantitative	CS / Eng.	Public	Learning occupancy and temperature model-predictive HVAC control	Quantitative method evaluations on data sets of sensor data
Mun et al. [3][9]	Quantitative	CS / Eng.	Trans.	Methods for estimating transportation emissions using mobile sensing	Quantitative evaluations on collected data sets of sensor data
Froehlich et al. [4]	Quantitative / Qualitative	CS	Trans.	Methods and design of eco-feedback technologies for transportation events	Quantitative surveys, experience sampling and sensing evaluations and qualitative interviews
Hargreaves [46]	Qualitative	Env. Ethno.	Work	Practice, process and power in the workplace	Ethnographic case study

Figure 1: Interplay between collective sensing and ethnographic inquiries.

With an inter-disciplinary and dialectic methodology new insights, which could not have been gained through separate quantitative technical analysis or qualitative approaches alone, are brought into play. The systematic ongoing interplay between methods from the different disciplines ensures that the findings and conclusions of the evaluation are cross-examined (triangulated) and thus validated on a wide range of criteria.

We have developed this methodology to raise opportunities for these different disciplines to challenge, unfold, and validate each other's analyses and results. E.g., qualitative results are validated both through quantitative sensor data and qualitative anthropological data. The sensor data provides a breadth by being collected 24/7/365, while the anthropological data are collected periodically, and at different times of day to ensure a certain dispersion in activities, but also so that it allows for comparing e.g. several mornings, through which patterns can emerge.

3.1 Anthropological Part of the Methodology

A previous anthropological study of energy consumption in the home involving 24 Danish families concludes that changing people's energy consumption habits is a complex process necessitating a reassessment of our current perception of energy consumption as a simple and practical practice [25]. Furthermore, it calls for new methods to research into the complexity of *how* and *why* people consume energy that takes into account what people *say* they do and what they actually *do*.

Activities with environmental impact, e.g. energy consumption in the home, are a '*mediated consumption*'. It is never a direct intentional action. In other words: energy is something we all consume more or less subconsciously in the pursuit of other and greater ends: ends, to which we all subconsciously or consciously ascribe emotional, social and/or cultural meaning as well as practical meaning. E.g., we use light for reading, we take care of our family by cooking for them, and we are relaxed and entertained by TVs and computers—all of which consume energy. But we do not do these things for the sake of consuming energy, and the consumption involved in our practice is usually hidden, and for these two reasons we seldom understand our daily life and work practices in energy related terms. This invisibility also poses a challenge for researchers to research into energy consumption, because people

cannot necessarily tell us what, how and why they consume energy. So to research into the mechanisms of energy consumption we need to apply methods such as qualitative interviews and participatory observations; more details on such ethnographic inquiries and methods will be given in Section 4.1. But as we have discovered in our previous studies, using these methods as stand-alone has its limitations. Especially actual behavior within the privacy of people's homes or cars has proven challenging to uncover through the use of traditional qualitative and quantitative social scientific methods (e.g. interviews, participatory observations and questionnaires).

3.2 Collective Sensing Part of the Methodology

Our methodology utilizes the many new opportunities provided by collective sensing for measuring both human behavior and environmental impacts in terms of electricity, heating, and water consumption, amount of waste, or amount of emitted pollution particles. Sensors able to measure such quantities are starting to become widely available and the growing political and commercial interest in greener living and green economy facilitates large-scale deployment of respective sensing installations as well as support for investigations including collective sensing initiatives using the widespread smartphones, see, e.g. [2][3][4][8][9].

Furthermore, the increasing abundance of sensors has enabled novel data processing techniques to extract from sensor data long-term and more accurate information about human behavior and environmental effects than obtainable by more traditional investigative means (such as interviews and human observation). These techniques include statistical aggregation, data mining, pattern extraction, spatio-temporal data structures and query processing, and sensor fusion techniques. Note that such techniques allow for, among others, human presence and activity recognition and thus allow to analyze not only environmental impacts, but also to infer human behavior and relate it to the measured environmental impacts accurately. Additionally, the participants' smartphones we utilize for sensor data gathering also offer a convenient channel for gathering situated participant feedback via experience sampling [30], where the user can be queried for, e.g., his current activity or subjective assessment of his current situation—as used also for environmental behavior profiling [4].

In the following we will briefly overview the uses and implications of the above techniques for investigations into both environmental behavior as well as impacts. Firstly, large amounts of continuously sensed data facilitate the application of statistical methods and data mining techniques for, among others, evidence-based testing of hypotheses as formulated by researchers. Herer, the high volume and frequency of data and also its complementing heterogeneous sources allow for a higher amount, accuracy and reliability, as is feasible to achieve by more traditional means such as sporadic human observations by researchers. Additionally, sensor-data-based testing is applicable also for verifying statements provided by interviewees regarding their actions and general behavior: Beyond verification, this also allows to correlate interviewee statements to their actual behavior, and thus also to uncover respective biases, and, in turn, allows for a more founded interpretation of interview and questionnaire data.

Secondly and beyond testing purposes, data mining and visual analysis techniques facilitate also the discovering and explanation of previously undetected or unexpected phenomena, and the shaping of new hypotheses. For instance, the distinguishing (and establishing of archetypes of) people with regards to their environmental behavior can be facilitated by clustering techniques when applied to the data inferred from sensing the environment and

behavior of participants (and, optionally, to supplementing questionnaire data).

For other use-cases, data mining techniques can be paired with intuitive visual analysis tools in order to provide to researchers and domain experts in environmental investigations the following: i) global pictures of sensor-derived data such as footprints of energy consumption and greenhouse gas emission –be it per day or by year, per user or also by building population or company workforce, ii) the identification of temporary, spatially or thematically local phenomena such as irregularities, but also opportunities for lowering footprints—by visual highlighting and by allowing the investigators to ‘zoom’ in an explorative manner into data, selecting arbitrary combinations of data dimensions and levels of detail, iii) uncovering and assessing trends over time in regards to local as well as global aspects, iv) the possibility to predict the impact of changes in the underlying data via the ability to operate on (combinations of) sensed and modeled data, when aiming to assess the potential environmental effects of, e.g., infrastructural alterations, e.g., regarding transport options, or of eco-awareness campaigns, or of changes in human behavior in general. Note that the historical sensed data alone also provides a solid basis for such predictive data modeling.

Note, that among the non-trivial challenges to be addressed when using collective sensing is the protection of the privacy of the participants. This issue also exists, when interviewing participants, but during the longer collective sensing stages the participant is often less aware of the data gathering and of which kinds of private information he is revealing as it may be deduced from the sensed data, see [31][32] for related discussions.

3.3 Combining the Parts

We propose to conduct the inter-disciplinary evaluation by using methods of collective sensing and anthropology alongside each other in a set of stages in which the different disciplines play different roles. In the following, we motivate, using prototypical example cases, the usage of an iterative inter-disciplinary process in which the disciplines interact in a set of stages in order to a) achieve for the subject of investigation a picture as complete as possible and to b) allow for recording developments and changes in behavior and experiences throughout the exploration or evaluation. The iterative process may also be repeating creating a cycling process that revisits stages. In the subsequent sections we will then present in more detail concrete examples of how we apply the method to different actual cases.

A prototypical set of stages when using CEE for an evaluation include an initial *collective sensing and visualization* stage, where the technical disciplines prepare quantitative results, analysis, and visualizations to the anthropologists. This data can then provide the anthropologists with focus points for *participatory observation and analysis*, which is conducted in parallel to continued collective sensing. In this stage, the anthropologists make observations and uncover existing practices relating to the focus points. Afterwards the technical disciplines typically prepare updated quantitative results, analyses and visualizations with sensor data from the observation period. A comparative assessment of the quantitative and qualitative data can then be employed to identify focus points for interviews in a stage of *semi structured interviews and analysis*. The results of the interviews typically include a report about findings and questions for sensor data. The technical disciplines can then analyze the sensor data from the whole evaluation period in regards to the questions in a *technical analysis and assessment* stage. Finally, a stage of *inter-disciplinary analysis* can bring together both computer scientists / engineers and an-

thropologists in a common analysis of qualitative questions from the reports and the new questions that are derived from the technical analysis.

When the type of the intended investigation is an exploratory study, CEE could include an initial *survey and analysis stage* to quantify the importance of different environmental practices and aspects. This allows to already focus on studying the most important aspects and practices, when the technical disciplines set up the *collection sensing and visualization stage*. The analysis of the sensing results can then create focus points for unstructured interviews. The topics discovered through evaluating the unstructured interviews can then be more thoroughly explored, e.g., by refocusing the collective sensing, and/or by augmenting it with experience sampling [30] to gather qualitative input on the respective focus topics during continued sensing. Finally, a stage of *inter-disciplinary analysis* could bring together both computer scientists / engineers and anthropologists in a common analysis of qualitative questions from the reports and the new questions that are derived from the technical analysis.

These examples of stages sketch proposals of how to combine collective sensing and anthropological methods to optimally foster interdisciplinary analysis in a given scenario. The goal is to combine methods, firstly, to initiate and facilitate the exchange of questions, hypotheses, analysis results as illustrated in Figure 1 and, secondly, to ground these in the two disciplines of computer science and anthropology, such that findings are questioning current practices and are interdisciplinary by nature.

4. COMPLETED CASE: TEST HOUSE

In the following, we present a case description of how Computational Environmental Ethnography has been successfully applied—namely to the “Test House” case, as part of the project *Minimum Configuration Home Automation*.

The driving idea behind the Test House case is to build a house that consumes less energy than it produces in its lifecycle. Furthermore, the intention is to build a house that gives the inhabitants the experience of a healthy and comfortable indoor climate and which supports the inhabitants in living their daily lives.

One of the associated project aims was to validate these different intentions using different types of evaluations: These included, first of all, a technical evaluation of the energy performance of the house; in other words, an assessment of whether the house and its inhabitants live up to predefined criteria and standards that had been estimated through theoretical calculations using the software tool Be06 [24]. This evaluation was based on vast amounts of energy consumption and production data collected during the test year. Besides this purely technical assessment, an additional aim was to obtain qualitative models of explanations for the actual energy consumption in the house and a qualitative evaluation of the quality of the house as experienced by the family living in the house.

For these purposes, the Test House was set up as a living lab in which a family, consisting of a couple, their son and two daughters, lived for just over a year to test the house and its extensive home automation technology. The test family had agreed to being monitored through sensors, meters, interviews and observations. 24 hours a day the following data was logged: CO₂-levels, temperature, humidity, light intensity, presence, energy consumption and production, as well as interaction with the home automation system. Additionally, every quarter two days of participant observation were carried out and followed up by interviews.

4.1 The Proposed CEE Methodology Applied

The inter-disciplinary evaluation that is envisioned in CEE is part of a forward development process and not just a retrospective evaluation. Therefore, the evaluation itself is an iterative process. A complete iteration of CEE evaluation is split into six stages as illustrated in Figure 2 and is conducted over a period of three months¹. The stages conducted in each of the iterations follow the prototypical scheme as described in Section 3.3. In the figure, the stages in their order are illustrated; for each stage it is signaled, by color, which party—technicians, anthropologists or both—carry the main responsibility for the outcome of the respective stage. Finally, the intertwined arrangement of the stages is intended to illustrate that the process's division into stages is not completely rigid, but allows instead for dynamic re-allocating of time frames for individual stages, for overlapping of stages, and specifically for extended interactive transitions between stages, when considered necessary or useful.

Figure 2 – Iterative Cycle of Computational Environmental Ethnographic analysis, as applied in the Test House case in four iterations.

Individual stages are summarized in Table 2, together with respective prototypical activities undertaken within them. We will in the following focus not on individual project results from the Test House case, but on how and to which end the methodology was applied in the case study in each stage. Furthermore, we will present the anthropological activities in greater detail, whereas we present the technical activities, for which general descriptions of the techniques to apply have been given in Section 3.2, in lesser detail.

¹ Live in homes in general—as well as specifically with respect to energy consumption, and related behaviour—changes quite substantially with the year's seasons. This is one of the reasons why we choose to have an iteration for each quarter of the year.

Table 2

Stage	Action Details
S1: Collective Sensing and Visualization	Sensing setup; initial assessment and visualization, focused on identifying interesting phenomena and benchmarking energy-efficiency
S2: Participant Observation and Analysis	Observations recording behavior, routines, interaction with the house and analysis of data
S3: Analysis and Visualization of Sensing Data	Analysis and visualization of behavior and energy-efficiency data; e.g. on floor plans, in focusable visualizations; merging with data from S2; extracting impacts for S4
S4: Semi-structured Interviews and Analysis	Interviews based on findings from S2 and S3, focusing on behavior and related meaning; compiling findings, with feedback from the family
S5: Combining Sensing and Interview Analysis	Combined analysis challenging the findings and questions compiled in S4 through analysis of sensor data
S6: Inter-disciplinary analysis	Analysis covering reasons for behaviors and energy impacts; Equitably involving all disciplines; summarizing findings

4.1.1 Stage 1: Collective Sensing and Visualization

In the first stage, computer scientist / engineers set up the collection of sensor data, and resulting data from a yet limited period is analyzed with the purpose of identifying interesting behavior or fluctuation, e.g., a high number of manual overrides of (a functional feature of) the home automation system, high/low indoor climate values, frequent opening and closing of windows). It is also assessed whether the inhabitants' use of the house is appropriate energy-wise. Results of the analysis are visualized and presented to the anthropologists in the form of statistical numbers, graphs, and floor plan overlays. Figure 3 shows an example of a visualization of: manual overrides, the nature of the overrides, their time stamp, presences, CO₂-levels and temperatures.²

Figure 3 - a visualization of manual overrides, their nature, and respective times, presences, CO₂-levels and temperatures.

² Note, that data output includes also inferred data; for instance, while the open vs. closed state of curtains and windows was sensed directly, such state was for outside doors inferred from CO₂ sensor data.

These results allowed the subsequent participant observations to be more focused—in this case, observations on overriding practices and social, cultural and practical contexts for these practices. Identifying this focus crucial would not have been possible without the collected sensor data and the respective preliminary technical analysis of this data.

4.1.2 Stage 2: Participant Observation and Analysis

In order to conduct participatory observations, on a routine observation day the anthropologist arrives at the Test House in the morning, before the family gets out of bed, and observes their morning. The anthropologist leaves the home together with the family and returns with them in the afternoon. During this period, family life is observed and the anthropologist participates in cooking, laundering, dishwashing, homework, playtime, and meals. Furthermore, the anthropologist has followed the family outside the home for shopping and picking up the kids from day care. The participant observation records also the ‘behavior’ of the house and system, and also how the family reacts to and interacts with the house and the system. The data is recorded in field notes, on floor plans, and via photos [34][52]. In this case smartphone sensing was not utilized but could potentially have provided an additional information channel for the behavior of the participants, e.g., outside of the house.

Participant observation uncovers the practices of daily life of the family and thereby the practical and socio-cultural context in which the family interacts with the house and control system. This context is important to include in order to understand not just what the family does and how often, but also under which circumstances. This contributes to an understanding of why they act as they do, and what meaning they attribute to their own behavior and to the house’s and the system’s behavior [48]. This understanding is crucial, if we want to affect the way people behave, and this cannot be achieved through sensor data alone.

A central challenge inherent in participant observation within the home is that the presence of an anthropologist/guest in the home often will affect behavior in the home in ways that not necessarily apply for the method of participant observations when used in other empirical fields. It turned out, though, that a family with children has very tight routines in the morning and around mealtimes, and this gave the impression that not much was out of the ordinary even though the anthropologist was present. Furthermore, reflection on and working consciously with different positions and roles (such as guest, au-pair, kid’s play-mate, etc.) in the home will help overcome parts of this challenge for the anthropologist [35][37][38].

Another challenge, even harder to overcome, is that the anthropologist is usually limited in her access to home life in more ways than one. In this case, the agreement with the family foresaw two days of observations per quarter. Additional observations could probably have been agreed on and carried out without bothering the family too much, but only to a limited extend, since most families are not willing to have an anthropologist/guest present in their home continuously.

Nonetheless, the main advantage in using participant observation, in the type of evaluation described here for the Test House case, is that this open and holistic approach enables and facilitates new questions that are not known to be relevant in the outset of the evaluation. Participant observation furthermore gives an embodied experience [36] to the anthropologist, which is helpful in the following interviews as it provides shared points of reference with the family and at the same time this experience allows anthropol-

ogists to ask the ‘right questions’ and interpret the answers within the context they arise [33].

4.1.3 Stage 3: Analysis and Visualization of Sensing Data

In this stage, computer scientists / engineers collect, analyze and energy-assess data from the periods of participant observation, and visualize the results for the anthropologist through graphs and floor plan overlays. These are presented and discussed in a meeting and hereby the qualitative data from the participant observations is contextualized with sensor data of, e.g., temperature or CO₂-levels. Sensor data (and data inferred from it) thus serve as a type of extended observation data in the sense that it registers actions and conditions that are not necessarily all registered by the anthropologist.

The energy and energy behavior related assessments are interesting here not as judgments of the family’s behavior but as a means to understand why the family has a need to override, e.g., standards set by engineers for indoor climate (as to be provided by the home automation system). When the energy assessment is compared with the qualitative study this produces knowledge that enables us to question and challenge the dominating assumptions of indoor climate, intelligent control, and comfort values. This knowledge is crucial if we are to design more energy efficient buildings, because inhabitants will override and domesticate technology if it does not meet their needs, regardless of the good intentions behind the system.

4.1.4 Stage 4: Semi-structured Interviews and Analysis

Questions derived from participant observations and technical analysis provide focus for the interviews, but the interviews are still open, so that the family gets the opportunity of contributing with relevant information, not necessarily included in the interview-guide [39]—thus ensuring, that the main focus is given to what *is* important and not on what anthropologists *believe* to be important [34].

The interviews are carried out in the home with each parent individually. An interview takes approximately 1.5 hours, and the technical data visualizations are used, if relevant, as a tool for dialogue. Such visualizations proved to be a good tool for getting the family to reflect on their practices of daily life—as concluded for the Test House case, but also observed by other researchers [51].

The family is encouraged in the interviews to be as concrete as possible and to give examples, e.g., of how they interact with the system. Therefore the interviews often involve home tours in which the family elaborates on their practices of daily life and on other issues. The interviews are taped, optionally with video, and transcribed, and the anthropologist subsequently analyses the compiled data.

Generally, the interview provides further insights in what meaning the family ascribe to their behavior in their home and their experiences with the house and its technology. In interplay with the sensor data and observational data it allows to reflect on and discuss conscious and subconscious behavior. As an example, the interviews provide insights in which significance it has for the family that they can override the automatic system. This knowledge could not have been generated through participant observation and sensor data alone – just as the actual identification of the significance and complex practice of overriding could not have emerged through interviews alone.

The different types of data employed provide different insights in practices of daily life and meaning, because they have been gathered through different methodologies, and therefore from different positions or views, each of which allows to uncover specific knowledge items, which cannot be identified by the complementing view alone [23]. This triangulation of data, i.e., the incorporation of different view points, also strengthens the validity of the obtained results.

As an outcome of this stage, the anthropologist compiles a report with the findings categorized into the emerged evaluation themes. The report is read and commented on by the family. Their changes and comments are included in the report when considered relevant. The report is sent to the engineers with questions to be answered by means of sensing and subsequent sensor data analysis.

4.1.5 Stage 5: Combining Sensing and Interview Analysis

Following the end of the evaluation period (every three months) the computer scientists / engineers analyze and assess the sensor data from the entire period (as well as from earlier periods to assess trends). In this analysis they are guided by the questions posed in the qualitative report from the anthropologists. For instance, the report contains an assumption that the family's overriding of the system is closely connected to sunshine (or, on occasion, to desires such as to listen to birds singing), and that thus the system's screening does not always meet the needs of the family. This assumption is then in this stage unfolded and challenged through the gathered sensor data and its analysis, which also provides insights into the circumstances (CO₂-levels, humidity, temperature, light intensity, desires) under which the family actually overrides the system. This provides useful knowledge to develop for the home automation a control of screening that better meets the needs of inhabitants.

4.1.6 Stage 6: Inter-disciplinary analysis

The inter-disciplinary analysis in this stage brings together both computer scientists / engineers, and anthropologists in a common analysis of qualitative questions from the report and new questions that are derived from the analysis. The different competences and organizational affiliations ensure that expertise on user behaviors, the house, the technology in the house, sensor data, energy assessment etc. is represented. This means that different participants can question each other's knowledge and hence develop models of explanations and conclusions that are validated by different disciplines and types of data.

An example of this is the theme of overriding (shown in sensor data and observed) which leads to a focus on the family's experience of high local indoor temperatures and their dissatisfaction with the automation system for not eliminating this problem (uncovered in interviews and home tours). Through the inter-disciplinary analysis it is uncovered that the family's earlier changes in desired default temperature in combination with the current control logic of the system causes the windows to remain shut even though the family feels there is a need or desire for the windows to be open. This causes dissatisfaction with both the indoor climate and the control system. It also causes the family to override the system and to open the windows in the house—which comes with the risk of cooling the house locally and thus causing it to heat up even more. Furthermore, there is a risk of overcooling the house in general or locally, thereby leading to a higher energy consumption for re-heating the house. Without inter-disciplinary analysis this conclusion and model of explanation could not have unfolded.

The model of explanation is valuable for the energy assessment of the house, because it helps explain why energy consumption is higher than calculated. But furthermore it also tells us about the relation between human and technology: It shows us that the automation system is too complex and not transparent. The users cannot see through the consequences of their actions, e.g. overrides, which leaves them frustrated and dissatisfied. From this follow further hypotheses and questions for research in the project regarding the matter of to which extent and by which means users should be enabled to configure the home themselves—which is a very crucial knowledge area when developing home automation systems.

Following the inter-disciplinary analysis the final and compiled evaluation report is collaboratively produced, and visualizations of sensor data support the qualitative findings and conclusions that have been unfolded through inter-disciplinary data and analysis.

The end of the report lists a number of questions related to the needs and challenges experienced by the users and the project. These questions are formulated in a constructive and positive manner, phrasing them in the form of 'How might we...?' questions, e.g.: "How might we ensure a indoor climate that meets the users needs for lower temperatures, while maintaining extensive inflow of natural light and view?"

Insights from the report and questions like these feed into the further development of home automation systems and sustainable architecture that better meet user's needs. We further discuss and summarize the performance of the methodology as applied in this case in Section 6, together with its performance in the case described in the following section.

5. ONGOING CASE: EXPLORING TRANSPORTATION NEEDS

In this section we present how to use CEE as an exploratory methodology in the area of transportation in the context of the research project EcoSense (ecosense.au.dk). We start by providing the background for the case, and subsequently describe how and to which end the stages of CEE are applied in this case.

5.1.1 Better Understanding of Transportation Needs

The transportation case aims to increase the sustainability of personal transportation by identifying and changing transportation behaviors of individuals. By 2008, transportation by road accounted for 22.7% of the total CO₂ equivalent emissions stemming from fuel consumption in total of all OECD countries [54]. Furthermore, for transportation by road its share as well as its absolute emission figures have not been reduced significantly in the last 20 years: Transportation by road is by far the largest contributor to CO₂ equivalent emissions caused by fuel combustion in transportation, outnumbering any other type of transportation by a factor 10. While these figures identify transportation by road as a major contributor to CO₂ equivalent emissions from fuel consumption, it does not address the behaviors in transportation that these figures are a result of. And without gaining knowledge of the actual behavior, efforts into decreasing these figures on an individual level will have uncertain outcomes. As transportation behaviors are a matter, which is not easily understood solely by means of quantitative data collection, this case is an obvious subject for CEE.

Within the EcoSense project these challenges were addressed with a focus on personal transportation in a community of neighboring companies. In an exploratory manner we aim to identify for this community, what means are prudent for lowering CO₂ equivalent

emissions. Due to the process being exploratory, there is not a prescribed outcome apart from that it should support increased sustainability in transportation behaviors in the community. Possible means for this include, but are not limited to, advanced ride-sharing services, company funded shuttle-busses, shared electric vehicles, and better local traffic planning.

In late 2011 the community of neighboring companies, employing ca. 10,000 people, commissioned a structured questionnaire survey to investigate the transportation behavior of the employees in the community across numerous metrics, such as travel distance between home and work, common errands during transportation, and transportation mode. While this survey provided an overview in hitherto unseen detail (ca. 5,000 respondents) of commute between the community area and its hinterland, it was severely limited by its questionnaire format. It also was constrained to a single temporal point of impact, and therefore must be either updated periodically or be considered invalidated over time.

This reasoning inspired the development and deployment of a smartphone application, which could replace a periodical survey with continuous pure quantitative data collection in a collective sensing manner, see Figure 4. In the first version the user is asked to input corrections to automatic estimations of transportation modes, but in the long term the application's transportation mode detection is planned to be improved and that thereby transportation behavior will be recorded more autonomously, while being framed in an application with functionality that would serve as a reason for users to download, install and use it.

Figure 4 – Screenshots of the smartphone application for sensing transportation events.

5.1.2 Applying CEE for exploration

An initial test of the smartphone application was conducted within a small company. However, the pickup among users was lower than expected. In reaction to that, rather than opting out of utilizing a smartphone application, it was decided to combine the smartphone based sensing with ethnographic expertise, and in effect doing computational environmental ethnography. The reason for this was two-fold: first, the decision for CEE enables the development of a smartphone application that is grounded in actual needs of users instead of desired collected data, and secondly, the study will gain the potential to link collected data about transportation behavior with the reasons underlying it.

Furthermore, while both the questionnaire survey and the smartphone application did provide meaningful results, we deemed their accuracy improvable and their scope extendible.

Therefore, we saw the need for applying a methodology, such as CEE, that integrates quantitative and qualitative studies in a unified approach. However, because this case had been launched before the formalization of CEE as a methodology, the application deviated from the prototypical order given in section 3.3—by way of swapping of stages 2 (Semi-structured Interviews and Analysis) and 4 (Participatory Observation and Analysis).

The status of the project and the application of CEE is that the two first stages have been completed, namely the aforementioned collective sensing via a smartphone application, followed by a semi-structured interview and analysis stage. This section will describe the two completed stages, as well as outline the four planned subsequent stages.

1. Collective Sensing: The initial collective sensing application has been deployed as described earlier, and the respective sensing initialized in this stage allows continuous monitoring and evaluation of transportation behaviors, adaption and evolution over time and throughout the CEE methodology's lifecycle. This stage also includes an initial analysis of the data gathered so far, which serves as a baseline.

2. Semi-structured Interviews and Analysis: As a follow up to the collective sensing deployment, an interview-survey was conducted amongst participants from the community of neighboring companies, focusing on concerns of the participating individuals' privacy and on sharing of sensing data in face of technology that enables to track people with fine-grained detail. One of the major insights gained was that even though privacy and willingness to share location-related data was a concern to the participants, they would be willing to trade in such data, if it was done in a transaction that presented them with sufficient gain. Such gains could be constituted by the availability of better services, monetary benefits, etc. Furthermore, to better address the ease of use for participants and their concerns, it was decided to revise the smartphone application design used for collective sensing based on the interview-survey.

3. Analysis and Visualization of Sensing Data: The status of the process is the pending deployment of the re-designed smartphone application. The re-design aims to provide potential users in the community of neighboring companies with a service of value substantial enough, so that it will incite widespread pick-up and regular use of the smartphone application and result in a more representative data collection. Following the app deployment and while collection is ongoing, the core procedure in this stage will be to perform a more thorough analysis of the data. To this end, focusable and focused visualizations will be pivotal in understanding the collected data in order to analyze and identify potentially relevant patterns in transportation behaviors as well as subsequently, and more importantly, rendering the data understandable for computer scientists, anthropologists, and possibly experts from other fields, in order to decide upon the focus for the following participatory observation activities.

4. Participatory Observation and Analysis: As designers can only speculate about actual usage behavior, and as collectively sensed data can provide only a limited reflection on behaviors, it becomes essential to study transportation behaviors by means such as participatory observation. This activity addresses the risks that a) the collectively sensed data becomes detached from the transportation behavior that it intends to reflect, and b) that the CEE process diverges inexpediently from what remains to be identified as prudent ways for lowering CO₂ equivalent emissions. This activity is therefore a crucial re-grounding of technically sensed reality in individual users' experienced reality.

5. Combining Sensing, Interview, and Observation Analysis: This stage will combine the insights gained in the previous stages, in order to distill likely diverging insights into a framework for the understanding of transportation behaviors in the community of neighboring companies. In this case-scenario, we deemed it crucial to communicate findings to external parties, such as decision makers or experts from disciplines that have hitherto not taken part in the process. Thus, the reason for keeping this stage separate from the following stage of interdisciplinary analysis is that before a combined analysis effort can take place, it is vital that the set of insights and evidences gathered or to be gathered are assessed and important items are carefully selected. Thus, the assessment, selection and preparation of data, analysis and visualizations for presentation should be considered in this stage with thorough consideration of details to in- or exclude.

6. Interdisciplinary Analysis: In the last stage the data selected and prepared in the previous stage is to be subjected to an interdisciplinary analysis. This stage marks the conclusion of the CEE methodology's lifecycle but it can serve also, and here more importantly, as the stage at which future directions and hypotheses are formulated for continued development, as in a second cycle of the CEE methodology's process.

In this case study, we have explored how we can use the CEE methodology to comprehensively understand the transportation habits of a community of neighboring companies. By not only sensing transportation habits alone, or relying on questionnaires and surveys alone, but actively using the gathered data (and visualizations thereof) to inform the participatory observations and analyses, and vice versa, a deeper understanding of people's transportation habits can be gained. Overall, the case exemplifies how early evaluation and development of means for lowering transportation eco-footprints in a community can be steered and guided into promising future directions, including a grounding in the actual motivations of the targeted individuals.

The outcome of the first lifecycle of applying the CEE methodology will be a body of knowledge including how the transportation in the given community is a composition of the behaviors and habits of individuals. This knowledge will be pivotal in a subsequent lifecycle of the CEE methodology, which will shift from being exploratory to focusing on development, deployment and evaluation of concrete means for increasing sustainability in transportation in the community. The outcome should not, however, be viewed as a recipe for success, but rather a set of guidelines that will substantially inform the design and development and that addresses actual needs of targeted individuals and therefore will have a high pickup rate.

6. Discussion and Conclusions

We presented Computational Environmental Ethnography (CEE) as a methodology to advance—in evaluation and iterative development—means to reduce environmental footprints. We showed how the methodology combines collective sensing methods from the disciplines of computer science/engineering with ethnographic inquiries from the discipline of anthropology.

Within CEE, collective sensing allows us to continuously gather data, and thereby provides the means to assess both human behavior as well as its impacts on the environment—in an accuracy, scope and density that would not be achievable by human observation or questionnaire data alone. Anthropological inquiries, including participatory observations and qualitative interviewing, allow for a detailed understanding of humans' situation and behavior, including the motivations and concerns that govern environmental behavior.

We argue, that for environmental science interdisciplinary methods and the types of data they collect can deliver—in their complementing combination and interplay—a holistic picture, descriptions and interpretations of the chosen subject of study. The interdisciplinary methodology we proposed explicitly challenges all involved disciplines, and thereby enables knowledge gains, that would not have been achievable through the use of solely qualitative or solely quantitative/technical studies.

We demonstrated and discussed the methodology's applicability and its benefits in practice by evaluating it and its application in several cases. Concrete benefits of the methodology beyond the ones mentioned above were distilled and validated from these evaluations: Benefits for correlating data inferred from sensors and detailed human observations included: 1) relating sensor data to human concerns, and 2) the interpretation of human experiences and statements from interviews, uncovering potential discrepancies between such statements and objective data. Further benefits arise from the methodology's division into several stages, which are governed alternatingly by one of the involved disciplines. This delivers the intended understanding between the involved parties and the correlation between their respective types of data, hypotheses, developments and results. Additionally, as shown for the addressed cases and related footprint-reducing means, using the methodology ensured that neither evaluation of cases, nor the development or the advancing of means for footprint reduction led into dead-ends: Instead, using the methodology, dead-ends and fruitless deviations were identified and avoided at early stages. This was ensured in particular for those proposed means that were a) conflicting with humans' motivations and needs rather than making use of them – which became apparent quickly through ethnographic enquires, especially through participatory observations; or that b) proved inferior in (combinations of) energy saving and adoption rate – which became apparent via analysis of collective sensing input.

Overall, in the covered cases both evaluations and development processes remained focused throughout and did not deviate towards unrealistic or false assumptions and thus did not lose real-world applicability. We attribute this to the methodology's inherent and continuous challenging of one discipline's results by another one, and by the resulting purposeful and rapid shaping of holistic pictures and interpretations that in turn lead to improved designs or approaches.

For future work we will focus on further integration and evaluation of tools supporting the methodology, i.e., by developing questionnaire support within the smartphone sensing apps, and data visualizations that cover also the results of ethnographic inquiries. Such new innovations in tools supporting the comparison and matching of quantitative and qualitative data will contribute to the scalability of the methodology to large-scale investigations and ongoing continuous probing of environmental behavior and the advancing of means to improve it.

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