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Transdisciplinary development of a life-cycle based approach to measure and communicate waste prevention effects in local authorities

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Abstract

Although waste prevention was promoted as the first priority for all EU member states in 2008, the actual implementation of activities has thus far been hesitant. Empirical evidence indicates that the reasons for this neglect include the limited measurability of waste prevention effects and the consequential lack of awareness, motivation and incentive systems. Our research aims to quantify waste prevention and its environmental impacts and, ultimately, to motivate the efficient implementation of waste prevention concepts by a target-group-specific communication of the results.

Embedded in a transdisciplinary research setting in close cooperation with practitioners, we develop a life-cycle based approach to calculate the effects of waste prevention in local authorities. This approach features an activity-based analysis that facilitates the assessment of both reduction of waste generated and the related environmental effects. The methodology of Life Cycle Assessment, used to calculate environmental impacts, is adapted to the specific requirements and constitutes an essential step in our measurement approach.

Finally, we demonstrate the application of this approach. Five activities deriving from real-world case studies are assessed. These case studies simulate the implementation of waste prevention in a mid-sized German city. We are able to reveal potential waste reduction of 74% and potential reduction of other environmental impacts ranging from 28% to 62% of the targeted material streams.

Keywords

Waste prevention, activity-based analysis, transdisciplinary, LCA, Dematerialization, Local Authorities

1 Introduction

With growing pressure, the need to reduce environmental impacts of human behavior attracts the attention of politics, industry and science (European Commission 2012; OECD 2000). Among the many eco- or anthropocentric concepts advanced to reach this goal, the Circular Economy has gained momentum (Sauvé et al. 2016). A Circular Economy aims at closing the flows of materials, thus reducing the need for primary resources and simultaneously reducing waste output (Andersen 2007; Haas et al. 2015). The growing popularity of this approach reflects concerns about the pressure of economic growth, the subsequent increased resource depletion and the perceived ineffectiveness of existing sustainability concepts (Hobson 2016; Tukker 2015).

The EU adopted a Circular Economy action plan as a part of the European flagship initiative towards resource efficiency (European Commission 2016). The Ellen MacArthur Foundation (2015) proposes a framework to support responsible actors, especially policymakers, in order to enable this transition, for which a great potential for waste prevention is revealed (Ellen MacArthur Foundation 2015; Eurostat 2016a, 2016b).

In general, two different types of waste prevention can be distinguished: The reduction of waste generated and the reduction of the impacts of waste generation on humans and the environment, e.g., reducing the hazardous content of waste (European Commission 2012). This prevention should occur before, during and after use. Pre-use, reduction at source can minimize material input in both mass and content of harmful substances. The intensification of use with sharing economy concepts can prevent waste during the use phase. Post-use, a prolongation of life leads to a longer period of product circulation and can be achieved by repairing and re-using goods (Hutner et al. 2017).

Waste prevention was promoted as the first priority for all EU member states in 2008 (European Parliament and Council), and it is argued that it should dominate over recycling (Allwood 2014). However, the implementation status of waste prevention activities remains low, as is frequently stated in literature (Gentil et al. 2011; Melanen et al. 2002; Wilts et al. 2013; Wilts 2012a; Zorpas et al. 2014). Reasons include, but are not limited to, the absence of valid measurement tools for waste prevention and the resulting lack of awareness, acceptance and incentives. Together, these barriers lead to a failure to take action towards waste prevention. The results of an empirical study in local authorities suggest that these obstacles can be overcome by quantifying the positive impacts of waste prevention on the environment and society (Hutner et al. 2017). Furthermore, with proper measurement of waste prevention effects, it is possible to define benchmarks, to provide incentive systems and to establish controlling mechanisms. Combined with suitable illustration and communication, such efforts can increase the motivation and willingness of stakeholders to act.

In Germany, local authorities are among the key actors towards waste prevention. Local authorities are not only charged with waste management, but also specifically asked to prepare waste prevention concepts by the Waste Prevention Programme of the German Government (BMU 2013). In addition, they hold considerable market power accounting for 60% of all public expanses in Germany in 2006 (McKinsey & Company 2008). This power, combined with their range of responsibilities, including construction, transportation, and environmental planning as well as legislative and administrative tasks, gives them the ability to influence waste prevention at various stages and levels, as described in Hutner et al. (2017).

Within this article, we develop an approach to raise awareness and motivate action towards waste prevention in local authorities in Germany. The two research questions can therefore be framed as follows:

- Q1: How can the effects of waste prevention be measured, taking into account both reduction of waste generated and related environmental effects?
- Q2: In which way(s) can the results be communicated to motivate the implementation of waste prevention activities?

To address these research questions, we scrutinize existing literature and, based on the results, follow a structured process to develop a measurement approach. This measurement approach is then presented, followed by an application and a validation of our approach in local authorities in Germany. Within the discussion, we match the application process to our research aim and reflect on advantages and shortcomings.

2 State of the art and research gap

Analyzing the literature on measuring waste prevention, some major deficits of existing approaches are revealed. Measuring waste prevention implies the quantification of something that is nonexistent, making direct measurement, for example by weighing or counting, impossible. The approach therefore has to be indirect, necessitating a comparison with the amount of waste that would have been generated without waste prevention (Sharp et al. 2010a). Consequently, measuring the related environmental effects also includes the comparison of impacts with and without waste prevention.

Attempts at measuring waste prevention include both statistical and activity- based approaches. Statistical approaches typically aim to measure the reduction of waste generated by using existing waste data. These data are then compared with modelled values to deduce how much waste has been or can be prevented. The modelling can be either a forecast or a retrospective analysis and is usually based on factors such as production (Bruvoll and Ibenholt 1997) and income (Mazzanti and Zoboli 2008). The difference between real and modelled values is credited to waste prevention. However, it is argued that decreasing amounts of waste do not automatically imply successful waste prevention; rather, they may reflect changes in economic activity (Wilts and Rademacher 2014). Additional influence factors that further complicate this approach include consumption patterns and household size as well as the time lag between the implementation of waste prevention activities and their effects. Reduction of waste generated, therefore, cannot be documented using solely statistical data (Statistisches Bundesamt 2018; Sharp et al. 2010a; Wilts and Rademacher 2014).

Activity-based approaches measure results at a micro level by actually gauging small-scale waste prevention. This measurement can be achieved by weighing, counting, timing or metering the amount of prevented waste associated with specific activities. The possible scope of application ranges from single activities to whole institutions or geographical areas (Tasaki and Yamakawa 2011; Salhofer et al. 2008; Sharp et al. 2010b; Wilts et al. 2013). While most activity-based approaches focus on reduction of waste generated (Wilts 2012b), some studies account for environmental impacts as well, applying Life Cycle Assessment (LCA) or related methodologies LCA is a tool to assess the environmental impacts of a product or service over all its life cycle stages, from raw material extraction, production, and distribution to use and, eventually, end-of-life. Aside from the amount of waste, Nessi, Rigamonti, and Grosso (2012) use cumulative energy demand (CED), global warming potential (GWP), abiotic resource depletion and eutrophication as impact categories for evaluating waste prevention, and expand their focus to 13 midpoint categories two years later (Nessi et al. 2014). Salemdeeb et al. (2017) analyze the prevention of food waste and focus on the greenhouse gas emissions as an environmental impact category, while Mirabella, Rigamonti, and Scalbi (2013) apply all IMPACT2002+ indicators in an LCA study that addresses dematerialization and thus covers waste prevention as a side effect.

Other than in those studies, LCA is rarely used to evaluate waste prevention; the reasons include various difficulties concerning the lack of operational methodology (Laurent et al. 2014) as well as the definition of the functional unit, if waste prevention is to be compared with waste management (Gentil et al. 2011). Waste prevention alters the functional unit, if that is based on mass. This may be solved by modelling the prevented quantity as a virtual flow (without environmental burden and no transformation in the waste management system) or by adjusting the functional unit. Detailed information on these possibilities is presented by Gentil, Gallo, and Christensen (2011) and Ekvall et al. (2007). The limited availability of data is a hindrance as well; in particular, there is little information about the environmental performance of waste prevention and the calculation of the amount of prevented waste (Gentil et al. 2011). In contrast to existing attempts, a measurement approach that addresses these two aspects is needed.

Further attempts at measuring waste prevention include hybrids of the presented procedures as well as other approaches, partially for specific waste streams or target groups. Laner and Rechberger (2009) propose an evaluation of environmental benefits by subtracting the environmental burdens before and after the implementation of waste prevention activities on the level of small and medium-sized enterprises. The burdens and, subsequently, the benefits are expressed using the CED, GWP and acidification potential. Even though taking into account environmental effects, the problem of calculating the amount of prevented waste from statistical data, including some data with poor quality, is not solved (Laner and Rechberger 2009). Sharp, Giorgi, and Wilson (2010a) introduce, among other methods, self-weighing, monitoring or reporting on a household level as well as attitude surveys to measure the reduction of waste generated, but they conclude that holistic approaches are time consuming and expensive. In Japan, payment data are analyzed to estimate waste prevention achieved through purchase of refill containers (Tasaki and Yamakawa 2011), but this approach is practical only in retail and for a very specific set of material streams. A broader view is promised by the Zero Waste Index (ZWI), which is a tool to evaluate the replacement of virgin materials with secondary resources. However, as the scope of this approach includes recycling, it is unusable for measuring waste prevention (Zaman 2014). With most of these approaches, limited data availability and insufficient data quality are major obstacles (Zaman and Lehmann 2013; Laner and Rechberger 2009; Sharp et al. 2010a).

In summary, a measurement approach meeting the requirements of waste prevention and featuring strategies for addressing challenges described above is needed. The literature review shows that, while issues like the identification of activities, the quantification of potentials, the analysis of barriers (Hutner et al. 2017) and the assessment of effects are covered, this only happens separately and thus, out of context of a specific target group. Moreover, the present measurement approaches fall short in either the quantification of the amount of prevented waste or the assessment of environmental impacts – both of which are requirements. Data availability and data quality are key challenges. Furthermore, methodological choices for state-of-the-art environmental assessment must fit the criteria of waste prevention. To address this gap, an approach based on a life cycle perspective and putting waste prevention in the context of a target group is necessary in order to enable and motivate action.

3 Methodology

The development process for the methodology can be divided into three subsequent research phases as displayed in figure 1 and is accompanied by a transdisciplinary steering board. Transdisciplinarity, extending interdisciplinarity, goes beyond the borders of academia and includes stakeholders, target groups and practitioners into the research process in order to solve complex real-world problems. Therefore, the board consists of specialists from academia representing the disciplines of resource strategy, environmental sciences, chemistry and economics, as well as representatives of the target group, and participating practitioners who specialize in resource management, waste management and administration. Throughout the research process, their role includes the identification of problems and strategies and consensus building concerning both adequacy and practicability. The instruments ensuring an integrative transdisciplinary knowledge generation include the steering board itself, workshops with practitioners, interviews, and questionnaires and thus, cover almost all levels of transdisciplinary participation (Stauffacher et al. 2008). For a detailed account, please see the Supporting Information (SI 1).

The first phase to developing a measurement approach involves obtaining knowledge of existing approaches. We therefore conduct a literature research including scientific articles, waste prevention studies and programs, and projects of different stakeholders and interest groups. The results of an empirical study covering 386 local authorities in Bavaria, Germany, complemented this information (Hutner et al. 2017). The findings were analyzed, evaluated and categorized according to their approach, advantages and drawbacks. The result of this first phase is a pool of existing measurement approaches with detailed information, which is presented in the State of the Art section. The results confirm the lack of a measurement approach combining quantification of reduction of waste generated and likely environmental benefits and identifies various shortcomings of existing approaches.

From the results gathered in the first phase, we establish criteria the measurement and communication approach has to meet. These criteria are as follows:

1. Capability to measure waste reduction and impact reduction
2. Verisimilitude (closeness to reality)
3. Communicability of results
4. Ease of use

As described above, a proper calculation of the amount of prevented waste is a basic requirement. The second issue is the assessment of associated environmental impacts. The calculation of prevented waste is crucial, as it forms the basis for the environmental assessment. The environmental assessment requires further data, for example, about the composition of prevented waste. Verisimilitude encompasses both the selection and appropriate modelling of activities, which are applicable within the target group. Because one of the main reasons for the development of this approach is to raise awareness and motivation among stakeholders, the communicability of the results is crucial. Thus, a balance between the complexity of reality and the simplicity of one-dimensional results is necessary. Finally, the ease of use is a main factor in the actual application of our approach. While criteria 1 is a necessity repeatedly stated in literature, criteria 2 to 4 derive mostly from an empirical study within local authorities (Hutner et al. 2017) and have been discussed and agreed on by the transdisciplinary steering board.

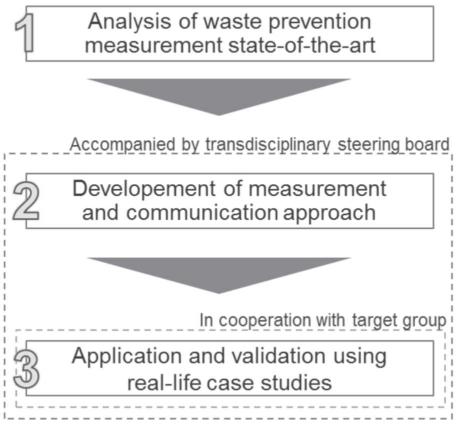

Figure 1: Methodology to develop measurement approach.

In phase 2, we develop the measurement and communication approach. The interaction with the transdisciplinary steering board is part of this phase. Existing methods, tools and approaches to measure waste prevention, assembled in phase 1, are compiled and discussed with experts in several workshops with respect to the established criteria. With this information, we create a generic approach that incorporates an adaptation of the most suitable methods and new approaches specifically designed for waste prevention.
The third phase of this research encompasses the validation of the approach developed. For this purpose, we apply the measurement approach to real-life case studies. The case studies are selected in cooperation with our target group and derive from the day-to-day business of public administration tasks within local authorities.

4 Measurement approach for waste prevention

We propose the following measurement approach featuring three steps to measure waste prevention and communicate the results (see figure 2). Building on the results of the literature review, we use an activity-based approach, thus enabling not only a measurement of reduction of waste generated and the related environmental effects, but also the assessment of specific activities. Accordingly, the approach starts with the identification of activities, the subsequent quantification and assessment of their waste prevention effects and the interpretation and communication of results.

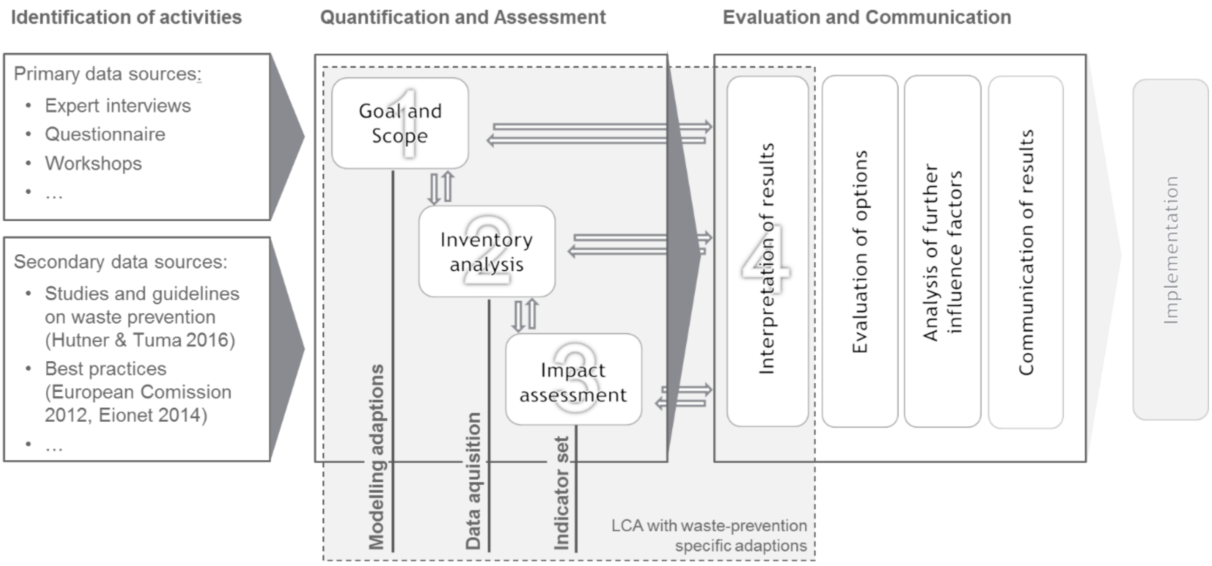

Figure 2: Measurement approach for waste prevention.

According to our assessment of the literature, the **Identification** of possible waste prevention activities can be accomplished by primary data collection or the use of secondary data sources. Primary data collection should focus on the target group and include tools such as expert interviews, questionnaires or topic-specific workshops. Secondary data sources include studies and guidelines on waste prevention as well as international and inter-sectoral compilations of best practices. The identification process includes four items and should be structured as follows: First, the status quo of waste prevention (e.g. existing activities, regulations etc.) is evaluated to recognize potentials, the second research item. Barriers as a third research item reveal obstacles for waste prevention. Subsequently, suitable activities to exploit this potential and overcome the barriers are identified. To improve data quality and applicability, this is best achieved in close cooperation with practitioners. Finally, the basic function of these activities and possible options to fulfill this function are defined and validated.

Quantification and Assessment form the second step of the measurement process. The primary goal of this step is the quantification of waste prevention effects for different activities by comparing the identified options to provide the functional unit against a baseline scenario (the status quo). With this, we estimate and communicate the positive impact waste prevention can achieve and identify the option with the largest environmental benefits. The state of the art approach to assess environmental impacts is LCA. We therefore apply LCA methodology based on ISO standards 14040 and 14044 (ISO 2006a, 2006b) and adopt several methodological choices to fit the domain of waste prevention. The following sections describe these adaptations within the LCA phases of Goal and Scope Definition, Life Cycle Inventory (LCI) and Life Cycle Impact Assessment (LCIA).

1. Modelling adaptations within Goal and Scope definition: The goal of this study is to provide information about the environmental performance of waste prevention activities. The focus of LCA in this context is the assessment of waste prevention to analyze whether and under which conditions specific waste prevention activities actually hold potential for reducing the environmental impacts of human consumption. In line with the guidelines provided by the International Reference Life Cycle Data System (European Commission 2010a), the intended application is policy information, and interactions with other systems are not accounted for. To assess all environmental impacts of waste prevention, the system boundaries encompass

the product life phases from the supply of resources to production and use. Impacts arising from the end-of-life are not considered because legally, waste prevention can only take place before a product, substance or material actually becomes waste (The European Parliament and the Council of European Union 2008). We choose functional units based on the underlying function for each case study. The different options to fulfill this function (resulting from the identification phase) are modelled and compared to the baseline scenario. As these options form the basis for the next phase of quantification and assessment, they must be assessed in as much detail as possible.

2. Data acquisition for the inventory: Ideally, the detailed modelling of lifecycle processes such as material quantities, lifetimes, transport distances etc. should mostly rely on specific data from primary sources. This step may include a data acquisition process within the institution that implements the measurement approach as well as inquiries at producers and distributors. In practice, data acquisition can start simultaneously with the Identification phase of the measurement approach (within the expert interviews). Generic data from the literature and LCA databases such as ecoinvent as well as estimated values complement the specific data. For reasons of practicability and communicability and with respect to the target group, we choose attributional modelling to assess the interdependencies and potential physical flows of all relevant options and model multifunctional processes with mass allocation (Klöpffer and Grahl 2009; Finnveden et al. 2009; European Commission 2010a).
3. Indicator set to assess environmental impacts: The indicators for the measurement of waste prevention must be familiar and tangible to ensure the communicability of results (criteria 3). Thus, well-known impact categories at midpoint level are selected, and their number is kept to five. We choose indicators that emerge from the European Waste Framework Directive (WFD) (The European Parliament and the Council of European Union 2008) and its definition of waste prevention. According to this directive, waste prevention reduces the quantity of waste, the adverse impacts of the generated waste on the environment and human health and the content of harmful substances. A short description of each indicator to reflect this definition is displayed in figure 3. The impact categories are Waste Generation (Waste) as a proxy for the quantity of waste, representative of the impacts on the environment; Global Warming Potential (GWP), Water Depletion (WD), and Metal Depletion (MD) to include negative impacts on the atmo-, hydro- and lithosphere as vital parts of the ecosphere; and finally Human Toxicity (HTox). These indicators qualify as well-known because of a wide media coverage concerning topics like climate change, critical metals and water scarcity. We used the ReCiPe v1.10 midpoint method for classification and characterization (Goedkoop et al. 2009) of all indicators except Waste, as it is expressed in mass units.

Waste prevention reduces* …	Indicator	Unit	Description
the quantity of waste,	Waste Generation (Waste)	kg or t	Waste Generation is calculated by the mass of the materials discarded at the End-of-Life of the goods needed to fulfill the basic function (functional unit).
the adverse impacts on the environment and human health or	Global Warming Potential (GWP)	kg CO_2 eq.	The GWP reflects the impact on the atmosphere and is one of the best known and best documented indicators for environmental performance (Klöpffer and Grahl 2009). It summarizes the cumulative greenhouse gas emissions over the product life cycle.
	Water Depletion (WD)	m³	Water is a life-enabling substance. Thus, its usage represents a special kind of abiotic resource depletion. The water depletion counts as a widely known environmental indicator.
	Metal Depletion (MD)	kg Fe eq.	The Mineral Resource Depletion evaluates the use of primary resources, some of them critical for technological progress and the maintaining of certain life styles and consumption patterns.
the content of harmful substances in materials and products	Human Toxicity (Htox)	kg 1,4-DB eq.	Toxicity Indicators account for the persistence and accumulation of toxic chemicals. HTox measures represents the content of harmful substances in products.

* According to the European Waste Framework Directive (Directive 2008/98/EC)

Figure 3: Selection of environmental impact categories.

The third step of our approach, the **Interpretation and Communication,** interprets and presents the results in a way that motivates the target group to act, e.g., by scaling the results or by addressing potential barriers. This step includes several elements to interpret, analyze, compare and interpret the assessed options in different contexts. One of these elements is the interpretation of results in accordance with the last phase of the LCA methodology. The interpretation includes testing the soundness and robustness of the former LCA phases using uncertainty and sensitivity analyses (de Bruijn et al. 2002; European Commission 2010b). On a meta level, the interpretation in this approach also puts the results in context with the overall research goal and the target group. For some activities and options, additional influencing factors may be of importance as well, such as possible investment, operational costs or simplification of processes. Afterwards, the preparation of communication material should be specific to the target group and may include booklets, information flyers, presentations, workshops or seminars. This approach addresses all criteria expressed in the Methodology section. The activity-based approach facilitates the direct measurement of waste prevented by a specific activity and consequently the measurement of associated environmental impacts (criteria 1). The integration of practitioners helps to increase the verisimilitude (criteria 2), especially concerning the identification of activities and the description of baseline scenarios, case studies, and options. Presenting the results using five tangible indicators illustrates the complexity of reality without compromising communicability (criteria 3). Furthermore, these indicators relate to the definition of waste prevention, which we argue makes them adequate for the case. Finally, ease of use is ensured by structuring our measurement approach in three distinct steps and by incorporating well-known and applicable tools into the setting (criteria 4). Even though the impact assessment with LCA assumes a static system and does not account for possible rebound or spillover effects, the results are still in line with the research goal, which is to provide information in order to raise awareness and motivation.

5 Application of proposed methodology

We validate our measurement approach by applying it to local authorities in Bavaria, Germany. The following sections describe the steps of our approach and relevant information concerning the case studies. The Quantification and Assessment step analyzes each of the case studies separately. Within the Interpretation and Communication, we demonstrate the overall reduction potential and its environmental impacts for a mid-sized German city.

5.1 Identification

The Identification process first establishes a knowledge base on the status quo and potentials of waste prevention within the target group. Primary data acquisition is conducted via 33 personal interviews, a questionnaire addressing 386 local authorities and a finalizing workshop. Secondary data sources include guidelines (European Commission 2012; BMU 2013), best practice compilations (EEA 2014; WRAP 2011) and scientific literature (Kopytziok 2011; Wilts and Rademacher 2014; Lebersorger and Schneider 2014; Sharp et al. 2010b). The results of this research in term of the four research items (status quo, potentials, barriers, and activities) highlights that in local authorities, the implementation status is low. The perception of potentials varies for different waste streams, but is mostly low as well. This is especially true for activities that focus on administrative processes. Barriers include a lack of awareness and information. For a thorough analysis of the process and the results, please see Hutner, Thorenz, and Tuma (2017). Additionally, 57 possible activities were identified. Out of these and via a questionnaire, five case studies are chosen by the transdisciplinary steering board for further assessment of their potential prevention effects. These case studies are the following:

1. Equipment for electronic workstations within the administration
2. The provision of drinking water in offices and public buildings
3. The use of refillables for events
4. The implementation of specific e-government applications
5. The configuration of lighting systems

For all of these case studies, practitioners provide information to determine the functional unit and possible options to fulfill these functions in semi-structured interviews. In most cases, these options are either already implemented in the local authority or planned to be implemented in the near future. For more information about the interview partners and their professional background as well as the activities and options they provided, please see the Supporting Information (SI 2). A detailed description of the interview process is given by Hutner, Thorenz, and Tuma (2017).

To successfully prevent the waste of electrical and electronic equipment, it is suggested to dematerialize electronic workplaces by securing the necessary scope of service in administrative offices with smaller devices such as “Mini-PC” or Server- based Thin Clients (STCs) instead of Desktop Computers. Water dispensers substitute drinking water from glass or plastic bottles by preparing tap water. The preparation can include filtering, carbonation, cooling, heating, and, in some cases, energizing. Water dispensers in offices and public buildings reduce the amount of packaging waste. Public events and private events on public properties can be subject to legislative regulations concerning the type of dishes to use. These regulations are often quoted as means to prevent waste if the use of disposable dishes is prohibited (Hutner and Tuma 2016). The distribution of online forms instead of actual paper forms is commonly considered to reduce not only paper waste but also environmental impacts related to their transport. This activity is an element of the transition towards e-government. Replacing common lights for communal fairs with a long-life and energy-efficient substitute is thought to greatly reduce the waste generation and environmental impact of this particular material stream. Together with practitioners, we define the functional units and identify options for these case studies (Table 1). A detailed description can be found in the Supporting Information (SI 2).

Table 1: Functional units and options for the five case studies.

	Case Study	Functional Unit		Options
1	Electronic workstations	Supply of an electronic workspace for 4 years of use in a public administration office	A	Desktop PC
			B	Laptop
			C	Mini-PC
			D	Server-based Thin Client
2	Water provision	Provision of drinking water for 25 employees in a public office building over 7 years	A	Glass bottles (50 km)
			B	Glass bottles (300 km)
			C	Plastic bottles
			D	Water dispenser
3	Refillables	Supply of soft drinks and beer in a sports stadium for 3 years in 0.5 liter vessels	A	Disposable PET cups
			B	Disposable PLA cups
			C	Reusable PP cups (# cycles: 41)
			D	Reusable, printed PP cups (# cycles: 6)
4	E-government	Handling forms between public administration and its citizens over a period of 5 years	A	Paper forms filled in at public administration offices
			B	Paper forms delivered by mail
			C	Printable online forms delivered by individual transport
			D	Printable online forms delivered by mail
			E	Online forms, digital delivery
5	Lighting	Lighting for 3,602 billion lumen hours	A	Incandescent light bulb (ILB)
			B	Compact fluorescent lamp (CFL)
			C	Light emitting diode (LED)

5.2 Quantification and Assessment

For each of these case studies and all options separately, the environmental impacts are quantified and assessed using the adapted LCA methodology. Then, the options are put in context to the baseline scenario (options A) to calculate their potential to reduce the environmental impact. We model the different options using SimaPro 8.4. Data sources include specific data from practitioners, industry data mostly concerning product composition, and secondary data from the literature. These data sources are complemented with existing material and process data within the databases available in SimaPro, mainly ecoinvent v3.01.

In some cases, similar LCA studies already exist. However, none of them exactly fit our goal and scope requirements or used all of the indicators that we choose to reflect waste prevention. We therefore model all cases individually, incorporating some information used in previous studies (Maga et al. 2013; Nessi et al. 2012; Kauertz et al. 2010; Vercalsteren et al. 2010; Garrido and Alvarez

del Castillo 2007; Mirabella et al. 2013). For a detailed list of all modelling choices, assumptions and data sources, please see the Supporting Information (SI 3).
Figure 4 shows the LCIA results for all 20 options. The results are presented as relative impacts compared to the maximum values of each category. The values for waste prevention are only subject to modelling decisions without additional uncertainties. The four life cycle impact categories are have some uncertainties according to the life cycle inventory calculations and characterization factors. Typically, these uncertainty ranges are lowest for the global warming potential and highest for human toxicity values. Results for alternative modelling choices are part of the sensitivity analysis in the Supporting Information (SI 3).

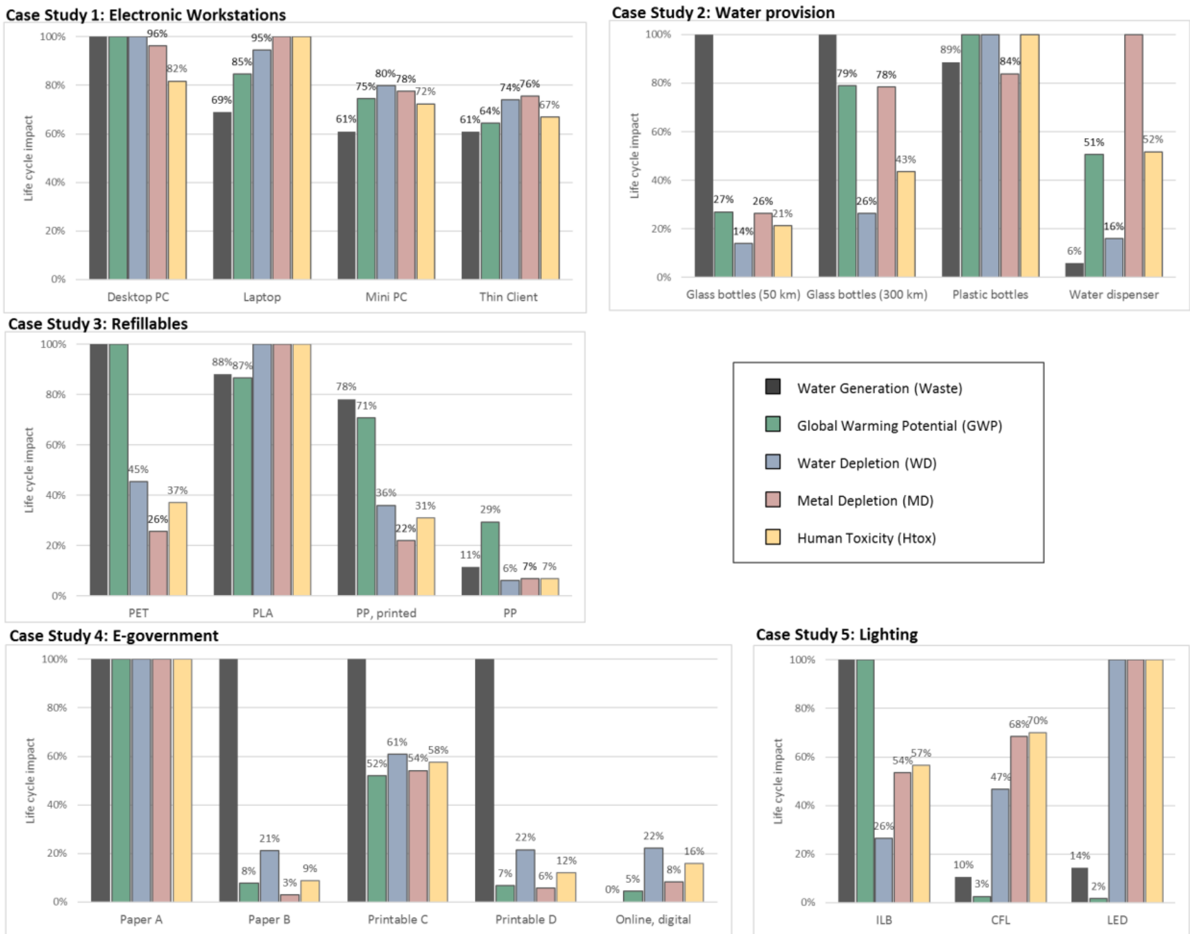

Figure 4: LCIA results for the case studies, normalized to the option (for each case study) with the highest impact for the respective indicator.

Electronic workstations

Electronic workstations in public administration offices are usually equipped with desktop computers (Koppmair and Wenger, pers. comm.). Changing this convention offers high potential to reduce environmental impacts. The environmental performance of both Mini-PCs and STCs are superior for all impact categories. Nearly 40% of waste will be prevented in these options, and the GWP is reduced by 25% if Mini-PCs are used and by 36% if STCs are used. This amounts to savings of 252 kg and 354 kg CO2 eq. All other indicators can be reduced by 21% to 33%. The calculation of prevented waste and assessment of environmental impacts demonstrates the effectiveness of waste prevention by dematerialization.

Water provision

The waste prevention potential of using a water dispenser to provide drinking water amounts to 1,240 kg of waste, which equals a 94% reduction compared to reusable glass bottles. Even single-use 1.5 liter plastic bottles with a weight of 33 g eventually sum to 1,170 kg of waste (including packaging). For all other indicators, regional bottled water with a transport distance of 50 km has the lowest environmental impacts. More than half of the MD and HTox impacts of the water dispenser originate from its cooling unit and its technical accessories. Due to the electricity need for its operation, the water dispenser has 75% higher impact on global warming than the base case of glass bottles.

Refillables

In terms of waste generation, reusable cups for events pose the best alternative, although they have roughly five times the weight of disposable cups. Unprinted polypropylene (PP) cups cause 11% of the category maximum of 18,100 kg, which arises with polyethylene terephthalate (PET) cups. All other categories are at their minimum with unprinted PP cups as well. However, as event organizers sometimes choose to individualize cups for the purpose of marketing, printed cups are common. As printed cups do not have as many return cycles, the results are not as clear. While waste generation is still at least 20% lower than the maximum, WD, MD and HTox do not vary significantly from that associated with disposable PET cups. Here, the modeling choices may be decisive.

E-government

All options in which forms must be printed generate 17,500 kg of waste. Digital delivery drastically reduces this number to only 11.3 kg, thus preventing 99% of waste. In particular, options with individual transport account for high CO2 emissions, water and resource depletion, and high toxicity. These can be reduced by delivering the forms via mail instead of personally bringing them to the public office. Delivery via mail accounts for even less MD and HTox than the use of digital forms.

Lighting

While both CFL and LED significantly reduce the quantity of waste and the GWP from 86% to 98%, the WD, MD and HTox performance is inferior to that associated with conventional light bulbs. However, the life span of LEDs significantly impacts the results. We model the life span with 15,000 hours according to manufacturer information (LEDVANCE 2018), but tests demonstrate that 50,000 hours are realistic (Chang et al. 2012).

We find that for most cases that offer either an advanced technological solution or digitalization of processes, the levels of MD and HTox typically increase, while less waste and, normally, less greenhouse gas emissions are generated. This outcome can be observed with the water dispenser, the LED and, to some extent, digitally returnable forms. It is argued that in some cases of dematerialization comes at the price of higher energy demand for new production processes and the need for more critical or rare materials (Knermann et al. 2011). Our results support these statements.

6 Sensitivity Analyses

Although some methodological choices within LCA must be preset for waste prevention, the modelling can still be decisive. In particular, the system boundaries and modelling assumptions influence the results. Therefore, sensitivity analyses (in the Supporting Information, SI 3) are used to verify the results (Vercalsteren et al. 2010; van der Harst et al. 2014). Smaller local authorities might have less than 100 workstations, but even with a lowered server utilization of just 20 workstations, thin clients still have the lowest impacts for the categories greenhouse gas emissions, water depletion, metal depletion and human toxicity. If two displays are modeled instead of just one, the relative waste reduction potential of mini PCs and thin clients is only reduced to 27% instead of 39%. In the case of only 10 employees, for example in a smaller local authority, the water dispenser still reduces the waste generation by 88% (instead of 94% in the base case of 25 employees), but the impacts for global warming potential, metal depletion and human toxicity are the highest of all options. The consumption share of carbonated water globally is much lower than the 60% in Germany, which is assumed for the base case. If this share is as low as 20%, the waste reduction potential of the water dispenser increases to 95% compared to glass bottles, because of decreased packaging material for the carbon cylinder. The impact of the refillables are highly dependent on the number of usage times for the PP cups. Unprinted PP cups remain the option with lowest impacts for all categories even if they are washed and reused only 20 times. Although using only public transportation for handing in paper forms may half the greenhouse gas emissions compared to the base case, using online forms or mail delivery still has 81% to 89% lower impacts in this category. For forms double the average length, the relative impacts from individual transport are also reduced a bit, but digital forms still have the lowest global warming potential and the waste reduction potential is even higher than in the base case. If the lighting concept of the Christmas fair is changed after 10 years and the use of any lighting material is discontinued, the waste reduction potential of LEDs is reduced from 86% to 41%. Interestingly, over the period of 10 years, using CFLs would then not only have lower water and metal depletion and human toxicity impacts than the LEDs, but even result in lower greenhouse gas emissions. Overall, the sensitivity analyses show the robustness of the case study results even in case of drastic changes to the model assumptions. Detailed results of the sensitivity analyses can be found in the Supporting Information (SI 3).

7 Interpretation and Communication of Options

This step of the measurement approach includes the interpretation of results with regard to the research goal. The overall goal of the study is to enable and motivate local authorities to implement waste prevention concepts by measuring and visualizing the effects of waste prevention. To do so, we communicate the results on two levels. The identified activities are published in a “Guideline for the Implementation of communal waste prevention concepts” (Hutner and Tuma 2016). This addresses the lack of information we identified in the identification phase of our approach (Hutner et al. 2017). Additionally, we apply the results of the base cases of all five LCAs to a model local authority, thus presenting the possible effects in a vivid and catchy way to raise awareness and motivation for the whole target group. This model local authority is roughly based on the characteristics of the cooperating city of Augsburg, with 250,000 citizens, 6,264 employees at local authorities, 2,800 office workspaces with an average utilization of 50%, a first league soccer club and a yearly Christmas market. The baseline scenario characterizes such a model local authority without previous waste prevention activities taken. In this baseline, we assume it uses desktop computers for all workstations, supplies drinking water for its employees by refillable glass bottles that are transported 300 km, provides disposable cups at the soccer stadium, issues paper forms and uses incandescent light bulbs for the Christmas fair (options A, see table 1). We further assume that the option mix Waste is implemented, thus choosing the option with lowest waste generation (option mix 1, see table 2) and that the effects will occur immediately. To model this, we use statistical data on a one-year basis rather than taking into account the time lag between the implementation of the activity and the occurrence of impacts. The quantification results of all options with a timeframe longer than one year are adapted accordingly. For example, if the desktop computer is replaced with a thin client that has an average life span of 4 years, ¼ of its environmental impacts will occur at the end of the first year. Ultimately, the yearly environmental impacts of the baseline scenario are compared with the yearly environmental impacts of the option mix 1 (Waste). The difference represents the waste prevention effects for the model community.

Table 2: Optimal choice of options for the base case depending on impact category emphasis (Scenario letter refer to options in table 1. GWP = Global Warming Potential, WD = Water Depletion, MD = Metal Depletion, HTox = Human Toxicity).

		Baseline	Optimal mix of options concerning impact category				
	Case Study	option	1: Waste	2: GWP	3: WD	4: MD	5: HTox
1	Electronic workstations	A	D	D	D	D	D
2	Water provision	B	D	A	A	A	A
3	Refillables	A	D	D	D	D	D
4	E-government	A	E	E	B	B	B
5	Lighting	A	B	C	A	A	A

Figure 5 shows that within one year, the model community could prevent 31,000 kg of waste if all activities are implemented. This amount translates to a waste prevention rate of 74%. The GWP would be reduced by 62%, and the WD, MD and HTox would decrease by 44%, 36% and 28%, respectively. The results clearly indicate that waste prevention is feasible and environmentally preferable.

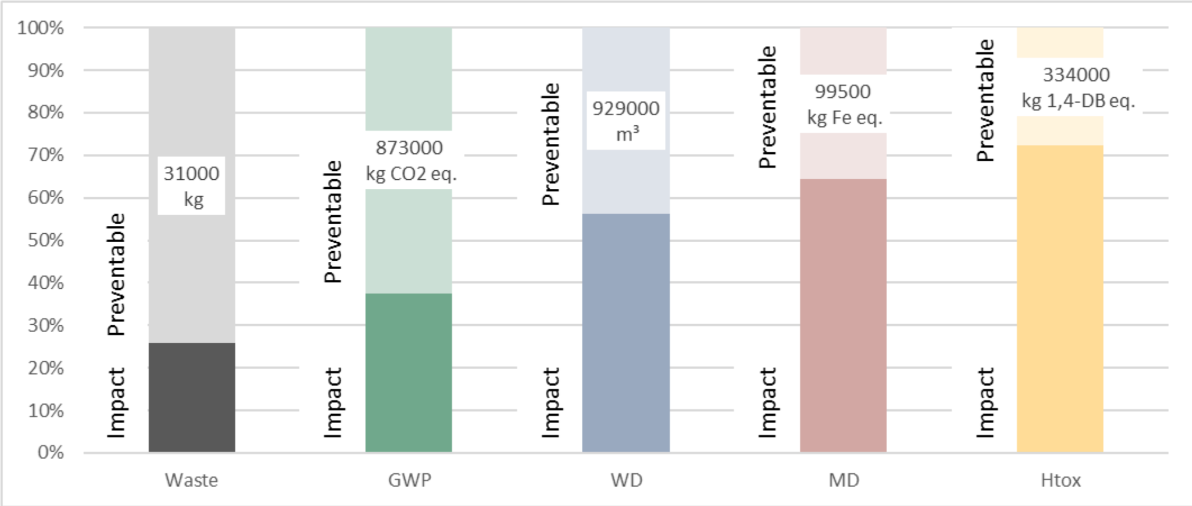

Figure 5: Waste prevention and related environmental effects for a model city. 100% equals the environmental impact of the model community with the baseline options. The Impact equals the environmental impact of the chosen waste prevention option. The difference between *baseline* and *waste prevention* option represents the waste prevention effects.

The assessed activities vary in their contribution to this overall prevention effects. Figure 6 presents the reduction potential of each option relative to the total environmental contribution. This option-based assessment is a major component of the measurement approach, as it forms the basis for the process of selecting activities and, consequently, the actual implementation of waste prevention.

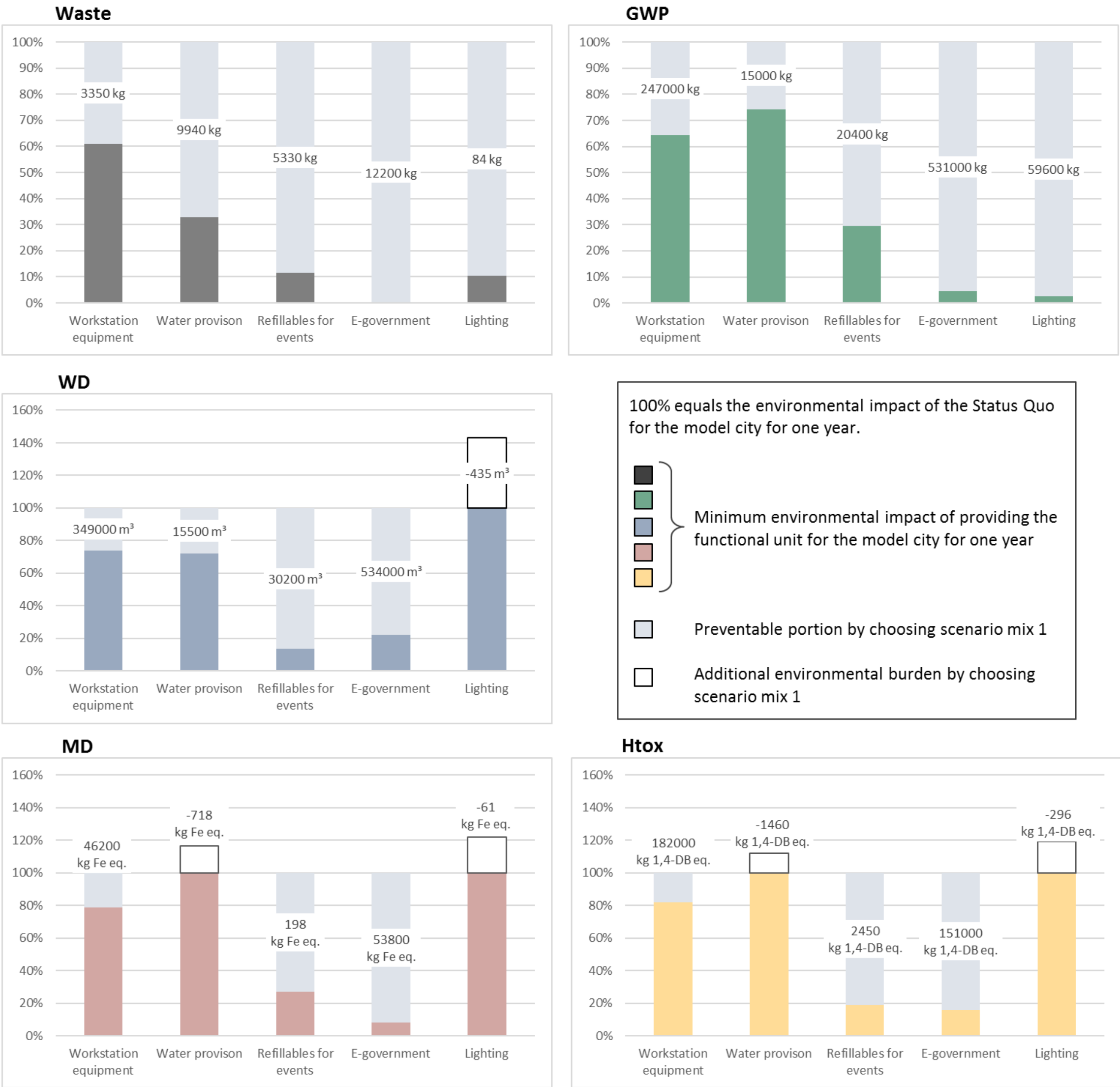

Figure 6: LCIA results for model city with option mix 1: Waste. The line at 100% depicts the environmental impact of the baseline scenario of each case study. The colored part of the bar displays the environmental impact of the chosen waste prevention option. The difference (in grey) represents the relative reduction potential. The absolute values are given to assess the overall effectiveness of each activity.

Concerning the reduction of waste quantity, the case studies show that the options for water provision and e-government are especially effective, each preventing about 10,000 kg of waste per year. The prevention potential of electronic workstations amounts to 39% of the total, corresponding to 3,400 kg. The relative impact of the choice of lighting systems is higher (90%), but only 84 kg of waste can be prevented.

E-government has the highest GWP reduction potential at more than 530,000 kg CO2 eq. per year. Although only 36% of the GWP of electronic workspaces can be prevented by the use of thin clients, this amount translates to 250,000 kg CO2 eq. Therefore, thin clients, together with e-government, are by far the most effective option for GWP reduction. The reduction potential of water provision, refillables and lighting is comparatively low, with water provision performing the worst (26% reduction potential, 15,000 kg CO2 eq.).

Similar to the GWP, the workstation equipment and digital forms show the highest potential for reducing WD. STCs decrease the WD by 26% and e-government by 78%. The highest relative reduction is reached by the usage of unprinted PP cups (87%). Lighting the Christmas fair with CFLs instead of the former ILBs actually requires 435 more liters of water.

Two of the activities actually increase the MD, WD or HTox. These are water provision with a water dispenser and lighting with CFLs. Combined, they account for an additional environmental burden of 780 kg Fe eq. and 1,760 kg 1,4-DB eq. Overall, though, a reduction in these impact categories can still be realized because option mix 1 compensates for these negative impacts. This result is mainly due to the large MD and HTox savings from thin client use and the electronic distribution of forms.

8 Discussion and Conclusion

The results demonstrate that the activity-based measurement is an adequate approach for measuring reduction of waste generated and the related environmental effects of waste prevention activities. We develop the measurement approach in close cooperation with practitioners by identifying essential criteria for the approach and then ensuring that these criteria are met. When applied, our measurement approach produces results on several levels: First, specific activities are identified, second, these activities are assessed. Lastly, the effects of the implementation of waste prevention by the target group are prepared for communication. The procedure allows stakeholders to choose the most fitting actions. According to their overall goals, decision makers can prioritize the five impact categories to find their optimal mix as presented in table 2, once the Quantification and Assessment phase is completed. The selected and assessed activities are then interpreted according to the size and characteristics of the target group to estimate possible overall environmental benefits. As the target group for our study are local authorities of different size and structure in Bavaria, Germany, we model a fictional city, which local authorities can relate to in general, rather than using a specific real local authority. Our set of indicators is selected in line with the definition of waste prevention in the WFD. It ensures the integration of effects that interact with ecosphere and anthroposphere as well and provides an overview of possible environmental repercussions. Additionally, the limitation on five indicators simplifies interpretation and communication.

Our approach successfully quantifies the waste prevention potentials of the model city. One of its effects is the establishment of a waste prevention concept in the German city of Augsburg, including the creation of a dedicated job for waste prevention in the city administration. The publication of a waste prevention guideline as part of the project helps identifying and implementing of waste prevention activities in other local authorities.

Nevertheless, data availability and data quality remain the key challenges in this approach. We propose to collect activity-based data in cooperation with practitioners. These data ideally cover attributes such as the functional unit, execution frequency, time horizon and, in particular, necessary products and materials as well as their characteristics. This usually needs to be complemented by using LCA databases, which can sometimes result in expenses. Additionally, known shortcomings and critical remarks for the LCA methodology must be acknowledged, since the second part of the measurement approach strongly relies on this standardized tool. However, since LCA is the state of the art, it is an essential and sensible component of our approach.

Other topics related to the LCA methodology are the selection of the modelling approach, the impact assessment method and the impact categories. In accordance with the transdisciplinary steering board and in line with our research question, we choose attributional modelling to quantify waste prevention effects and compare options. This improves the practicability of our approach for non-academia users and reduces the uncertainty that comes with system expansion. However, it may still be argued that consequential modelling better reflects how markets, both primary and end-of-life, are affected by decisions towards waste prevention. Additionally, while necessary to ensure the communicability of results, the limitation to 5 indicators on midpoint-level may be subject for further discussion. Endpoint-based assessment includes more than these 5 impact categories and would have been more comprehensive. Regardless, as midpoint units are more tangible and, as confirmed by the transdisciplinary steering board, also easier to understand, we use these for this study. Summing up, as the main research goal is to motivate stakeholders within the target group to use this approach, we strongly suggest that the modelling, assessment and communication be kept as simple and transparent as possible.

The validation of our approach using real-world case studies hints at possible challenges. The sensitivity analyses of the five case studies show that overall the results are robust to altered modelling choices. However, in some cases the optimal choice of options concerning the five impact categories may change if an important modelling parameter or choice deviates strongly from the base case. Therefore, special attention must be paid to the choice of options and model parameters with the involvement of stakeholders.

The case studies also emphasize both the drawbacks and benefits of using midpoint impact categories instead of a single score. On the one hand, the results are not inevitably decisive, and there are no globally accepted characterization factors to compare 1 kg of CO_2 eq. with 1 kg of waste and 1 m^3 of water to compare options. In the case of the water dispenser, the prevented waste would need to be weighed against the higher GWP and HTox, and, especially, against the MD, which is the maximum value (349 kg Fe eq.) for the case studies. On the other hand, the impact categories on midpoint level allow practitioners to set their own emphases according to their overall goals.

In conclusion, we argue that the advantages of our approach outweigh its limitations. The measurement process closes the existing research gap and presents the structured methodology requested by politics and practitioners alike. A commonly shared approach not only enables the comparison of waste prevention within and between different target groups but also allows viable benchmarks to be set.

Further research and future projects should aim for a database of reference activities. This would simplify the data acquisition process and improve ease of use. Although options for activities vary for different target groups, existing results may give a general idea about potential waste prevention effects. The selection of the optimal mix of activities and options is another possible area of research. To achieve this, a multi-criterial optimization algorithm can account for the challenge of weighting different impact categories. Beside the environmental impacts of waste prevention, also economic and social aspects of the activities should be taken into account in the future in order to encompass all three dimensions of sustainability. Only then, a decision whether and to which extent waste prevention contributes to sustainable resource management will be possible. For this area of further research, the issues of data availability and data quality as well as comparison and weighting between different impact categories have to be addressed.

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Postprint

Transdisciplinary development of a life-cycle based approach to measure and communicate waste prevention effects in local authorities

Supporting Information

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SI 1: Transdisciplinary research setting – procedure and instruments

The instruments of transdisciplinary research can be depicted depending on the intensity of involvement (Stauffacher et al. 2008). Figure SI 1 depicts the elements we used within this project according to the research phases.

The steering board consisting of experts and practitioners in the fields of resource strategy, environmental sciences, chemistry, economics, and communal administration accompanies and guides all research phases from the framing of research items, goal, and methodology (preparation phase) to the implementation of the approach. Workshops with different kinds of stakeholders are mostly used for the *Identification of activities* and the *Evaluation and Communication*. A two-study research design featuring personal interviews and a questionnaire provides information about activities for the Identification and Quantification. Table SI 1 presents an overview on the interview partners and the information gained in these interviews. Presentations and the publication of results are among the communication instruments on a purely informational level.

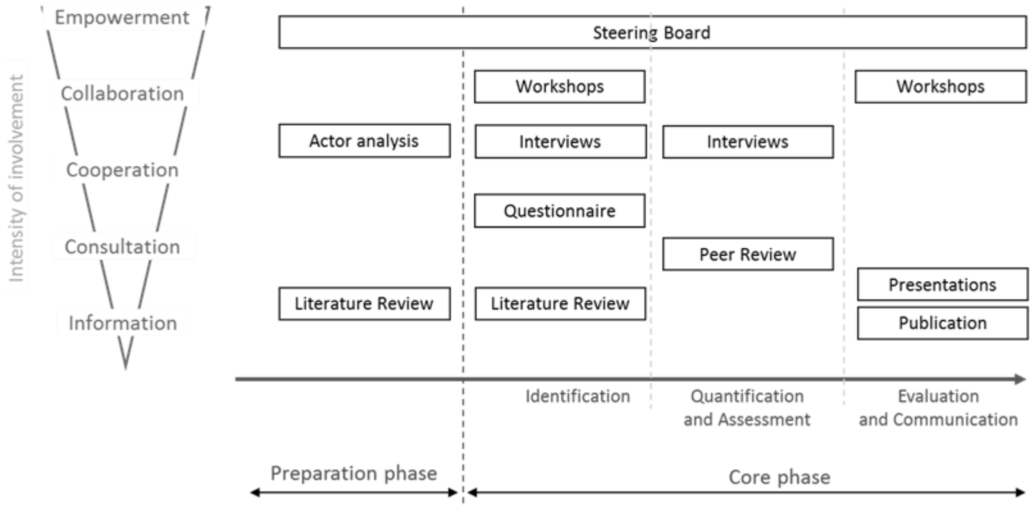

Figure SI 1: Instruments of transdiciplinary research used whithin this research project.

SI 2: Interview partners and selection of case studies

Table SI 2: Overview on interview partners and information input

#	Local authority	Departement	Unit	Position	Case Study	Input for options
1	Augsburg	Social		Employee		
2	Augsburg	Construction	Civil engineering	Head of unit		
3	Augsburg	Education	Schools	Employee		
4	Augsburg	Odnungsreferat		Employee	Case Study 5	Option C (LED)
5	Augsburg	Organisation	IT	Employee	Case Study 1	Option C (Mini PC)
6	Augsburg	Organisation	IT	Head of unit	Case Study 1	Options A, C (Desktop PC, Mini PC)
7	Augsburg	Education	Kindergardens	Employee		
8	Augsburg	Environment	Environment	Employee	Case Study 3	Options A, B, C, D
9	Augsburg	Economy	Estates	Employee		
10	Augsburg	Organisation	Main office	Employee	Case Study 4	
11	Augsburg	Cultural affairs and Sports	Public swimming pools	Employee		
12	Miesbach	Construction and Environment	Waste management	Employee		
13	Augsburg	Construction	Regulatory agency	Head of unit	Case Study 4	
14	Augsburg	Construction	Building construction	Head of unit		
15	Augsburg	Finance and HR		Head of departement	Case Study 4	
16	Munich	Communal affairs	Infrastructural services	Employee	Case Study 2	Option D (Aquatower)
17	Munich	Work and Economy	Events	Employee		
18	Munich	Communal affairs	Markets	Employee		
19	Munich	Work and Economy	Events	Head of unit	Case Study 3	Options A, D
20	Munich	Work and Economy	Events	Employee	Case Study 3	

21	Munich	Communal affairs	Markets	Head of unit		
22	Munich	Communal affairs	Markets	Employee		
23	Munich	Communal affairs	Infrastructural services	Head of unit		
24	Augsburg	Cultural affairs and Sports	Sports infrastructure	Employee	Case Study 3	Options A, D
25	Augsburg	Cultural affairs and Sports	Sports infrastructure	Employee		
26	Munich	Environment and Health	Waste management	Employee	Case Study 2	Options A, B, C, D
27	Munich	Environment and Health	Inherited waste	Employee		
28	Munich	Organisation	Main office	Employee		
29	Munich	Organisation	Controlling	Employee		
30	Munich	Municipal enterprise	it@M	Employee	Case Study 1	Options A, D (Desktop PC, STC)
31	Munich	Municipal enterprise	it@M	Employee	Case Study 1	Options A, D (Desktop PC, STC)
32	Munich	Municipal enterprise	AWM	Angestellt		

SI 3: Description and modelling details of case studies

Case study 1: Electronic Workstations

To successfully prevent waste of electrical and electronic equipment, it is suggested to dematerialize electronic workplaces. This can be done by securing the necessary scope of service with smaller devices such as “Mini-PC” or Server based Thin Clients (STC) instead of Desktop Computers. Administration of local authorities and schools are possible fields of application within local authorities. This case study is currently a subject of discussion in the German cities of Augsburg (option of choice: Mini PC) and Munich (option of choice: STC) (Koppmair and Wenger 2013, pers. comm.; Mairgünther and Lopes 2014, pers. comm.). A standard electronic working space consists of a workstation, display, pointing device and keyboard. With option A, the workstation is a tower. Option B and C feature a laptop or a Mini PC as workstation, while in D additionally to the thin client the proportionate server is modelled. The server supplies 100 thin clients. Additional information about the characteristics of each option is given in the Modelling details.

According to personal interviews with practitioners, electronic workstations in administrative offices of local authorities are replaced every 4 to 5 years (Koppmair and Wenger 2013, pers. comm.; Mairgünther and Lopes 2014, pers. comm.). This information affects our modelling in two ways: First, we assume that, since an exchange is inevitable, the old devices have to be discarded anyway and thus exclude the dismantling and end-of-life of existing desktop computers from our modelling. Secondly, we assume a lifetime of 4 years for the new devices, with 220 workdays per year. The usage time therefore amounts to 880 workdays. The intensity of use and energy demand differs between active, sleep and off mode. We assume that the material composition of all products variated only slightly in the last couple of years, thus allowing us to use older data where needed. This data is adjusted to current conditions by using an adaption factor based on mass (see table SI 2). We assume further that the material composition of the desktop PC and server are similar and that the server therefore also can be modelled by a factor based on weight (Maga et al. 2013).The same approach is used for Mini PC. The weights we used are average values for options A and B and specific product information for C and D (Maga et al. 2013; Fujitsu 2014).

The first part of the following table presents the data sources (Literature, Personal communication, and LCI data) used for modelling. The second part describes the modelling characteristics of each option in detail. The numbers in brackets refer to the data sources in the first part.

Table SI 3: Adaption factors based on weight

Option #	Option	Average Weight	Weight in existing dataset	Adaptation factor for existing dataset
A	Desktop PC	6.37 kg	11.3 kg	0.56
B	Laptop	2.57 kg	3.15 kg	0.82
C	Mini PC	1.6 kg	11.3 kg	0.14

Case Study 1	Reference #	
Literature used for modelling	1	(Duan et al. 2009)
	2	(Fraunhofer UMSICHT 2011)
	3	(Fujitsu 2014)
	4	(IVF 2007)
	5	(Maga et al. 2013)
	6	(Stiel and Teuteberg 2013)
Personal communication used for modelling	7	(Mayer 2013, pers. comm.)
	8	(Mairgünther and Lopes 2014, pers. comm.)
	9	(Koppmair and Wenger 2013, pers. comm.)
LCI data used for modelling (main processes) ecoinvent v3.01	10	Acrylonitrile-butadiene-styrene copolymer {GLO}| market for | Alloc Def, U
	11	Capacitor, for surface-mounting {GLO}| market for | Alloc Def, U
	12	Computer, desktop, without screen {GLO}| production | Alloc Def, U
	13	Copper wire, technology mix, consumption mix, at plant, cross section 1 mm² EU-15 S
	14	Display, liquid crystal, 17 inches {GLO}| production | Alloc Def, U
	15	Electric connector, peripheral component interconnect buss {GLO}| market for | Alloc Def, U
	16	Electricity mix, AC, consumption mix, at consumer, < 1kV DE S
	17	Ferrite {GLO}| market for | Alloc Def, U
	18	Folding boxboard/chipboard {GLO}| market for | Alloc Def, U
	19	Galvanized steel sheet, at plant/RNA
	20	Integrated circuit, memory type {GLO}| market for | Alloc Def, U
	21	Keyboard {GLO}| production | Alloc Def, U
	22	Pointing device, optical mouse, with cable {GLO}| production | Alloc Def, U
	23	Printed wiring board, surface mounted, unspecified, Pb containing {GLO}| market for | Alloc Def, U
	24	Printed wiring board, surface mounted, unspecified, Pb free {GLO}| market for | Alloc Def, U
	25	Steel, chromium steel 18/8, hot rolled {GLO}| market for | Alloc Def, U

SCOPE				
Usage time, years	4 [7, 9]			
Workdays per year	220			
Active mode, hours per day	6.48 [4]			
Sleep mode, hours per day	8.64 [4]			
Off mode, hours per day	8.88 [4]			
Days of operation	880			
Max. server utilization	130 [5]			
Assumed server utilization	100			
MODELING				
	Desktop PC	**Laptop**	**Mini PC**	**Thin Client (and Server)**
Quantity				
Weight, kg	6.37	2.57	1.6 [3]	2.69 [5]
Electricity use				
Active, kWh per hour	0.0782 [4]	0.032 [4]	0.0391	0.0115 [5]
Sleep, kWh per hour	0.0022 [4]	0.003 [4]	0.0011	0.0019 [5]
Off, kWh per hour	0.0027[4]	0.0015 [4]	0.0014	0.0019 [5]
Overall, kWh	468,01	210.82	234.4	124.56
EXEMPLARY BILL OF MATERIALS FOR THIN CLIENT				
Material				
Ferrite		8.3	g	

Steel, chromium steel 18/8, hot rolled	120.7	g
Galvanized steel sheet	785.16	g
Copper wire, technology mix, consumption mix	180.6	g
Iron-nickel-chromium alloy	45.3	g
Acrylonitrile-butadiene-styrene copolymer	345.74	g
Polyethylene, low density	11.9	g
Polycarbonate	1.16	g
Polyurethane, flexible foam	2	g
Printed wiring board, surface mounted, unspecified, Pb free	120.59	g
Integrated circuit, memory type	23.47	g
Capacitor, for surface-mounting	347.02	g
Solder, bar, Sn95.5Ag3.9Cu0.6, for electronics industry	12.77	g
Electric connector, peripheral component interconnect buss	96.75	g
Printed wiring board, mounted mainboard, desktop computer, Pb free	32.17	g
Light emitting diode	10.26	g
Folding boxboard/chipboard	546	g
Graphic paper, 100% recycled	0.13	g
Production		
Electricity mix	937	MJ
Process water	384	kg
Cooling Water	228	l

Sensitivity Analysis 1: Electronic Workstations

We assume two altered modelling choices for the case study of electronic workstations.

In the first sensitivity case, we assume that the thin-client system has a lower server utilization of only 20 thin-clients per server, instead of 100. This increases the impacts of only the option D.

In the second sensitivity case, we assume that all workstations are equipped with two displays, instead of only one. This increases the impact of all options.

Altered modeling parameter	Base case (1A0, 1B0, 1C0, 1D0)	Sensitivity case 1 (1A1, 1B1, 1C1, 1D1)	Sensitivity case 2 (1A2, 1B2, 1C2, 1D2)
Server utilization (Thin Client)	100 (1D0)	20 (1D0)	100 (1D2 unchanged)
Display, number (all options)	1 (all options)	1 (unchanged)	2 (all options)

Results sensitivity analyses electronic workstations:

Sensitivity case		1A0	1B0	1C0	1D0	1A1	1B1	1C1	1D1	1A2	1B2	1C2	1D2
Modelling choice		Desktop PC	Laptop	Mini PC	Thin Client	Base case	Base case	Base case	20 users only	Two Displays	Two Displays	Two Displays	Two Displays
Waste Generation (Waste)	kg	12.2	8.4	7.5	7.4	12.2	8.4	7.5	7.6	17.3	13.5	12.5	12.5
Global Warming Potential (GWP)	kg CO_2 eq	993	840	740	639	993	840	740	642	1478	1.325	1225	1.124
Water Depletion (WD)	m³	1926	1822	1538	1427	1926	1822	1538	1441	3100	2.996	2712	2.601
Metal Depletion (MD)	kg Fe eq	308	320	249	242	308	320	249	246	473	485	414	407
Human Toxicity (Htox)	kg 1,4-DB eq	1448	1771	1283	1187	1448	1771	1283	1199	2336	2.659	2171	2.075

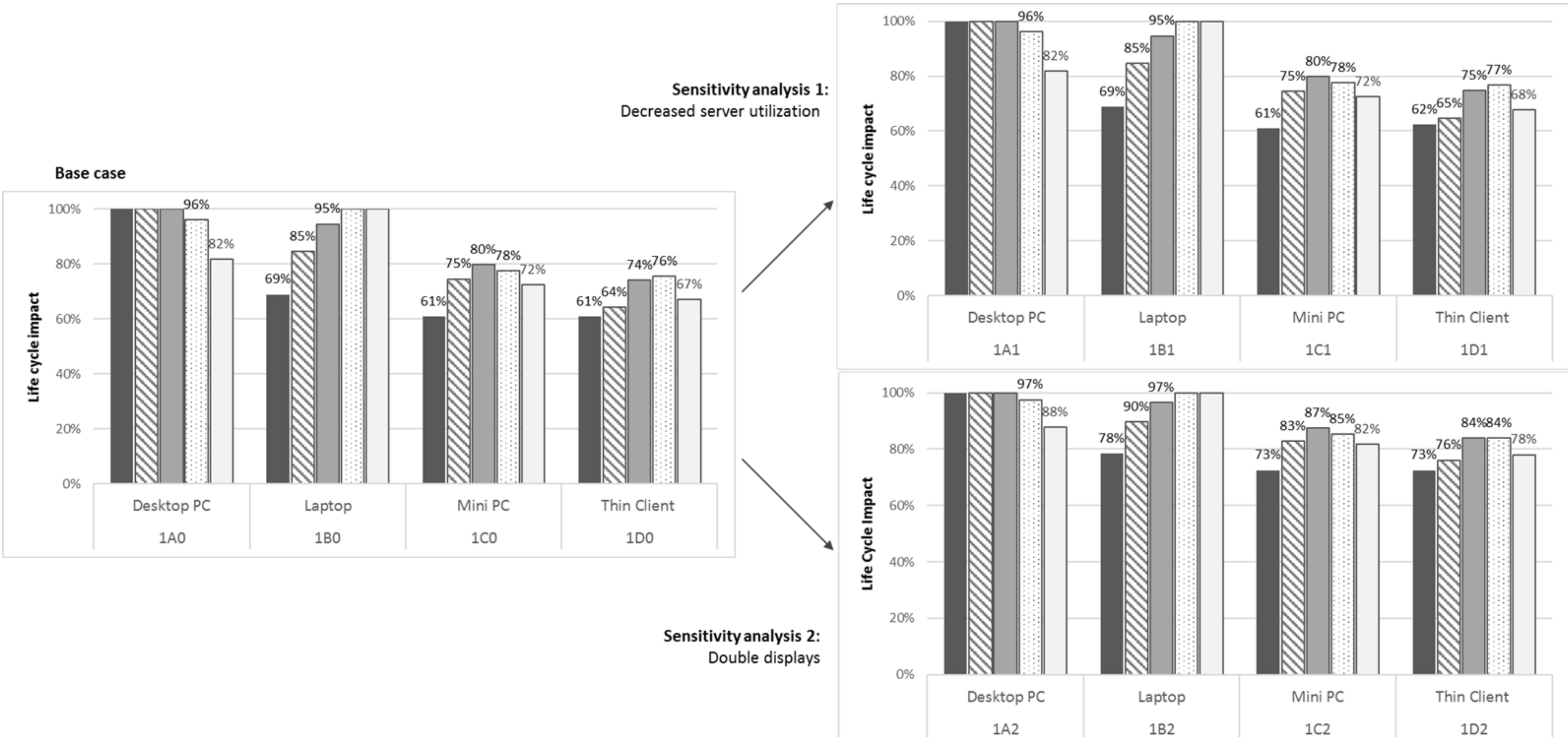

Figure SI 2: Relative life cycle impacts of the options Desktop PC, Laptop Mini PC and Thin Client in the base case and the two alternative modelling choices: (i) only 20 thin clients per server and (ii) two displays per electronic workstation.

Case study 2: Water provision

Water dispensers substitute drinking water from glass or plastic bottles by preparing tap water. The preparation can include filtering, carbonation, cooling, heating, and, in some cases, energizing. The equipment used in Munich and currently under installation in Augsburg is called “water bars”, the manufacturer is BRITA. Water dispensers in offices and public buildings reduces the amount of packaging waste. In agreement with interview results from Munich and the manufacturer, the supply of drinking water for an office with 25 employees is assessed (Barth-Ilg 2014, pers. comm.; BRITA Ionox 2015, pers. comm.). In option A and B, the water is supplied in common 0.7 liter refillable glass bottles with a respective transportation distance of 50 and 300 km. Option C features the use of 1.5 liter one-way PET bottles. In all three options, the transportation is within the system boundaries. The water dispenser “Sodamaster 50 Aquatower”, which provides still and sparkling water directly out of the water pipe, is assessed along with the necessary carbon cylinders and filter systems. Respective to German consumption patterns, we assume a proportion of 60% sparkling and 40% still water (VDM 2016).

We assume a consumption of one liter per person per workday with 220 workdays a year. The LCA covers a period of 7 years which mirrors the realistic lifetime of the equipment (BRITA Ionox 2015). The total amount of water is 38,500 liters.

The first part of the following table presents the data sources (Literature, Personal communication, and LCI data) used for modelling. The second part describes the modelling characteristics of each option in detail. The numbers in brackets refer to the data sources in the first part.

Case Study 2	Reference #	
Literature used for modelling	1	(Fantin et al. 2014)
	2	(Kauertz et al. 2010)
	3	(Nessi et al. 2012)
	4	(VDM 2016)
Personal communication used for modelling	5	(Barth-Ilg 2014, pers. comm.)
	6	(BRITA Ionox 2014, pers. comm.)
	7	(BRITA Ionox 2015, pers. comm.)
	8	(Langer 2014, pers. comm.)
	9	(Sodastream 2015, pers. comm.)
LCI data used for modelling (main processes)	10	Aluminium, primary, ingot {GLO}| production | Alloc Def, U
	11	Brass {CH}| production | Alloc Def, U
ecoinvent v3.01	12	Carbon dioxide, liquid {RER}| production | Alloc Def, U
	13	Charcoal {GLO}| production | Alloc Def, U
	14	Copper {RER}| production, primary | Alloc Def, U
	15	EUR-flat pallet {RER}| production | Alloc Def, U
	16	Fleece, polyethylene {RER}| production | Alloc Def, U
	17	HDPE resin E
	18	Iron-nickel-chromium alloy {RER}| production | Alloc Def, U
	19	Metal working, average for aluminium product manufacturing {RER}| processing | Alloc Def, U
	20	Packaging film, low density polyethylene {RER}| production | Alloc Def, U
	21	Polyethylene terephthalate, granulate, bottle grade {RER}| production | Alloc Def, U
	22	Polyethylene, low density, granulate {RER}| production | Alloc Def, U
	23	Polypropylene, granulate {RER}| production | Alloc Def, U
	24	Pump, 40W {RoW}| production | Alloc Def, U
	25	Steel, low-alloyed {RER}| steel production, converter, low-alloyed | Alloc Def, U
	26	Synthetic rubber {RER}| production | Alloc Def, U
	27	Transport, freight, lorry >32 metric ton, EURO5 {RER}| transport, freight, lorry >32 metric ton, EURO5 | Alloc Def, U

SCOPE	
Usage time, years	7 [6]
Workdays per year	220
Employees	25
Consumption per person	1 litre
Consumption, overall	38,500 litres
Share of carbonated water	60% [4]

MODELING				
	Glass bottles, 50 km	**Glass bottles, 300 km**	**One-way plastic bottles**	**Water dispenser**
Quantity				
Volume, litres	0.7	0.7	1.5	38,500
Usage times	40 [2]	40 [2]	1	
Number of vessels	1,375	1,375	25,667	1
Weight of vessel, kg	0.5932 [2]	0.5932 [2]	0.033 [2]	51.1 [7]
Carbon cylinders, produced number				0.233 [6]
Carbon cylinders, weight, kg				1.400 [7]
Carbon cylinders packaging, weight, kg				0.6
Carbon cylinders, packaging, number				39
Filter, number				4 [6]
Filter, weight, kg				0.696 [7]

Packaging				
Crates, 1.4 kg, number	4,584 [2]	4,584 [2]		
EURO palets, 24 kg, number	102 [2]	102 [2]		0.036
GDB palets, 30 kg number	20 [2]	20 [2]		
DHP palets, 9,5 kg, number			107 [2]	
Plastic foil, 16 g, number			4,278 [2]	
Interim pad, 179 g, number			428 [2]	
Strech foil, 179g, number			107 [2]	
Electricity, kWh				4,861.11 [7]
Transport				
Road, distance, km	50	300	300	
Road, tkm	6,145.97	36,876.00	12,228.52	132.75

Sensitivity Analysis 2: Water provision

We assume two altered modelling choices for the case study of water provision.

In the first sensitivity case, we reduce the amount of employees from 25 to 10. This reduces the amount of water from 37,500 liters to 15,000 liters.

In the second sensitivity case, we assume that only 20% of the water used is carbonated water, instead of 60%. This effectively reduces the amount of carbon dioxide used and the amount of carbon cylinders required in the option D (water dispenser).

Modeling parameter	Base case (2A0, 2B0, 2C0, 2D0)	Sensitivity case 1 (2A1, 2B1, 2C1, 2D1)	Sensitivity case 2 (2A2, 2B2, 2C2, 2D2)
Employees, number	25 (all options)	10 (all options)	25 (unchanged)
Consumption, overall	38,500 liters (all options)	15,400 liters (all options)	38,500 (unchanged)
Share of carbonated water	60% (all options)	60% (unchanged)	20% (all options)
Carbon cylinders used, number	39 (all options)	39 (all options)	13 (all options)

Results sensitivity analyses water provision:

Sensitivity case		2A0	2B0	2C0	2D0	2A1	2B1	2C1	2D1	2A2	2B2	2C2	2D2
Modelling choice		Glass bottles (50 km)	Glass bottles (300 km)	Plastic bottles	Water dispenser	10 employees	10 employees	10 employees	10 employees	20/80 carbonated	20/80 carbonated water	20/80 carbonated water	20/80 carbonated water
Waste Generation (Waste)	kg	1321	1321	1172	79	529	529	469	63	1321	1321	1172	63
Global Warming Potential (GWP)	kg CO_2 eq	1781	5207	6599	3336	712	2083	2640	3205	1667	5093	6485	3204
Water Depletion (WD)	m³	2614	4957	18860	3015	1045	1983	7544	2631	2311	4654	18557	2667
Metal Depletion (MD)	kg Fe eq	110	327	349	417	44	131	140	405	99	317	339	405
Human Toxicity (Htox)	kg 1,4-DB eq	470	958	2205	1141	188	383	882	1080	415	903	2150	1079

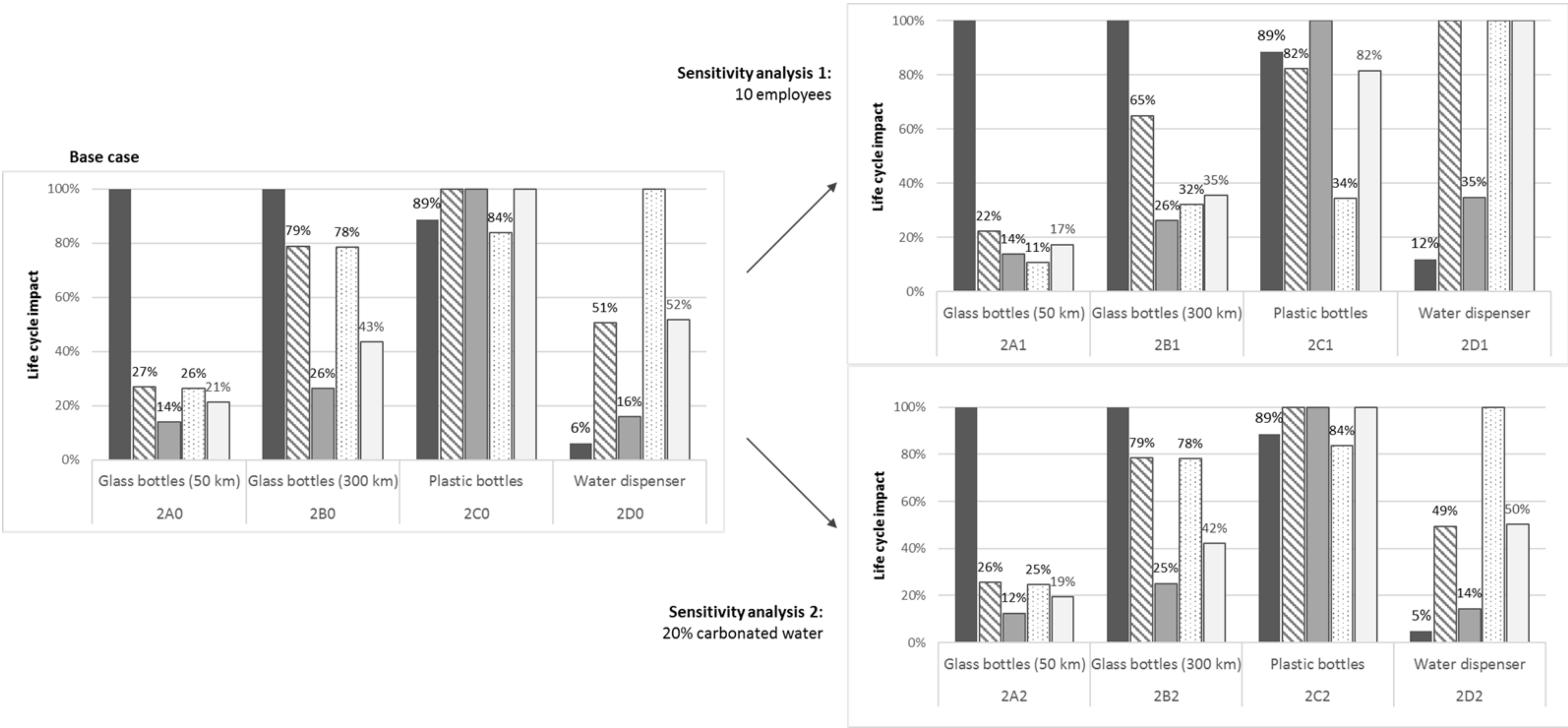

Figure SI 3: Relative life cycle impacts of the options glass bottles (50 km), glass bottles (300 km), plastic bottles and water dispenser in the base case and the two alternative modelling choices: (1) only 10 employees and (2) only 20% consumption share of carbonated water.

Case study 3: Refillables

Public events and private events on public properties can be subject to legislative regulations concerning the type of dishes to use. These regulations have often been quoted as a means to prevent waste, if use of one-way dishes is prohibited (Hutner and Tuma 2016). Even if no prohibition is possible, the use of refillables can be encouraged. As the target group of this study are local authorities in Germany, the modelling is based on data for the soccer stadium of the Bundesliga club FC Augsburg. The average audience count is 29,163 people (Transfermarkt 2018), we assume that on average every person consumes one half liter beverage. We assessed the environmental performance of the containers necessary to serve all 17 home games of each season (Bundesliga 2016) for three seasons. Two kinds of one-way cups were compared to refillable cups. We modelled one-way polyethylene terephthalate (PET) cups with a weight of 11,5 g and polylactic acid (PLA) cups with 10 g (Pladerer et al.). The refillables are made of polypropylene (PP) with a weight of 56 g (Engelking-Mala 2015, pers. comm.).

For the refillable cups, transport to and from the washing station as well as the washing process after every match is included in the scope. The average number of circulations for a cup in German sports stadiums is 107, which was set as the maximal possible value (Pladerer et al.). However, with events like the Bundesliga, the decrease of cups, for example if fans take the cup as a souvenir, has to be considered. An average use of 41 times for non-printed cups and 6 times for printed cups seems realistic (Deutsche Umwelthilfe 2014).

The first part of the following table presents the data sources (Literature, Personal communication, and LCI data) used for modelling. The second part describes the modelling characteristics of each option in detail. The numbers in brackets refer to the data sources in the first part.

Case Study 3

Literature used for modelling	1	(Bundesliga 2016)
	2	(Deutsche Umwelthilfe 2014)
	4	(Garrido and Alvarez del Castillo 2007)
	3	(Kopytziok 2011)
	5	(OVAM 2006)
	6	(Pladerer et al.)
	7	(Transfermarkt 2018)
	8	(Vercalsteren et al. 2010)
Personal communication used for modelling	9	(Engelking-Mala 2015, pers. comm.)
LCI data used for modelling (main processes)	10	Polyethylene terephthalate (PET) granulate, production mix, at plant, bottle grade RER
	11	Transport, freight, lorry >32 metric ton, EURO5 {RER}| transport, freight, lorry >32 metric ton, EURO5 | Alloc Def, U
ecoinvent v3.01	12	Electricity mix, AC, consumption mix, at consumer, < 1kV DE S
	13	Corrugated board box {RER}| production | Alloc Def, U
	14	Packaging film, low density polyethylene {RER}| production | Alloc Def, U
	15	Polylactide, granulate {GLO}| production | Alloc Def, U
	16	Transport, freight train {DE}| processing | Alloc Def, U
	17	Transport, freight, sea, transoceanic tanker {GLO}| processing | Alloc Def, U
	18	Polypropylene, granulate {RER}| production | Alloc Def, U
	19	Tap water, at user {Europe without Switzerland}| tap water production and supply | Alloc Def, U
	20	Sodium hydroxide (50% NaOH), production mix/RER Mass
	21	Printing ink, offset, without solvent, in 47.5% solution state {GLO}| market for | Alloc Def, U
	22	Injection moulding {RER}| processing | Alloc Def, U

SCOPE				
Matches per season	17 [1]			
Usage time, seasons	3			
Visitors per match	29,163 [7]			

MODELING				
	PET	**PLA**	**PP, printed**	**PP**
Quantity				
Usage times	1	1	6 [2]	41 [6, 2]
Weight, g	11.5 [6]	10 [6]	56 [9]	56 [9]
Number of cups, 1 season	495,771	495,771	82,629	12,092
Number of cups, 3 seasons	1,487,313	1,487,313	247,887	36,276
Waste generation, kg	18,055.98	15,890.88	14,121.26	2,066.72
Production				
Printing color, offset, 47,5 % solvent			0.0001596 [5, 3]	
Electricity, kWh	0.00605 [5]	0.00605 [5]	0.00605 [5]	0.00605 [5]
Packaging				
PE-Film, g	0.08 [5]	0.042857143 [5]	0.005 [5]	0.005 [5]
Cardboard box, g	0.56 [5]	0.641428571 [5]	0.961538462 [5]	0.961538462 [5]
Electricity, kWh	0.000045 [5]	0.000045 [5]	0.000045 [5]	0.000045 [5]

Transport to distributor				
Road, distance, km	100 [5]		100 [5]	100 [5]
Road, tkm	0.00115		0.0056	0.0056
Sea, distance, km		6,000 [5]		
Sea, tkm		0.06		
Railway, distance, km		2,000 [5]		
Railway, tkm		0.02		
Transport, road				
Distributor to stadium, km	100 [6]	100 [6]	100 [6]	100 [6]
Stadium to washing, km			100 [6]	100 [6]
Washing				
Electricity, kWh			0.0616 [5]	0.6006 [5]
Water, l			0.704 [5]	6.864 [5]
detergent, g			1.6 [5]	15.6 [5]

Sensitivity Analysis 3: Refillables

We assume two altered modelling choices for the case study of refillables.

In the first sensitivity case, we reduce the usage times of the unprinted PP cups from 41 to 20.

In the second sensitivity case, we increase the usage times of the printed PP cups from 6 to 12.

Modeling parameter	Base case (3A0, 3B0, 3C0, 3D0)	Sensitivity case 1 (3C1)	Sensitivity case 2 (3D2)
Usage times PP, printed (option C)	6 (3C0)	12 (3C1)	6 (unchanged)
Usage times PP, unprinted (option D)	41 (3D0)	41 (unchanged)	20 (3D2)
Washing processes per cup, PP, number	5 (3C0), 40 (3D0)	11 (3C1)	10 (3D2)
Number of cups, 3 seasons	1,487,313(3A0, 3B0) 247,887 (3C0) 36,276 (3D0)	123948 (3C1)	74366 (3D2)

Results sensitivity analyses refillables:

Sensitivity case		3A0	3B0	3C0	3C1	3D0	3D2
Modelling choice		PET	PLA	PP, printed	12 times of useage	PP	20 times of useage
Waste Generation (Waste)	kg	18056	15891	14121	7061	2067	4236
Global Warming Potential (GWP)	kg CO_2 eq	86748	75084	61470	40435	25556	32021
Water Depletion (WD)	m³	104772	230818	83227	42751	14122	26561
Metal Depletion (MD)	kg Fe eq	815	3178	698	419	222	308
Human Toxicity (Htox)	kg 1,4-DB eq	9044	24330	7539	4116	1695	2747

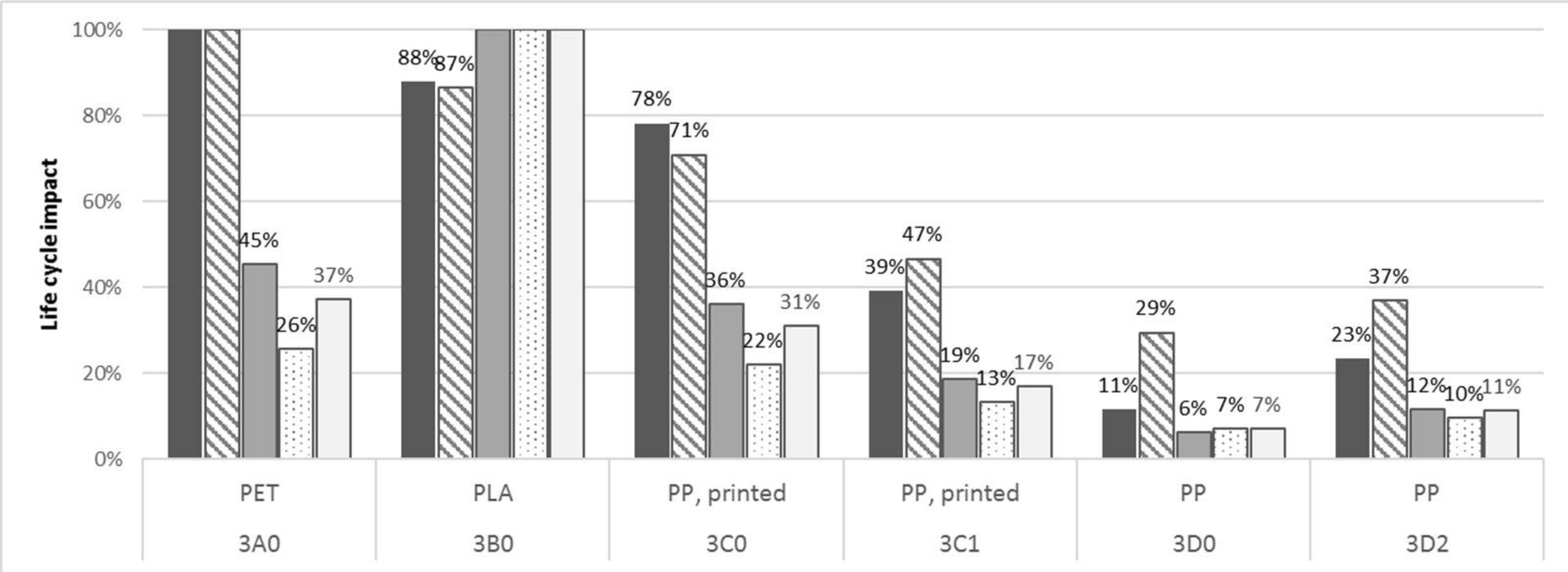

Figure SI 4: Relative life cycle impacts of the options PET cups, PLA cups, printed PP cups and unprinted PP cups and the two alternative modelling choices: (1) 12 usage times for printed PP cups and (2) only 20 usage times for unprinted PP cups.

Case study 4: E-Government

The distribution of online forms instead of actual paper forms is supposed to not only reduce paper waste, but the environmental impacts related to paper production and necessary transport. However, recent studies show ambiguous results in the comparison of paper and online communication (Arushanyan et al. 2014). As indicated by (Achachlouei and Moberg 2015), the number of users can be decisive. Therefore, we model the distribution of forms for the application in a local authority administration.

Online forms are an element of the transition towards e-government. Up to now, the communication between citizens and public administration mostly consists of letters, fax messages, phone calls and personal conversations (Mehlich 2002). In Germany, the average amount of contacts between each citizen and responsible public administration office is 2 to 5 times a year (Initiative D21 and ipima 2014). For the modelling, we assume 4 contacts per year over a period of 5 years for each citizen. 50% of these contacts are assumed to require forms of some sort.

The exchange of these forms takes place in one of 5 ways: A paper form is provided by the public administration. This form is either filled in by the citizen at the public administration office (option A) or sent to the citizen by mail (option B). If filled in at the public administration office, we the transportation mode is modelled according to the modal split of Germany (UBA 2012). For option B, we model the environmental impacts of the mail shipment according to the Deutsche Post AG (2003). If the form is provided electronically, there are three major options we identified within the personal interviews. If a handwritten signature is needed, the form can be printed at home and then brought back to the public administration office personally (option C) or sent by mail (option D). If filling in the form and signing it can take place electronically as well, it can be delivered digitally. For this, we assume a processing time of 5 minutes per page and model the respective energy demand.

The first part of the following table presents the data sources (Literature, Personal communication, and LCI data) used for modelling. The second part describes the modelling characteristics of each option in detail. The numbers in brackets refer to the data sources in the first part.

Case Study 4

Literature used for modelling	1	(Deutsche Post AG 2003)
	2	(Maga et al. 2013)
	3	(Mehlich 2002)
	4	(Mirabella et al. 2013)
	5	(Initiative D21 and ipima 2014)
	6	(Quack and Möller 2005)
	7	(UBA 2012)
Personal communication used for modelling	8	(Geiger 2014, pers. comm.)
	9	(Hüngerl 2013, pers. comm.)
LCI data used for modelling (main processes)	10	Operation, computer, desktop, with liquid crystal display, active mode {Europe without Switzerland}| processing | Alloc Def, U
	11	Printed paper {DE}| operation, printer, laser, black/white, per kg | Alloc Def, U
ecoinvent v3.01	12	Printed paper, offset {CH_vgl}| offset printing, per kg printed paper | Alloc Def, U
	13	Transport, freight, light commercial vehicle {Europe without Switzerland}| processing | Alloc Def, U
	14	Transport, freight, lorry 3.5-7.5 metric ton, EURO4 {RER}| transport, freight, lorry 3.5-7.5 metric ton, EURO4 | Alloc Def, U
	15	Transport, passenger car {RER}| processing | Alloc Def, U
	16	Transport, passenger, bicycle| processing | Alloc Def, U
	17	Transport, regular bus {RoW}| processing | Alloc Def, U
	18	Transport, tram {DE}| processing | Alloc Def, U

SCOPE					
Time, years	5				
Citizen contact with public administration (pa)	4				
Contacts with forms	50%				
Average length of form	5 pages				
Weight of page, g	5				
Citizens	70,000				
Average distance to pa, km	2				

MODELING					
	Paper forms, individual transport to public office	**Paper forms, delivery by mail**	**Printable online forms, delivery by individual transport**	**Printable online forms, delivery by mail**	**Online forms, digital delivery**
Quantity					
Paper, weight, kg	17,500	17,500	17,500	17,500	
Weight, g					11,3 [2, 4]
Transport					
Distance	2,800,000	2,157.5	1,400,000	1,575	
Means	Modal Split Germany [6]	Postal service [1, 5]	Modal Split Germany [6]	Postal service [1, 5]	
	Passenger car 75.8%		Passenger car 75.8%		
	Local services 18.5%		Local services 18.5%		
	Bicycle 2.7%		Bicycle 2.7%		
	On foot 2.9%		On foot 2.9%		
Sorting, kg CO_2		8,765 [1]		8,765 [1]	
Digital progressing					
Progressing time per form					5 minutes

Sensitivity Analysis 4: E-Government

We assume two altered modelling choices for the case study of e-government.

In the first sensitivity case, we assume that all transportation to the administration is handled by local public transportation, instead of the German modal split.

In the second sensitivity case, we increase the forms have double the average length, making it 10 pages instead of 5 pages.

Modeling parameter	Base case (4A0, 4B0, 4C0, 4D0, 4E0)	Sensitivity case 1 (4A1, 4C1)	Sensitivity case 2 (4A2, 4B2, 4C2, 4D2, 4E2)
Transportation mix	German modal mix (75,8% passenger car, 18.5% local services, 2.7% bicycle, 2.9% foot)	Only public transportation (50% tram, 50% bus)	German modal mix (unchanged)
Average form length, pages	5 (all options)	5 (unchanged)	10 (all options)

Results sensitivity analyses E-government:

Sensitivity case		4A0	4B0	4C0	4D0	4E0	4A1	4B1	4C1	4D1	4E1	4A2	4B2	4C2	4D2	4E2
Modelling choice		Paper A	Paper B	Printable C	Printable D	Online, digital	only public transport	Base case	only public transport	Base case	Base case	double form length	double form length	double form length	double form length	double form length
Waste Generation (Waste)	kg	17500	17500	17500	17500	11	17500	17500	17500	17500	11	35000	35000	35000	35000	23
Global Warming Potential (GWP)	kg CO_2 eq	793987	61904	413647	52924	35950	322223	61904	177765	52924	35950	844405	115043	455508	97082	70063
Water Depletion (WD)	m³	981083	206717	597187	211083	218176	624771	206717	419031	211083	218176	1184915	413433	805749	422166	435772
Metal Depletion (MD)	kg Fe eq	83882	2460	45429	4820	6993	17659	2460	12318	4820	6993	86069	4920	50011	9640	13854
Human Toxicity (Htox)	kg 1,4-DB eq	255673	22413	147089	30780	40385	114273	22413	76390	30780	40385	277251	44826	177133	61560	80434

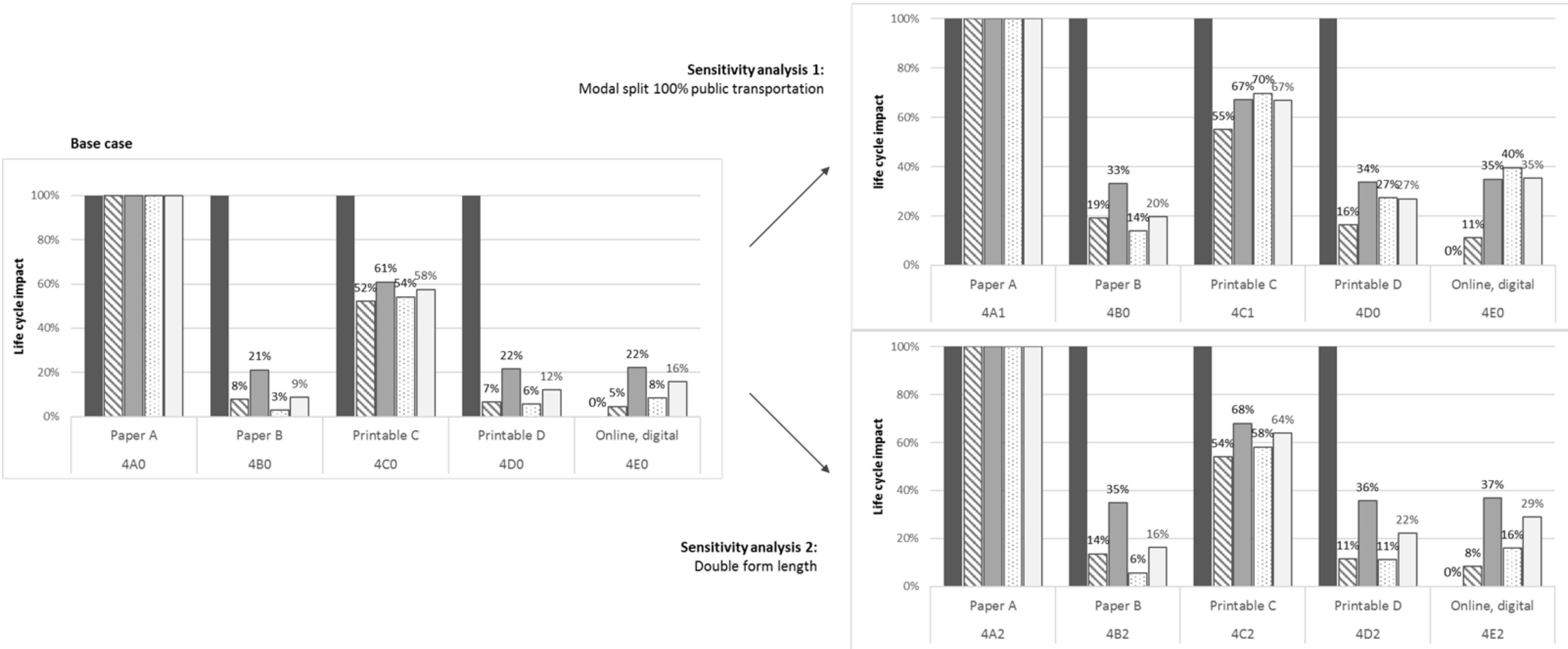

Figure SI 5: Relative life cycle impacts of the options paper forms filled in at public administration offices (A), paper forms delivered by mail (B), printable online forms delivered by individual transport (C), printable online forms delivered by mail (D) and online forms with digital delivery as well as the two alternative modelling choices: (1) transportation by local service public transportation and (2) doubled form length.

Case study 5: Lighting

Replacing common lights for communal fairs with a long-life and energy-efficient substitute is thought to reduce the waste generation and environmental impact of this particular material stream enormously. In Augsburg this conviction lead to a replacement of the lighting for the Christmas fair with light emitting diodes (LED).

The scope for this LCA is the necessary light stream for lighting a communal fair. We assess the environmental impacts of incandescent light bulbs (ILB), compact fluorescent lamps (CFL) and LED for 10 years. The case study this LCA is based on is Augsburg (Hüngerl 2013, pers. comm.). The fair is open for 31 days with 8 hours of lighting every day. Roughly 3,500 lamps are used for illuminating the main market place and pedestrian zone. We assume 415 lumen per lamp. For modelling reasons, we base the functional unit on the overall light stream for this setting, which amounts to 3,602,200,000 lumen hours. The number of lamps necessary to provide this light stream varies between the technologies, as the lamps have different life spans and, thus, a different amount of lumen hours per lamp.

The first part of the following table presents the data sources (Literature, Personal communication, and LCI data) used for modelling. The second part describes the modelling characteristics of each option in detail. The numbers in brackets refer to the data sources in the first part.

Case Study 5		
Literature used for modelling	1	(DEL-KO)
	2	(LEDVANCE 2018a)
	3	(LEDVANCE 2018b)
	4	(OSRAM 2016)
	5	(OSRAM 2007)
	6	(OSRAM 2008)
	7	(OSRAM 2011)
Personal communication used for modelling	8	(Hüngerl 2013, pers. comm.)
LCI data used for modelling (main processes)	9	Aluminium, primary, ingot {GLO}| production | Alloc Def, U
	10	Argon, liquid {RER}| production | Alloc Def, U
ecoinvent v3.01	11	Brass {CH}| production | Alloc Def, U
	12	Calcium carbonate > 63 microns, production, at plant EU-27 S
	13	Copper {RER}| production, primary | Alloc Def, U
	14	Corrugated board box {RER}| production | Alloc Def, U
	15	Flat glass, coated {RER}| production | Alloc Def, U
	16	Iron-nickel-chromium alloy {RER}| production | Alloc Def, U
	17	Light emitting diode {GLO}| production | Alloc Def, U
	18	Mercury {GLO}| production | Alloc Def, U
	19	Molybdenum {RER}| production | Alloc Def, U
	20	Nickel sulfate {GLO}| production | Alloc Def, U
	21	Phosphorous chloride {RER}| production | Alloc Def, U
	22	Polycarbonate {RER}| production | Alloc Def, U
	23	Printed wiring board, surface mounted, unspecified, Pb free {GLO}| market for | Alloc Def, U
	24	Screw_Steel, low-alloyed {RER}| steel production, electric, low-alloyed | Alloc Def, U
	25	Tin {RER}| production | Alloc Def, U

SCOPE	
Years	10
Days per year	31
Lighting hours	8 (17:00 – 23:00)
Number of lamps	3,500 [1]
Lightstream per lamp	415 lumen
Total lightstream	3,602,200,000 lumen hours

MODELING			
	Incadescent light bulb	**Compact fluorescent lamp (CFL)**	**Light emitting diode (LED)**
Product name (OSRAM)	Classic A CL 40 [2]	Dulux Superstar Stick 8 W/825 B22D	Parathom Classic A 40 5 W/827 E27 CS [3]
Watt	40 [2]	8 [4]	5 [3]
Lumen	415 [2]	430 [4]	470 [3]
Life span	1,000 [2]	10,000 [4]	15,000 [3]
Weight, g	24 [2]	44 [4]	180 [3]
Quantity			
Lumen hours per lamp	415,000	4,300,000	7,050,000
Number of lamps	8,680	838	511
Weight, kg	208.32	36.87	91.98
Production			
LCI according to	OSRAM Material Declaration Sheet [5]	OSRAM Material Declaration Sheet [6]	OSRAM Material Declaration Sheet [7]

Packaging			
Cardboard box, g	84	73.31 [4]	74.2 [3]
Electricity, kWh	861,056	16,625.92	6,336.4

Sensitivity Analysis 5: Lighting

We assume only one altered modelling choice for the case study of lighting.

In this sensitivity case, we assume that despite the potential longer technical lifetime of CFLs and LEDs, all light bulbs are not used anymore after the 10 year period of the functional unit. This could be the case e.g. due to a changed lighting concept for the Christmas fair, or due to technological improvements which justify the installation of even more energy efficient lighting systems.

Modeling parameter	Base case (5A0, 5B0, 5C0)	Sensitivity case 1 (5A1, 5B1, 5C1)
ILBs total over 10 years, number	8,680 (5A0)	8,680 (5A1)
CFLs total over 10 years, number	838 (5B0)	3,378 (5B1)
LEDs total over 10 years, number	511 (5C0)	30,90 (5C1)

Results sensitivity analysis lighting:

Sensitivity case		5A0	5B0	5C0	5A1	5B1	5C1
Modelling choice		ILB	CFL	LED	Basecase	3378 lamps (430 Lumen)	3090 lamps (470 Lumen)
Waste Generation (Waste)	kg	937	98	135	937	149	556
Global Warming Potential (GWP)	kg CO_2 eq	611800	15860	10072	611800	23733	33691
Water Depletion (WD)	m³	5659	10005	21401	5659	40236	129350
Metal Depletion (MD)	kg Fe eq	2210	2820	4125	2210	11356	24935
Human Toxicity (Htox)	kg 1,4-DB eq	12515	15480	22144	12515	61620	133375

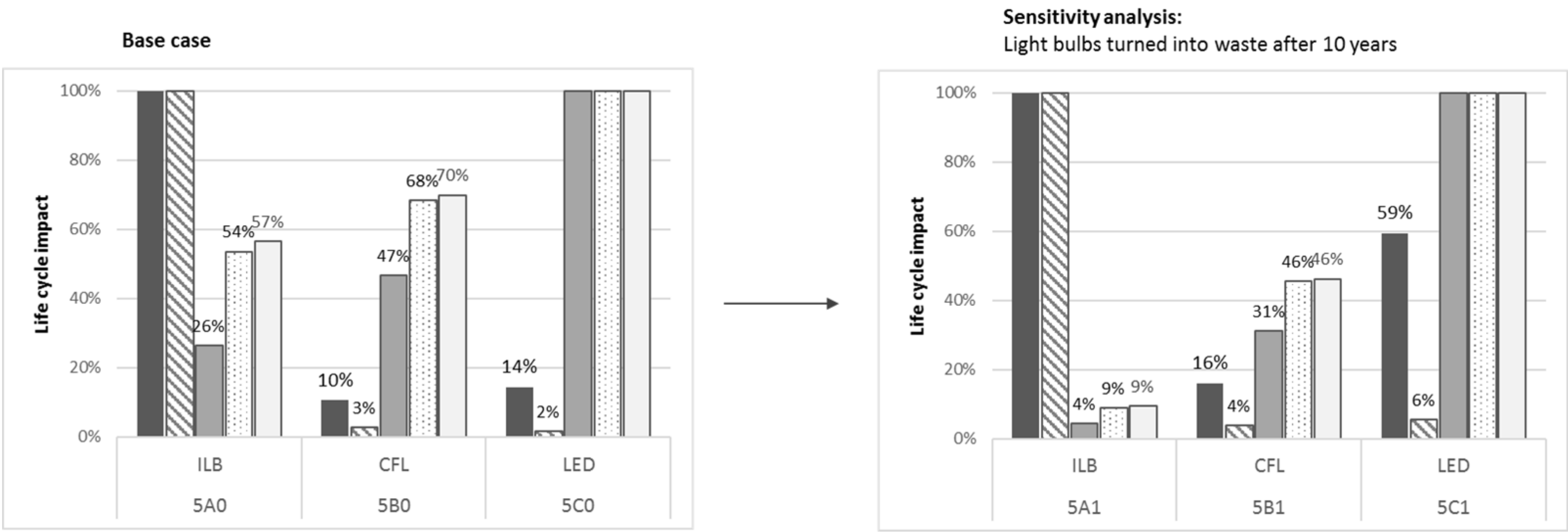

Figure SI 6: Relative life cycle impacts of the options incandescent light bulbs (ILB), compact fluorescent lambs (CFL) and light-emitting diodes (LED) as well as for the alternative modelling scenario with waste generation after 10 years regardless of technical lifetime.

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