Life cycle assessment of digitalization in buildings: The case of a building monitoring system

Shoaib Azizi
KTH Digital Futures, KTH Climate Action Center, Department of Sustainable Development, Environmental Science and Engineering
KTH Royal Institute of Technology
Stockholm, Sweden
sazizi@kth.se

Anna Furberg
KTH Digital Futures, KTH Climate Action Center, Department of Sustainable Development, Environmental Science and Engineering
KTH Royal Institute of Technology
Stockholm, Sweden
annafur@kth.se

Marco Molinari
Department of Energy Technology
KTH Royal Institute of Technology
Stockholm, Sweden
marcomo@kth.se

Göran Finnveden
KTH Digital Futures, KTH Climate Action Center, Department of Sustainable Development, Environmental Science and Engineering
KTH Royal Institute of Technology
Stockholm, Sweden
goran.finnveden@abe.kth.se

***Abstract*— Digital solutions based on information and communication technologies (ICT) provide many opportunities in buildings to achieve resource and energy efficiency. In general, these solutions enable either monitoring or advanced control of buildings. The ICT solutions' overall impacts on the environment are often presumed positive without a holistic approach based on life cycle thinking. The research on energy and indoor monitoring systems usually focuses on system performance and potential benefits rather than the entire system and it thus misses the life cycle impacts of the system itself. To address this limitation, the aims of this study are to assess life cycle environmental and resource impacts of a building monitoring system (BMS) and to identify hotspots in this system. The case study of KTH Living Lab represents an extensive BMS. It was applied and assessed using Life Cycle Assessment (LCA) methodology. The results show that wires, sensors and data acquisition equipment constitute hotspots for all the environmental and resource impacts assessed in this study. Thus, the impacts of these devices are important to consider by, e.g. building managers.**

Keywords—LCA, ICT solutions, environmental assessment, sustainability

I. Introduction

The advancements in Information and Communication Technology (ICT) have industrialized data collection, processing and storage on a large scale. Many applications of ICT and digitalization improve the conventional operations and processes which can contribute to environmental sustainability [1]. The environmental effects of digital solutions can be described as first, second and higher order effects [2], [3]. The first order effects, which also are referred to as direct effects, are the negative impacts from raw material extraction, production, transportation, use, and disposal of ICT. The second order effects are usually positive substitution and optimization effects which correspond to the purpose of the system. The higher order effects could be negative such as direct and indirect rebound and induction effects or positive such as promoting sustainable lifestyles [4]. The environmental impacts of ICT can be tracked to every life cycle phase of ICT although the majority of environmental impacts of ICT commonly are related to the production of electronics and especially when they are battery-powered [5]. The current carbon footprint of ICT is estimated to be about 1000-2000 MtCO_2-eq which stands for 2%-4% of the world's greenhouse gas (GHG) emissions [5].

Buildings are resource- and energy-intensive and reducing their impacts on the environment is significant to mitigate the overall anthropogenic environmental impacts. Decarbonization of buildings is important for climate change mitigation as the building sector is responsible for 40% of the world's final energy use [6], and a quarter of greenhouse gas emissions [7]. A large share of GHG emissions of buildings is related to their operation phase [8], [9]. However, in the context of Sweden where the energy sector has been mostly decarbonized, the majority of the emissions occur during the production phase of buildings [10], and the installations are a significant part [11], [12].

The applications of ICT in buildings are based on the ability to monitor the buildings' components and processes and optimize them for improved functionality which are referred to as positive enabling effects [1]. Smart building is defined as when the sensors, appliances, and other devices are linked by communication networks to enable monitoring and control functions [13]. This definition is entangled with digitalization in buildings. The concept of Internet of Things (IoT) shares a similar approach as it pushes the everyday devices to be connected to the cloud, which requires connectivity features and computing capabilities. IoT can be considered as an enabler for the smart building concept. There are two different smart home ambitions, one focuses on energy efficiency while the other one is associated with luxury and modern life [14]. Regardless of the purpose, smart building requires extensive deployment of electronic and mechanical devices for sensing, data acquisition, network and data transmission, data storage, and actuating.

The applications of ICT for the operation of buildings are also developing and the related components such as sensors, their connectivity, and the middleware platforms are becoming easy-to-use and cost-efficient [15]. The applications of ICT solutions in buildings are related to either technical building management or building automation and

XXX-X-XXXX-XXXX-X/XX/$XX.00 ©20XX IEEE

control [16]. Monitoring of indoor environment parameters, human-building interactions (occupancy), and energy use enable technical building management by applications such as space use management [17], fault detection [18], and promoting more sustainable use of buildings. Building automation solutions consists of ICT solutions for control of various building components, which can reduce the negative effects of occupants' behavior and inefficient building control on energy use [19].

Digitalization is often perceived as a process leading to reduced environmental impacts. Such inferences are undertaken without adopting a holistic approach on both positive and negative effects of using ICT solutions. A holistic approach is specifically important when ICT solutions are used with the intention to have a positive effect on environmental sustainability for example by reducing greenhouse gas (GHG) emissions. This also applies to the building sector where the environmental benefits achieved by ICT solutions in buildings are often taken for granted without considering the lifecycle impact of the enabling technologies. The presumption of ICT solutions being environmentally sustainable may not be true considering some ICT components are material-intensive and require considerable power to operate. The direct environmental impacts of ICT devices during their life cycle is often overlooked [20]. This limited view on the effects of digital solutions is likely to lead to overestimation of their environmental benefits. The environmental concerns related to smart technologies need to be considered when evaluating their benefits [21].

Life cycle assessment (LCA) methodology can be used for assessing the environmental impacts of a product, service or system, including ICT solutions [22]. The production, use and waste management of ICT components are all associated with environmental impacts that can be assessed by LCA. LCA allows understanding the compromise between the environmental burdens and benefits and also for analyzing which parts and components are most important from an environmental perspective and how impacts can be reduced.

Previous research shows that the sustainability of ICT solutions in buildings such IoT sensors depends on their embodied carbon during their production, the ecotoxicity of their e-waste, and the internet traffic of the generated data [23], [24]. Pirson and Bol [20] presented a parametric framework based on hardware profiles for LCA of IoT edge devices which might be used in buildings. There are a few studies on LCA of ICT in buildings [25], [26], however, the quantitative analyses are still scarce. The literature emphasizes the importance of considering the environmental effects of the smart solutions in buildings along their lifecycle [27]. There is currently a need for more LCA case studies that assess the overall impacts resulted from ICT solutions which are often promoted to as a tool to de-carbonize buildings. The need for conducting such studies can be underlined, as the use of ICT solutions becomes a market trend. Such solutions have even come to the European Union's attention which encourages the adoption of intelligent metering and active control systems in buildings with the aim of energy efficiency [28].

This study analyzes environmental and resource impacts of increased digitalization and use of ICT in buildings. To address knowledge gaps in this area, the aims of this study are to assess life cycle environmental and resource impacts of a BMS and to identify related hotspots. This is done to address the following research question: *What are the hotspots in terms of environmental and resource impacts of the BMS system?* LCA methodology is applied on a case study of a sensor-based BMS, representing a high level of digitalization and sophistication in buildings. The BMS as well as the infrastructure supporting this system, including the network and data storage infrastructure, are included in the analysis.

II. METHODOLOGY

LCA was applied and five impact categories were included. Building monitoring systems consist of many components, which could differ from case to case based on the system provider and the functionality. The compositions of the analyzed systems are based on the observation and assessment of the real cases.

The analysis in this paper is based on cradle-to-gate LCA methodology considering sensing, edge and cloud devices similar to the approach in previous study by [29]. The analysis is based on assumptions and simplifications, which are explained in the next section. The environmental assessment of smart technologies in buildings is challenging due to the high complexity of electronic devices and the lack of data [20] which requires simplification and assumptions.

A. Case Description

The KTH live-in lab BMS was selected as the case for this study and represents a building with comprehensive BMS. The lab is a real-life platform to investigate the technologies, their associated risks user behavior, operation aspects and new skills [18]. The lab is 300 m^2 and consists of four student rooms, two shared bathrooms, a shared kitchen and living rooms. In addition, there are an office and a technical room for researchers. One of the main considerations for KTH live-in lab has been smart building features and thus it is equipped with an extended sensor network. The high level of building monitoring with extensive data collection is enabled by 200 installed sensors. The sensors are deployed to monitor indoor environment parameters such as temperature, humidity and CO_2, noise level, and illuminance.

Fig. 1. Illustration of the flow of data in the building monitoring system case.

Fig. 2. The components related to data acquisition and network in the KTH live-in lab.

Moreover, the energy for space heating is metered. The monitored parameters allow a better understanding of building dynamics with the main function of monitoring indoor environment and energy use. Fig. 1 depicts the flow of data and illustrates different parts of the system, of which some are composed of several components. The electronic components related to data acquisition and some of the components related to data transmission can be seen in Fig. 2. Table 1 presents the components that are included in the analysis.

B. *Life Cycle Assessment*

The LCA methodology in this study is based on the ISO140040 Standards series. The goal of this study is to analyze the environmental impacts of implementing a digital solution for building monitoring in residential buildings. The LCA model is conducted to represent cradle-to-cradle approach. The scope of the study is in Sweden except for the production, why a Swedish energy mix was used for the operation phase. The sourcing of most of the components was assumed to take place worldwide. This study took into account production, use and end of life (EoL) phases. The lifetime of sensors and electronic components are considered to be 10 years as recommended by most of the components' manufacturers. For data transmission, the electronic components installed in the cases are analyzed based on all their lifecycle phases but for the main part of the process, only the use phase is taken into account. For data storage in cloud servers, only the operational phase was considered as the embodied emissions of this part of the system are relatively negligible [30]. A flowchart for the system is provided in Fig. 3.

TABLE I. LIST OF THE COMPONENTS INCLUDED IN THE ANALYSIS. THE COMPONENT NAMES WITHIN PARENTHESIS ARE THE FULL NAMES APPLIED FOR THESE COMPONENTS BY THE COMPONENT MANUFACTURERS. (RP STANDS FOR *REPRESENTATIVE PRODUCT)*

Components	**Description**	**KTH live-in lab**
Sensors	Occupancy sensors are used as representative for various types of sensors. The product is assumed to be in active mode 50% of the time with a power use of 0.36W and in stand-by mode 50% of the time with a power use of 0.2W. All 3 lifecycle phases are considered for the analysis.	200 pieces
Input/output module (”SmartXcontroller UI-16”)	Input/output module, the production is based on representative product RP1	5 pieces
Analogue output (“Controller AO_V_8_H”)	Analogue output, the production is modelled based on representative product RP1	2 pieces
Power supply (“SmartXcontroller PS-24V”)	All 3 lifecycle phases are considered for the analysis.	1 piece
Connector (“Terminal Base TB-IO-W1”)	All 3 lifecycle phases are considered for the analysis.	1 piece
Digital output (“Smart Controller DO_FA_12_H”)	Digital output, the production is based on representative product RP1. All 3 lifecycle phases are considered for the analysis.	1 piece
Controller server (“Smartcontroller X AS-P”)	All 3 lifecycle phases are considered for the analysis.	1 piece
M-Bus master 1 (“Elvaco CMeX50”)	M-Bus receiver, constantly exchanging data with the M-Bus meters, the production is modelled based on representative product RP2. All 3 lifecycle phases are considered for the analysis.	1 piece
M-Bus meter 2 (“Elvaco CMe3100”)	M-Bus Metering Gateway for fixed network, the production is modelled based on representative product RP2. All 3 lifecycle phases are considered for the analysis.	1 piece
Wires	1.5 mm wire diameter. The production and disposal are included in LCA.	3200 meter
Box	The boxes are made of galvanized steel. The production and disposal phases are included in LCA	150 kg
Data network	Data network consists of a fixed energy use intensity for a certain data volume which is included in LCA.	2 GB per week
Data storage and processing	Data storage and processing is assumed to be performed in AWS infrastructure in Ireland. A fixed energy use intensity during use phase is included in LCA	2 GB per week

Regarding the inventory analysis, Appendix A presents the technical information and inventory of the components taken from the manufacturers. The material composition for most of the electronic components are collected from the manufacturers and proxy devices are used for some others. The SimaPro version 9.5.0.1 software and the Ecoinvent 3.5 database were used for inventory analysis and impact assessment.

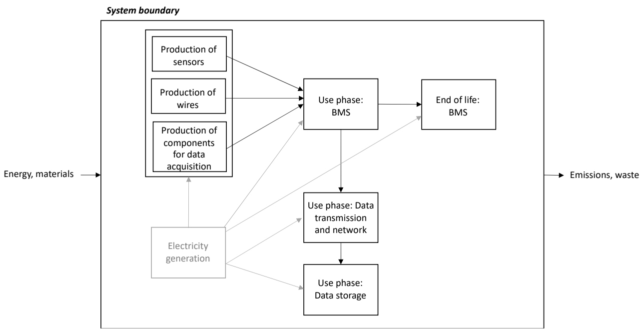

Fig. 3. Flowchart for the KTH live-in lab case.

Previous studies on ICT solutions in buildings considered it useful to define the functional unit in connection to the household and the living condition [26]. Accordingly, the functional unit is energy and indoor environmental monitoring for 4 single occupant apartments during 10 years of operation. The product system is based on the usage motive to provide better comfort, fault detection and operational optimization which can directly or indirectly lead to improvements in energy management and energy savings. All the components that may not be ICT-related are outside the system boundary including the parts related to control and actuation. Sensitivity analysis is conducted based on the scenarios with changes in system's service life and electricity grid mix to provide an overview of their effects on the global warming potential.

The weight-based representative products RP1and RP2 are selected based on the production phase of two electronic components with similarities to the components used in the case study systems. RP1 and RP2 were designated to some of the products with missing information on their production and material composition. This simplification is necessary as collecting all the inventory data for ICT devices is often challenging [31].

The manufacturers for some of the electronic components have provided average electricity use. For the other components it was assumed that they run on nominal electricity use due to lack of information on their standby times. As the system is implemented in a building in Sweden, the energy use for the operation of devices and components is assumed to be from Swedish electricity grid mix. The connections of sensors and smart devices to the network were wired while such systems could be designed with wireless connection. The wired connections are considered more reliable and are more commonly used in commercial applications in which the data is used for control and automation.

The energy use for data transmission and storage is related to electricity use of network and cloud storage. The calculation of the energy demand for data transmission from data acquisition part to cloud during the use phase is based on a study that shows downloading one Gigabyte (GB) data in Europe from a cloud-based data center located in the United States requires 0.022 kWh of electricity [32]. Modifying this value while considering the emission factor for the average European grid mix and US grid mix shows that 17.8% (0.004 kWh/GB) of the energy intensity corresponds to data transmission. This value is in line with the results from another study, which estimates the electricity intensity of the transmission network (core and access networks) in 2015 to be 0.06 kWh/GB [33]. Since the year 2000, in developed countries, the average energy intensity has decreased approximately by half every two years, which leads to the estimation of 0.004 kWh/GB energy intensity in average for the year 2023. This estimation deviates only 3% from the calculated ratio.

Regarding data storage, the study considers the sensor data is stored for 10 years as the historical data have applications for system optimization, fault detection and diagnosis. The duration of data storage is assumed independent from the lifetime of the rest of the system. For the energy intensity of data storage, a data centre in Ireland operated by AWS with power use effectiveness (PUE) of 1.135 is considered and evaluated. The storage of data on a disk in a data center in Ireland is estimated to be 1.988 Wh/GB per month [34]. The energy use from other parts of the data centre is estimated based on the information presented in a study on environmental impacts of data centres [35]. It can be assumed that the energy demand in a data center is related to servers (49.7%), storage (14.2%), networking equipment (7.1%), cooling (3.6%), switchgear and distribution losses (1.4%), and UPS losses (6.0%). The data centres are likely to exchange data which is assumed to be done among different geographical data centers in Ireland and electricity intensity for data exchange to be 0.001 kWh/GB with AWS's PUE [34].

The box/cabinet that accommodates the electronics is made of steel and does not require air-conditioning. The disposal phase related to this component is related to the recycling of metal. The disposal phases for the electronics and the wires are considered by specific processes corresponding processes presented in Table III in Appendix A.

Life Cycle Impact Assessment (LCIA) was conducted for the impact categories of Climate Change (GWP), Human Carcinogenic Toxicity (HCT), Human non-Carcinogenic toxicity (HNCT), and mineral resource scarcity (MRS) based on Recipe 2016 v1.1 (H) method. In addition to this, the primary energy demand (PED) based on Cumulative Energy Demand V1.11 method was also assessed. GWP and PED are related to the primary function of such digital solutions, which is energy use optimization. MRS indicates the impact from the minerals in the electronic components. HCT and HNCT measure the toxicity to human during the life cycle of the system. The choice of impact categories is in line with previous studies of digital solutions in buildings [26].

III. RESULTS AND DISCUSSION

A. *Life Cycle Impact Assessment Results*

The LCIA results for the five included impact categories for the KTH live-in lab BMS are presented in Fig. 4. The majority of impacts stem from the life cycle of sensors, wires and electronic components of the data acquisition part. Sensors are largest contributors to GWP and PED at 44% and 60%, respectively. Thus, sensors have higher responsibility for impacts related to the main function of BMS, which is energy efficiency. With 20%-40% of impacts, sensors are not the largest contributor compared to the other parts of the system for HCT, HNCT and MRS. Wires dominate the impacts for HCT, HNCT and MRS at 51%, 76%, and 61%, respectively. Wires' share of impact is relatively large for GWP at 24%. Data acquisition components in Case 1 are more significant for GWP and PED with 28% and 22% shares of impacts, respectively. Their shares are significantly lower for HCT, HNCT and MRS, which are less than 11%. The impacts of network and data transmission part accounts for 10% of PED impact and less than 3% of other impact categories. Data acquisition components, data transmission and network, and data storage processes have relatively smaller share in all the impact categories. The share of data storage is insignificant.

Further analysis was conducted for the different life cycle phases of the case, including manufacturing, use, and disposal and the results are shown in Fig. 5. Climate impacts of the building monitoring systems during their production, use and disposal are 1684 kg CO_2 eq. The production phase dominates the GWP impacts of the BMS with 76% of the impacts. Production of sensors is responsible for 30% of the emissions related to GWP impacts. The production of wires in leads to 20% of the GWP impacts. The production of electronic parts for data acquisition is significant for the GWP impacts at 24% and 29% of GWP impacts.

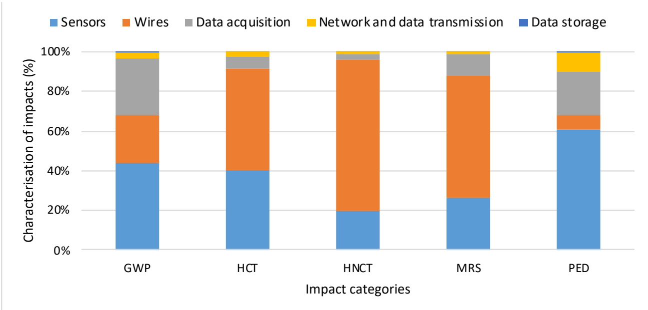

Fig. 4. Environmental and resource impacts for the KTH live-in lab case.

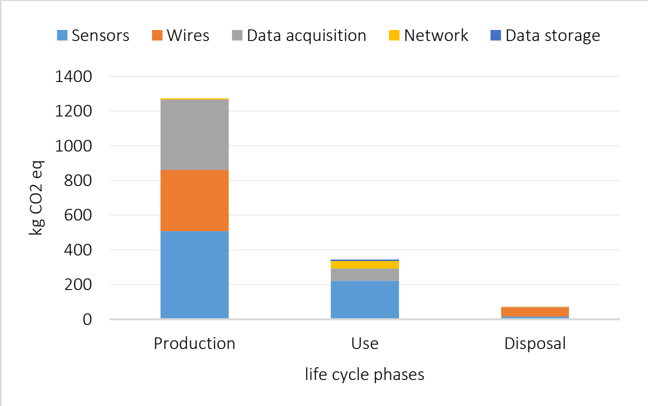

Fig. 5. Global warming potential for different life cycle phases for the KTH live-in lab case.

The use phase consists of mainly the electricity use for operating various parts of system, which causes 222 kg CO_2 eq. A significant part of the emissions from the use phase originates from the operation of sensors and electronic components. The disposal phase causes about 7 kg CO_2 eq, which is almost negligible compared to the total emissions.

As the information for second order effects of the building monitoring system is not available, the amount of GHG emissions by direct effects are used to estimate the minimum energy efficiency to offset the footprint of the BMS and the results are presented in Table 2. Calculating a break-even point is common practice in LCA studies [36]. Accordingly, the break-even point for the BMS to compensate for its direct effects on GWP impact by energy efficiency is when it can lead to 24% energy saving. This result is based on the electricity used from Swedish grid mix. Emission factor for electricity in Sweden is considered to be 0.045 kg CO2/kWh while electricity use of building is 51 kWh/m^2/year.

TABLE 2. ESTIMATION OF THE MINIMUM REQUIRED ENERGY SAVING IN SWEDEN

KTH live-in lab and the effects of BMS	Estimations
Total emissions of building monitoring system (kg CO_2 eq)	1684
Total energy use of building (kWh)	153000
Total emissions by energy use of building (kg CO_2 eq)	6931
Minimum required energy saving	24%

B. *Discussion*

ICT solutions can have various compositions, configurations and designs which could be related to usage motive [26], or technical limitations. There is significant heterogeneity to ICT devices footprints as the difference could reach 150x [20], thus, the generalizability of the results could be limited. A study on the environmental impacts of ICT solutions for building energy management shows their lifecycle GWP impacts are significantly smaller than their effects from the abatement of GHG emissions [25]. The results of our study indicates the net effects of such solutions are not always positive or largely positive depending on the factors such as the type and configurations of ICT solutions, the building's baseline energy performance, the geographical location and emissions factors of the energy systems, etc.

The analysis in this study and the results are case-dependent. The results could differ for other cases with different system design and different system providers and manufacturers. One example is the use of wireless sensors instead of wired sensors which eliminates the use of wires and their environmental impacts. However, the use of additional components for sensors' network connection and the use of battery needs to be considered in LCA which might reverse the result.

BMS can be leveraged for several applications, such as energy efficiency but also for improving comfort and building maintenance. The two latter functions are challenging to quantify and include in an LCA. Even when BMS is installed for energy efficiency purposes which can be quantified by energy meters, or energy simulations, a better understanding of their environmental effects requires considering other side effects related to, e.g. behavioral changes such as rebound effects resulting from efficiency gains, and induction effects leading to increased device purchases [1].

IV. CONCLUSIONS AND FUTURE RESEARCH

The adoption of ICT solutions in buildings has accelerated as the related technologies have become more economic, reliable and user-friendly. There is extensive research on developing ICT applications in buildings, however, studies on their environmental burden with a life cycle perspective are scarce. The findings are useful for manufacturers, building managers, researchers, and policymakers to develop a holistic view on the effects of the ICT solutions in buildings. The results indicate the importance of lifecycle thinking on assessing BMS performance due to the significant impacts of the system during various lifecycle phases. The results highlight the negative effect of over-use of sensors and data collection. Wires, sensors and equipment for data acquisition are contributing the most to the assessed environmental impacts and can be considered as hotspots. It is important to avoid redundant data and ensure the data collected is used. The number of sensors installed has to be optimal to the intended function. It is important to realize that digitalization comes with a cost and that this investment should be used efficiently. The results show that it is necessary to consider the environmental constraints when designing and implementing ICT solutions in buildings. The lack of life cycle thinking in adoption of ICT solutions may lead to failure in achieving the environmental aspiration intended for the system and even the opposite results than what expected of the ICT solutions.

For future research, more cases and additional studies are needed. Future research should investigate how the environmental and resource impacts of BMS relates to potential energy savings, typically reported to be about 20% for smart control of energy systems in buildings [37], and what level of energy savings that are needed to have net benefits from the system. Furthermore, second order effects of BMS, which could be assessed by a comparison of a reference building without an ICT-enabled automation system and a building with BMS, should be assessed. Another method is to establish a theoretical baseline with the assumptions for a building which may not exist. Such a building can be modeled in an energy performance simulation software such as IDA ICE. Other areas for future research are improving the simplified model used for data transmission in this study, the role of various system designs and configurations, adding additional parts such as software to LCA model, and the effect of recycling material in production of electronic components.

Acknowledgment

The authors gratefully acknowledge Ericsson AB, KTH Digital Futures and KTH Climate Action Center for their funding and advices on research direction. The authors are solely responsible for the content of this paper and all decisions related to it.

References

[1] L. M. Hilty and B. Aebischer, "ICT for Sustainability: An Emerging Research Field," vol. 310, Switzerland: Springer International Publishing AG, 2015, pp. 3–36. doi: 10.1007/978-3-319-09228-7_1.

[2] L. M. Hilty and B. Aebischer, *ICT Innovations for Sustainability*, 1st ed. 20. Cham: Springer International Publishing, 2015. doi: 10.1007/978-3-319-09228-7.

[3] J. Pohl, L. M. Hilty, and M. Finkbeiner, "How LCA contributes to the environmental assessment of higher order effects of ICT application: A review of different approaches," *J. Clean. Prod.*, vol. 219, pp. 698–712, 2019, doi: https://doi.org/10.1016/j.jclepro.2019.02.018.

[4] M. Börjesson Rivera, C. Håkansson, Å. Svenfelt, and G. Finnveden, "Including second order effects in environmental assessments of ICT," *Environ. Model. Softw.*, vol. 56, pp. 105–115, 2014, doi: https://doi.org/10.1016/j.envsoft.2014.02.005.

[5] C. Freitag, M. Berners-Lee, K. Widdicks, B. Knowles, G. Blair, and A. Friday, "The climate impact of ICT: A review of estimates, trends and regulations," *arXiv Prepr. arXiv2102.02622*, 2021.

[6] IEA, "World energy balance overview 2017," 2017.

[7] IEA and UNEP, *2019 global status report for buildings and construction*. 2019.

[8] C. B. Aktas and M. M. Bilec, "Impact of lifetime on US residential building LCA results," *Int. J. Life Cycle Assess.*, vol. 17, no. 3, pp. 337–349, 2012, doi: 10.1007/s11367-011-0363-x.

[9] A. P. Ruuska and T. M. Häkkinen, "The significance of various factors for GHG emissions of buildings," *Int. J. Sustain. Eng.*, vol. 8, no. 4–5, pp. 317–330, 2015, doi: 10.1080/19397038.2014.934931.

[10] S. Toller, A. Carlsson, A. Wadeskog, S. Miliutenko, and G. Finnveden, "Indicators for environmental monitoring of the Swedish building and real estate management sector," *Build. Res. Inf. Int. J. Res. Dev. Demonstr.*, vol. 41, no. 2, pp. 146–155, 2013, doi: 10.1080/09613218.2012.749747.

[11] T. Malmqvist, S. Borgström, J. Brismark, and M. Erlandsson, "Referensvärden för klimatpåverkan vid uppförande av byggnader. Version 2, 2023," Stockholm, 2023. [Online]. Available: https://kth.diva-portal.org/smash/get/diva2:1744370/FULLTEXT01.pdf

[12] C. Kiamili, A. Hollberg, and G. Habert, "Detailed Assessment of Embodied Carbon of HVAC Systems for a New Office Building Based on BIM," *Sustainability*, vol. 12, no. 8. 2020. doi: 10.3390/su12083372.

[13] K. Gram-Hanssen and S. J. Darby, "'Home is where the smart is'? Evaluating smart home research and approaches against the concept of home," *Energy Res. Soc. Sci.*, vol. 37, pp. 94–101, 2018, doi: https://doi.org/10.1016/j.erss.2017.09.037.

[14] S. J. Darby, "Smart technology in the home: time for more clarity," *Build. Res. Inf.*, vol. 46, no. 1, pp. 140–147, Jan. 2018, doi: 10.1080/09613218.2017.1301707.

[15] F. Wortmann and K. Flüchter, "Internet of Things," *Bus. Inf. Syst. Eng.*, vol. 57, no. 3, pp. 221–224, 2015, doi: 10.1007/s12599-015-0383-3.

[16] SIS, "Svensk standard ss-en 15232-1:2017," Stockholm, Sweden, 2017. [Online]. Available: https://www.sis.se/produkter/byggnadsmaterial-och-byggnader/skydd-av-och-i-byggnader/varmeisolering/ss-en-15232-12017/

[17] S. Azizi, G. Nair, R. Rabiee, and T. Olofsson, "Application of Internet of Things in academic buildings for space use efficiency using occupancy and booking data," *Build. Environ.*, vol. 186, 2020, doi: 10.1016/j.buildenv.2020.107355.

[18] M. Molinari, J. Anund Vogel, D. Rolando, and P. Lundqvist, "Using living labs to tackle innovation bottlenecks: the KTH Live-In Lab case study," *Appl. Energy*, vol. 338, p. 120877, 2023, doi: https://doi.org/10.1016/j.apenergy.2023.120877.

[19] O. T. Masoso and L. J. Grobler, "The dark side of occupants' behaviour on building energy use," *Energy Build.*, vol. 42, no. 2, pp. 173–177, 2010.

[20] T. Pirson and D. Bol, "Assessing the embodied carbon footprint of IoT edge devices with a bottom-up life-cycle approach," *J. Clean. Prod.*, vol. 322, p. 128966, 2021, doi: 10.1016/j.jclepro.2021.128966.

[21] S. Nižetić, N. Djilali, A. Papadopoulos, and J. J. P. C. Rodrigues, "Smart technologies for promotion of energy efficiency, utilization of sustainable resources and waste management," *J. Clean. Prod.*, vol. 231, pp. 565–591, 2019, doi: https://doi.org/10.1016/j.jclepro.2019.04.397.

[22] Y. Arushanyan, E. Ekener-Petersen, and G. Finnveden, "Lessons learned – Review of LCAs for ICT products and services," *Comput. Ind.*, vol. 65, no. 2, pp. 211–234, 2014, doi: 10.1016/j.compind.2013.10.003.

[23] D. Bol *et al.*, "Green SoCs for a sustainable Internet-of-Things," in *2013 IEEE Faible Tension Faible Consommation*, 2013, pp. 1–4. doi: 10.1109/FTFC.2013.6577767.

[24] D. Bol, G. de Streel, and D. Flandre, "Can we connect trillions of IoT sensors in a sustainable way? A technology/circuit perspective (Invited)," in *2015 IEEE SOI-3D-Subthreshold Microelectronics Technology Unified Conference (S3S)*, 2015, pp. 1–3. doi: 10.1109/S3S.2015.7333500.

[25] S. Beucker, J. D. Bergesen, and T. Gibon, "Building

Energy Management Systems: Global Potentials and Environmental Implications of Deployment: Building Energy Management Systems,” *J. Ind. Ecol.*, vol. 20, no. 2, pp. 223–233, 2016, doi: 10.1111/jiec.12378.

[26] J. Pohl, V. Frick, A. Hoefner, T. Santarius, and M. Finkbeiner, “Environmental saving potentials of a smart home system from a life cycle perspective: How green is the smart home?,” *J. Clean. Prod.*, vol. 312, p. 127845, 2021, doi: https://doi.org/10.1016/j.jclepro.2021.127845.

[27] S. S. van Dam, C. A. Bakker, and J. C. Buiter, “Do home energy management systems make sense? Assessing their overall lifecycle impact,” *Energy Policy*, vol. 63, pp. 398–407, 2013, doi: https://doi.org/10.1016/j.enpol.2013.09.041.

[28] EU, “EPBD, DIRECTIVE (EU) 2018/844 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 30 May 2018,” *Off. J. Eur. Union*, 2018, [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018L0844&from=EN

[29] E. Quisbert-Trujillo, T. Ernst, K. E. Samuel, E. Cor, and E. Monnier, “Lifecycle modeling for the eco design of the Internet of Things,” *Procedia CIRP*, vol. 90, pp. 97–101, 2020, doi: https://doi.org/10.1016/j.procir.2020.02.120.

[30] J. Malmodin, D. Lundén, Å. Moberg, G. Andersson, and M. Nilsson, “Life Cycle Assessment of ICT,” *J. Ind. Ecol.*, vol. 18, no. 6, pp. 829–845, Dec. 2014, doi: https://doi.org/10.1111/jiec.12145.

[31] Å. Moberg *et al.*, “Simplifying a life cycle assessment of a mobile phone,” *Int. J. Life Cycle Assess.*, vol. 19, no. 5, pp. 979–993, 2014, doi: 10.1007/s11367-014-0721-6.

[32] N. Ullrich, F. M. Piontek, C. Herrmann, A. Saraev, and T. Viere, “Estimating the resource intensity of the Internet: A meta-model to account for cloud-based services in LCA,” *Procedia CIRP*, vol. 105, pp. 80–85, 2022, doi: https://doi.org/10.1016/j.procir.2022.02.014.

[33] J. Aslan, K. Mayers, J. G. Koomey, and C. France, “Electricity Intensity of Internet Data Transmission: Untangling the Estimates,” *J. Ind. Ecol.*, vol. 22, no. 4, pp. 785–798, 2018, doi: 10.1111/jiec.12630.

[34] Cloud Carbon Footprint, “Cloud Carbon Footprint,” 2023. https://www.cloudcarbonfootprint.org/docs/methodology (accessed Jan. 24, 2024).

[35] B. Whitehead, D. Andrews, A. Shah, and G. Maidment, “Assessing the environmental impact of data centres part 2: Building environmental assessment methods and life cycle assessment,” *Build. Environ.*, vol. 93, pp. 395–405, 2015, doi: https://doi.org/10.1016/j.buildenv.2014.08.015.

[36] S. Hellweg, E. Benetto, M. A. J. Huijbregts, F. Verones, and R. Wood, “Life-cycle assessment to guide solutions for the triple planetary crisis,” *Nat. Rev. Earth Environ.*, vol. 4, no. 7, pp. 471–486, 2023, doi: 10.1038/s43017-023-00449-2.

[37] S. Azizi, G. Nair, and T. Olofsson, “Demand-controlled energy systems in commercial and institutional buildings : a review of methods and potentials,” *eceee 2019 Summer Study proceedings*. pp. 1443–1450, 2019. [Online]. Available: https://www.eceee.org/library/conference_proceedings/eceee_Summer_Studies/2019/

APPENDIX A

TABLE II. MATERIAL COMPOSITION OF THE ELECTRONIC COMPONENTS

Inputs from Technosphere: materials/fuels	Material Percentage	Amount per piece/ meter	Amount in KTH live-in lab case	Unit	Ecoinvent process
Sensors	100	0.25	50.3	kg	
PE Polyethylene	4.3	1.08E-05	2E-3	kg	Polyethylene, high density, granulate {GLO}| market for polyethylene, high density, granulate | Cut-off, U
PC Polycarbonate	54.4	0.136	27.4	kg	Polycarbonate {GLO}| market for polycarbonate | Cut-off, U
Copper	0.2	5.03E-4	0.100	kg	Copper-rich materials {GLO}| market for copper-rich materials | Cut-off, U
Cardboard	23.8	0.060	12	kg	Carton board box production, with gravure printing {GLO}| market for carton board box production, with gravure printing | Cut-off, U
Electronic components	8.8	0.022	4.42	kg	Electronic component, passive, unspecified {GLO}| market for electronic component, passive, unspecified | Cut-off, U
Paper	7.9	0.020	3.97	kg	Printed paper {GLO}| market for printed paper | Cut-off, U
Steel	0.6	0.001	0.301	kg	Sheet rolling, steel {GLO}| market for sheet rolling, steel | Cut-off, U
Electricity	-	0.35	70	kWh	Electricity, medium voltage {GLO}| market group for electricity, medium voltage | Cut-off, U
Wires		0.018	208	kg	Cable, unspecified {GLO}| market for cable, unspecified | Cut-off, U
RP 1: SmartX Controller DO-FC-8-H	100	0.235	1.18	kg	
polycarbonate (PC)	31.6	6.66E-2	0.333	kg	Polycarbonate {GLO}| market for polycarbonate | Cut-off, U

Inputs from Technosphere: materials/fuels	Material Percentage	Amount per piece/ meter	Amount in KTH live-in lab case	Unit	Ecoinvent process
acrylonitrile butadiene styrene (ABS)	7.6	0.016	0.08	kg	Polystyrene, general purpose {GLO}| market for polystyrene, general purpose | Cut-off, U
epoxy resin	6.3	0.013	0.066	kg	Epoxy resin, liquid {RER}| market for epoxy resin, liquid | Cut-off, U
polyethylene (PE)	1.5	0.003	0.015	kg	Polyethylene, high density, granulate {GLO}| market for polyethylene, high density, granulate | Cut-off, U
aluminium	5.5	0.011	0.058	kg	Aluminium alloy, metal matrix composite {GLO}| market for aluminium alloy, metal matrix composite | Cut-off, U
ferrites	5.4	0.011	0.056	kg	Ferrite {GLO}| market for ferrite | Cut-off, U
copper	5.1	0.01	0.053	kg	Copper-rich materials {GLO}| market for copper-rich materials | Cut-off, U
tin	2.8	0.006	0.029	kg	Tin {GLO}| market for tin | Cut-off, U
glass fibre	8.7	0.018	0.091	kg	Glass fibre {GLO}| market for glass fibre | Cut-off, U
cardboard	8.4	0.017	0.088	kg	Carton board box production, with gravure printing {GLO}| market for carton board box production, with gravure printing | Cut-off, U
General elctronics	4.7	0.009	0.049	kg	Electronics, for control units {GLO}| market for electronics, for control units | Cut-off, U
triphenyl phosphate	3.8	0.008	0.04	kg	Triphenyl phosphate {GLO}| market for triphenyl phosphate | Cut-off, U
paper	3.2	0.006	0.033	kg	Printed paper {GLO}| market for printed paper | Cut-off, U
electrolyte	2.8	0.006	0.029	kg	Electrolyte, copper-rich {GLO}| market for electrolyte, copper-rich | Cut-off, U
Electricity	-	0.35		kWh	Electricity, medium voltage {GLO}| market group for electricity, medium voltage | Cut-off, U
SmartX Controller Terminal Base TB-IO-W1	100	0.148	0.148	kg	
polycarbonate (PC)	29.8	0.044	0.044	kg	Polycarbonate {GLO}| market for polycarbonate | Cut-off, U
polyamide resin 6 (PA6)	11.6	0.017	0.017	kg	Glass fibre reinforced plastic, polyamide, injection moulded {GLO}| market for glass fibre reinforced plastic, polyamide, injection moulded | Cut-off, U
acrylonitrile butadiene styrene (ABS)	8.5	0.012	0.012	kg	Acrylonitrile-butadiene-styrene copolymer {GLO}| market for acrylonitrile-butadiene-styrene copolymer | Cut-off, U
polyester resin	1.6	0.002	0.002	kg	Polyester resin, unsaturated {RER}| market for polyester resin, unsaturated | Cut-off, U
epoxy resin	1.3	0.002	0.002	kg	Epoxy resin, liquid {RER}| epoxy resin production, liquid | Cut-off, U
copper	11.8	0.017	0.017	kg	Copper-rich materials {GLO}| copper, anode to generic market for copper-rich materials | Cut-off, U
steel	5	0.007	0.007	kg	Steel, low-alloyed {GLO}| market for steel, low-alloyed | Cut-off, U
zinc	2.8	0.004	0.004	kg	Zinc {GLO}| market for zinc | Cut-off, U
brass	2.8	0.004	0.004	kg	Brass {RoW}| market for brass | Cut-off, U
tin	0.7	0.001	0.001	kg	Tin {GLO}| market for tin | Cut-off, U
lead (under RoHS exemption)	0.3	4E-4	4E-4	kg	Lead {GLO}| market for lead | Cut-off, U
cardboard	13.4	0.02	0.02	kg	Carton board box production, with gravure printing {GLO}| market for carton board box production, with gravure printing | Cut-off, U
triphenyl phosphate	4.3	0.006	0.006	kg	Triphenyl phosphate {GLO}| market for triphenyl phosphate | Cut-off, U
paper	3.5	0.005	0.005	kg	Printed paper {GLO}| market for printed paper | Cut-off, U
glass fibre	1.9	0.003	0.003	kg	Glass fibre {GLO}| market for glass fibre | Cut-off, U
General elctronics	0.7	0.001	0.001	kg	Electronics, for control units {GLO}| market for electronics, for control units | Cut-off, U
Electricity	-	0.22			Electricity, medium voltage {GLO}| market group for electricity, medium voltage | Cut-off, U
AO-V-8-H (RP1)		0.235	0.47	kg	
SmartController DO_FA_12_H (RP1)		0.235	0.235	kg	
SmartXcontroller UI-16 (RP1)		0.235	1.175	kg	
SmartXcontroll er PS-24V	100	0.211	0.211	kg	

Inputs from Technosphere: materials/fuels	Material Percentage	Amount per piece/ meter	Amount in KTH live-in lab case	Unit	Ecoinvent process
polycarbonate (PC)	31.6	0.066	0.066	kg	Polycarbonate {GLO}| market for polycarbonate | Cut-off, U
acrylonitrile butadiene styrene (ABS)	7.6	0.016	0.016	kg	Acrylonitrile-butadiene-styrene copolymer {GLO}| market for acrylonitrile-butadiene-styrene copolymer | Cut-off, U
epoxy resin	6.3	0.013	0.013	kg	Epoxy resin, liquid {RER}| epoxy resin production, liquid | Cut-off, U
polyethylene (PE)	1.5	0.003	0.003	kg	Polyethylene, high density, granulate {GLO}| market for polyethylene, high density, granulate | Cut-off, U
phenolic resin	1.4	0.003	0.003	kg	Phenolic resin {GLO}| market for | Cut-off, U
polyethylene terephthalate (PET)	1.1	0.002	0.002	kg	Polyethylene terephthalate, granulate, amorphous {GLO}| market for polyethylene terephthalate, granulate, amorphous | Cut-off, U
aluminium	5.5	0.011	0.011	kg	Aluminium alloy, metal matrix composite {GLO}| market for aluminium alloy, metal matrix composite | Cut-off, U
ferrites	5.4	0.011	0.011	kg	Ferrite {GLO}| market for ferrite | Cut-off, U
copper	5.1	0.01	0.01	kg	Copper-rich materials {GLO}| market for copper-rich materials | Cut-off, U
tin	2.8	0.006	0.006	kg	Tin {GLO}| market for tin | Cut-off, U
glass fibre	8.7	0.018	0.018	kg	Glass fibre {GLO}| market for glass fibre | Cut-off, U
cardboard	8.4	0.017	0.018	kg	Carton board box production, with gravure printing {GLO}| market for carton board box production, with gravure printing | Cut-off, U
various	4.7	0.01	0.01	kg	Electronics, for control units {GLO}| market for electronics, for control units | Cut-off, U
triphenyl phosphate	3.8	0.008	0.008	kg	Triphenyl phosphate {GLO}| market for triphenyl phosphate | Cut-off, U
paper	3.2	0.007	0.007	kg	Printed paper {GLO}| market for printed paper | Cut-off, U
electrolyte	2.8	0.006	0.006	kg	Electrolyte, copper-rich {GLO}| market for electrolyte, copper-rich | Cut-off, U
Electricity	-	0.35	0.35	kWh	Electricity, medium voltage {GLO}| market group for electricity, medium voltage | Cut-off, U
RP 2: SpaceLogic AS-P Controller	100	0.276	0.276	kg	
PC Polycarbonate	32.2	0.088	0.088	kg	Polycarbonate {GLO}| market for polycarbonate | Cut-off, U
PE Polyethylene	0.7	0.001	0.001	kg	Polyethylene, high density, granulate {GLO}| market for polyethylene, high density, granulate | Cut-off, U
PET Polyethilene Terephtalate	0.3	8E-4	8E-4	kg	Polyethylene terephthalate, granulate, amorphous {GLO}| market for polyethylene terephthalate, granulate, amorphous | Cut-off, U
Aluminium	8.4	0.023	0.023	kg	Aluminium alloy, metal matrix composite {GLO}| market for aluminium alloy, metal matrix composite | Cut-off, U
Electronic components	46.4	0.128	0.128	kg	Electronics, for control units {GLO}| market for electronics, for control units | Cut-off, U
Cardboard	9.4	0.025	0.025	kg	Carton board box production, with gravure printing {GLO}| market for carton board box production, with gravure printing | Cut-off, U
Paper	2.6	0.007	0.007	kg	Printed paper {GLO}| market for printed paper | Cut-off, U
Electricity	-	0.35	0.35	kWh	Electricity, medium voltage {GLO}| market group for electricity, medium voltage | Cut-off, U
Wireless M-Bus receiver Elvaco CMeX50 (RP2)		0.19	0.19	kg	
M-Bus Metering Gateway Elvaco CMe3100 (RP2)		0.22	0.22	kg	
Cabinet (box)		150	150	kg	
Galvanized steel			150	kg	Steel hot dip galvanized (ILCD), blast furnace route, production mix, at plant, 1kg, typical thickness between 0.3 - 3 mm. typical width between 600 - 2100 mm. GLO S

TABLE III. PROCESSES DURING USE AND DISPOSAL PHASES

Processes	Amount per unit	Amount in KTH live-in lab case	Unit	Comment
Data transfer	3.75E-3		kWh/GB	
Electricity		3.9	kWh	Electricity, low voltage {SE}| market for electricity, low voltage | Cut-off, U
Cloud/Internet	0.017		Wh/GB/ month	
Electricity		18.2	kWh	Electricity, medium voltage {IE}| market for electricity, medium voltage | Cut-off, U
Use phase electricity use		7360	kWh	Electricity, low voltage {SE}| market for electricity, low voltage | Cut-off, U
Waste treatment of electronics		53.1	kg	Disposal, industrial devices, to WEEE treatment/CH U
Waste treatment of wires		57.6	kg	Disposal, treatment of cables/GLO U
Waste treatment of steel		150	kg	Scrap steel {Europe without Switzerland}| market for scrap steel | APOS, U