# Challenges and Opportunities of Internet-of-Things in Occupant-Centric Building Operations: Towards a Life Cycle Assessment Framework

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The urgency to address the environmental impacts of the building sector, particularly emissions allocated to building operation, necessitates immediate, informed action. Occupant behaviour is a known driver of building operation emissions. Use of Internet of Things (IoT) devices holds great potential in mitigating and distributing occupancy-driven energy demand, ultimately aiming for net-zero emissions. However, a full accounting of the environmental impacts and advantages is still lacking. As the adoption of IoT scales up, what will be the environmental impact of the tools used, from sensor life cycle to data storage? This study reviews the interdisciplinary literature on life cycle assessment of IoT in buildings, encompassing emissions from pre-deployment to end-of-life, as well as savings from reduced building operations emissions. This opens a vital discourse on the opportunities and challenges of building-related IoT.

## Highlights

- There is emerging evidence that the lifecycle impacts of IoT may not be negligible.
- An adapted LCA framework is suitable for assessing the impacts from IoT in buildings.
- The choice of boundaries, functional unit, impact categories, service lifetime and expected IoT benefits will influence results, and may differ from the context of a building LCA.

## Introduction

The Internet of Things (IoT) may be defined as “objects that have the capacity to auto-organise, share information, data and resources, reacting and acting in face of situations and changes in the environment” [1]. IoT is now integral to almost every building project and has become critical to the operation of buildings. IoT systems are aimed at the health and well-being of building users and the functioning of the building (e.g., hazard detection, energy monitoring, etc.). Building related IoT systems are becoming pervasive with the recent introduction of mandatory fittings and metres in many countries. For example, the amended Energy Performance of Buildings Directive [2] includes requirements on the installation of building automation and control systems and on the devices that regulate temperature at room level. This exploratory review is concerned with building-related IoT relevant for automating indoor environmental control, for example heating/cooling demand or air quality.

Building users expect a comfortable environment with good air quality, but there are consequences if this comfort is to be supported by IoT systems. The net effects need to be assessed. On economic and environmental sustainability, IoT systems may not always reduce energy demand nor operational cost: a well-documented pattern is the rebound effect [3], where part of the energy conservation due to the IoT is lost as the occupants change their choices (for example to increase the time or amount of using a service such as cooling, in response to the introduction of IoT technology for conserving cooling energy). The benefit is reduced, or inverted when factoring in parasitic loads, the embodied costs of using batteries and ongoing maintenance. Considering occupant behaviours, both energy-saving and possible rebound effects, what are the net benefits of IoT in buildings? The related concepts of digital sobriety [4] and digital sufficiency [5] have been advocated elsewhere arguing for the necessity of undertaking an environmental transformation in a more holistic manner. However, the scientific literature to date does not provide detailed and holistic answers.

Looking into building IoT systems' sustainability entails a shift in the conventional culture for both building managers and researchers. The prevailing assumption has been that the environmental impact, namely embodied carbon, and operational energy use related carbon emission of building automation systems, is thought of as being negligible in comparison with the operational energy use related carbon emissions for heating, ventilation, cooling, and lighting. In terms of embodied carbon, a systematic review of 240 case studies noted that services were ignored in many studies [6]. In terms of operational energy use and the related carbon emissions, long-standing assumptions are being questioned. Kräuchi et al. [7] challenged the prevailing assumptions by showing that building automation systems may account for 2 to 5 kWh/m² per year, which equals 3 to 9% of the final energy use for a low energy office building (25 kWh/m² per year). Achieving a "green" IoT has been recognized as requiring new, effective measures for hardware, software, and communication [8]. However, to date, no review has been conducted to characterise net embodied and operational environmental impacts.

To begin to address this question, we turn to life cycle assessment (LCA), a well-vetted framework for the systematic analysis of environmental impacts and environmental product declarations (EPDs). Therefore, we performed an exploratory review of existing literature related to life cycle assessment of IoT in buildings as a basis to reflect on the question how the existing LCA framework needs to be adapted and extended to include aspects that are unique to IoT.

## Current approaches in LCA

Scholars have offered numerous definitions of life cycle assessment (LCA) [9–12],which generally align with one another. For instance, Ilgin and Gupta's definition will be presented here, wherein LCA as "a method used to evaluate the environmental impact of a product through its life cycle encompassing extraction and processing of the raw materials, manufacturing, distribution, use, recycling, and final disposal" [11]. Despite the consistency in definitions, there exists substantial variation in approaches, concepts, and boundaries across disciplines and applications. However, an exhaustive account of these differences would be beyond the scope of the work; interested readers are referred to corresponding summaries [13–16] or international standards e.g. EN 15978 [17], EN ISO 14040 [18] and EN ISO 14044 [19]. LCA refers to environmental impacts (e.g.,[14–16] and as such does neither include economic (dealt with in life cycle costing - LCC) nor social aspects (social life cycle assessment - SLCA). Each of these require separate treatments. For instance, IoT in buildings raises questions of social sustainability whenever occupants' presence and behaviour in buildings need to be tracked to respond to changes such as ventilating a space when two occupants are meeting, which may raise privacy issues. Thus, both LCC and SLCA would be required for an even more holistic life cycle sustainability assessment of IoT [20], however these are not within the scope of this exploratory review.

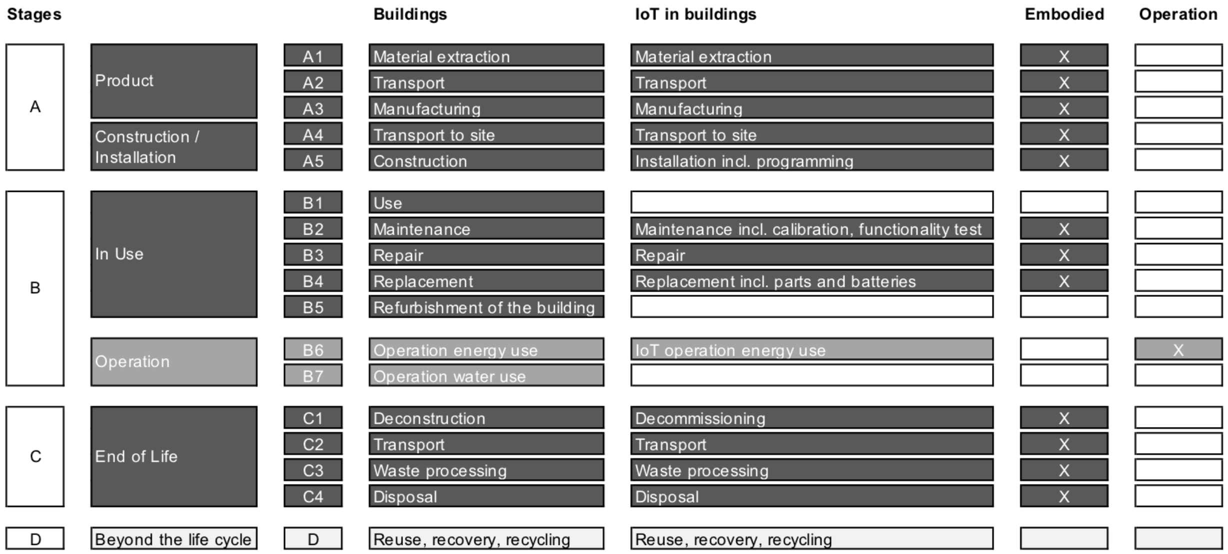
## LCA Boundaries and Functional Unit for IoT

The boundaries of LCA are crucial with respect to the understanding of potential unintended environmental rebounds of IoT. As stated by Li et al. [21], the definition of boundaries is a challenge and beyond scientific standard methods. They address four categories of boundaries, namely environmental, technical, geographical, and temporal. Similar categories are used by Tillman et al. [22]. They conclude with respect to the technical systems' dimension, that in many cases it is the processes outside the direct process tree of a system, namely within the technological whole system and socio-economic whole system, which are affecting the results to a larger extent than addressing further details within the process tree. Related to IoT in buildings, such a point gets obvious without further analysis when considering solely the sensor itself, required installation, potential servers and their server spaces or the building. In addition, when considering potential artificial intelligence (AI) or machine learning approaches connected to those sensors, it is important to consider not only the energy and sources related to computational power for training and application. As demanded by Kaack [23] based on general thoughts on AI and climate change mitigation , the impact through required hardware including CPUs and GPUs as well as the building structures and building-related energy use for hosting servers needs to be addressed, but so far is largely ignored.

The functional unit, which expresses the services or impact per unit of what is being assessed, is the reference basis for reporting results. In LCAs of buildings, frequently used functional units are the energy use or carbon emissions per inhabited floor area (kWh/m² or tCO2/m²) and more seldom, the energy use or carbon emissions per occupant (kWh/m² or tCO2/inhabitant). The choice of this functional unit, while it does not alter outcomes, can influence the interpretation of results. For example, over time while the energy use per m² inhabited floor area decreases in German residential buildings, the energy use per inhabitant is largely unchanged due to the floor area per inhabitant increasing from 20 m² per person in the 1960s to around 45 m² per person today [24]. The functional unit for an LCA for IoT should adopt the same metrics and an assessment of the building with which they are associated. However, additional functional units could be helpful for articulating the special nature of a given service or benefit of the technology.

## Framework: LCA and Impact Categories for IoT

LCA considers the lifetime of systems, which themselves may be of various scales. A building or a component of a building (e.g., IoT) can be analysed with the same framework. This is a strength of LCA, enabling comparison between and within systems. The framework presented in this paper is based on EN 15978 [25] and CIBSE TM65:2021 [26] and includes four stages (see Figure 1, column 1-4). Within these four stages, there are two components, embodied environmental impacts and operational environmental impacts (Fig 1, column 6-7). Embodied environmental impacts are associated with all of the lifecycle except operational environmental and stage D emissions. However, the existing LCA framework for buildings needs to be adapted and extended to describe aspects that are unique to building-related IoT as we propose in Figure 1 (5th column). In this paper, embodied environmental impacts address building and product level IoT devices, it does not include ‘off-site’ data storage facilities. Operational environmental impacts are associated with Stage B, ‘operation’. In this paper, operational environmental impacts address individual building and product level IoT devices and ‘on-site’ as well as ‘off-site’ data storage and processing.



| Stages | | | Buildings | IoT in buildings | Embodied | Operation |
|---|---|---|---|---|---|---|
| A | Product | A1 | Material extraction | Material extraction | X | |
| | | A2 | Transport | Transport | X | |
| | | A3 | Manufacturing | Manufacturing | X | |
| | Construction / Installation | A4 | Transport to site | Transport to site | X | |
| | | A5 | Construction | Installation incl. programming | X | |
| B | In Use | B1 | Use | | | |
| | | B2 | Maintenance | Maintenance incl. calibration, functionality test | X | |
| | | B3 | Repair | Repair | X | |
| | | B4 | Replacement | Replacement incl. parts and batteries | X | |
| | | B5 | Refurbishment of the building | | | |
| | Operation | B6 | Operation energy use | IoT operation energy use | | X |
| | | B7 | Operation water use | | | |
| C | End of Life | C1 | Deconstruction | Decommissioning | X | |
| | | C2 | Transport | Transport | X | |
| | | C3 | Waste processing | Waste processing | X | |
| | | C4 | Disposal | Disposal | X | |
| D | Beyond the life cycle | D | Reuse, recovery, recycling | Reuse, recovery, recycling | | |

**Figure 1**. Life cycle assessment as defined by EN 15978 [27] applied to Building (CIBSE TM65:2021 [26]) and extended specifically to building-related IoT, including embodied elements (in dark grey), operational elements (in grey) and further elements included in the whole life environmental impact(Stage D, in pale grey).

The framework includes a space for including the impact of IoT operation alongside that of the building; ultimately, attributing some savings in energy at the building-scale to the use of IoT will only be noticed if the LCA accounts for the building and the IoT in the same assessment framework.

LCA provides a comprehensive analysis of the environmental effects of a system, while impact categories help categorise and quantify the specific environmental impacts within that analysis.

Impact categories are specific areas of environmental concern, such as greenhouse gas emissions, water consumption, or toxic releases, which are quantified and evaluated within the LCA framework to understand the overall environmental performance and potential impacts associated with the analysed system. Building LCAs may use any of twenty-two impact categories, however only six of these are commonly reported: global warming potential (greenhouse gases); depletion of the stratospheric ozone layer; acidification of land and water sources; eutrophication; formation of tropospheric ozone; and depletion of non-renewable energy resources. These six are ISO 14044-compliant, follow the TRACI methodology [28], and are part of the Leadership in Energy and Environmental Design (LEED) LCA credit [29][30]. Notably, these do not overlap with the impact categories of concern for electrical and electronic equipment. A review on the applicability LCA for waste electronic equipment found that the production of hardware for IoT had net positive impacts in the global warming categories, but net negative impacts in four impact categories: freshwater eutrophication, freshwater ecotoxicity, marine ecotoxicity, and human non-carcinogenic toxicity [31]. Thus, it is a recommendation of this review to go beyond the categories needed for compliance in typical building LCAs and include those relevant to the IoT technology being assessed - namely those listed above.

## Average service lifetime of connected devices

A report prepared for the International Energy Agency IEA 4E EDNA from 2019 [32] reports on the average service life time of connected devices which was defined as the years of life at which 50% of the products remain in service [32]: residential IoT sensors in low energy networks (Bluetooth, ZigBee NB-IoT, etc), and Wi-Fi networks as well as network connected controls for blinds and windows are given with an average service life time of 5 years; residential automation for space conditioning (smart thermostat, air conditioners) and water heaters are given with 12 years average service life time; utility connected smart metres in the public sector are given as well with 12 years of service life [32]. In comparison, building services components (‘hardware’ like heat generators, pipes, storage tanks, insulation etc.) typically have a service life of 15-40 years [33]. In common life cycle assessment methodology e.g., [30], the service life of buildings is assumed to be 50 years, though we know that large parts of the European building stock was built more than 50 years ago and a considerable share of buildings is more than 100 years old. However, given a building’s service life of 50 years, IoT sensors and systems would need to be replaced 5 to 10 times during the service life of the entire building. Whether energy conservation through automation leads to decreased environmental impacts depends on the service lifetime and how energy efficient those IoT sensors and systems are.

## Sensors reviewed as input values to the LCA framework

One specific study could be found that included the non-operational use phases of a building IoT device: Manz et al. assessed an “intelligent smoke detector” [34]. They noted that the use phase was the largest contributor to emissions; and that emissions overall were “marginal” but freshwater and marine ecotoxicity were important impact categories [34]. This conclusion supports the finding that electronic waste will require inclusion of impact categories not typical of building LCAs.

Operations-phase environmental impacts of IoT for buildings have been reported by Kräuchi et al. [35], who determined the energy use of wired building and room automation systems based on 6 real buildings (5 schools, 1 office building). The relative proportion of the energy used for room automation was estimated as 3 to 9% of the overall energy demand of standard energy efficient buildings which is around 45 kWh/m² per year, in the climate of Switzerland. The energy use of the installed sensors was between 0.2 and 0.4 kWh/m² per year. Sensors, gateways and power supplies contributed 6 to 28% to the final energy use of room automation. Power supplies, mainly due to their long standby or partial load periods and significant electricity use in standby mode, used 12 to 65% of the room automation energy use [7].  This agrees with findings from Tønnesen and Novakovic [36], who determined the electrical standby power to operate room automation (KNX-bus system) for a single office or a meeting room an office in a passive house office building, with respectively 0.91 and 2.00 kWh/m² per year solely for operating the automatic system on room level. Kräuchi et al. [35], also measured several air sensors, e.g., for determining air quality, presence and illuminance. The power use of the sensors was usually between 0.1 and 0.2 W. A weather station, which can be found on almost all automated buildings, had a power use of 3.7 W. An NDIR sensor for CO2 measurement had a power use of 0.8 W whereas a mixed gas sensor VOC had a power use of approximately 0.2 W.

In parallel to the academic literature, environmental product declarations (EPD) also give useful estimates of the energy consumption of typical IoT devices used in buildings. A few exemplary examples were added to Table 1. Some of those declarations (e.g., [37] ) give information on other categories of LCA such as global warming potential, acidification, Eutrophication etc. and inform about the distribution over the life stages. Other EPDs are limited to information on energy consumption per year. In addition, mandatory compliance information regarding the EU's Directive on the restriction of use of certain hazardous substances in electrical and electronic equipment is given.

The IEA 4E EDNA report [32] summarised active and standby power use for connected devices based on sales and stock numbers developing a Total Energy Model for Connected Devices which includes use phase energy consumption originating from the operation of IoT and other connected devices. Residential IoT gateways in low energy networks and Wi-Fi networks have 1.4 W in active and standby mode. Residential IoT sensors in low energy networks (Bluetooth, ZigBee NB-IoT, etc) have 0.001 W and in Wi-Fi networks 1.2 W for both active and standby mode. Residential automation for space conditioning (smart thermostat, air conditioners) and water heaters are given with 1.22 W and 2 W respectively for both modes. Utility connected smart metres in the public sector are given with 2 W in both modes. Examples from a range of typical IoT sensors for buildings are described in Table 1.

**Table 1**. Exemplary power use and energy use of buildings, room automation and IoT devices used in buildings.

| Energy using element | Type | Power use [W] | Energy use [kWh/year or %] | Ref |
|---|---|---|---|---|
| Non-residential energy efficient building, Switzerland | building | - | 45 kWh/m2/year | [35] |
| | Share of room automation | - | 3-9% | |
| | Installed sensors | - | 0.2-0.4 kWh/m2/year | |

| | | | | |
|---|---|---|---|---|
| | Sensors, gateways, power supply | - | 6-28% of room automation electricity | |
| Single office room automation (KNX-bus) | Standby | | 0.91-2.0 kWh/m2/year | [36] |
| Non-residential buildings, sensors e.g., for determining presence and illuminance | sensors | 0.1-0.2 | | [35] |
| Room unit with sensor, setpoint and operating mode selector, display and PPS2 interface | NTC sensor | | 1.0 | [38] |
| Non-residential buildings, sensor air quality | NDIR CO2 | 0.8 | | [35] |
| Air quality CO2 sensor, Room Transducer | NDIR CO2 | | 13.7 | [37] |
| Non-residential buildings, sensor air quality | VOC | 0.2 | | [35] |
| Residential IoT sensors in low energy networks (Bluetooth, ZigBee NB-IoT, etc), active and standby mode | | 0.001 | | [32] |
| Residential IoT sensors in Wi-Fi networks, active and standby mode | | 1.2 | | [32] |
| Residential automation for space conditioning (smart thermostat, air conditioners) and water heaters | | 1.22-2 | | [32] |
| Non-residential | Weather station | 3.7 | | [35] |
| Smoke detector | Optical | | 0.07 | [39] |

|  |  |  |  |
|---|---|---|---|
| Touch screen room thermostat with KNX communications, for heating application |  | 20 | [40] |
| Residential IoT gateways in low energy networks and Wi-Fi networks, active and standby mode | 1.4 |  | [32] |
| Utility connected smart metres in the public sector | 2 |  | [32] |

Notes: no maintenance was included in any of the annual energy consumption demand totals

There may be further aspects to consider on IoT energy use and related carbon emissions, including the frequency of sensing, the protocol of communication and data transmission, as well as the impact of data storage from local to distributed storage [32].

## Energy use of connected devices

The values given serve to estimate the total energy consumption of connected devices. Network standby-related energy use of connected devices for automation was projected to grow from 65 TWh in 2019 (0.2% of total electricity demand) to 161 TWh in 2030 (0.6% of total electricity demand) with an increasing total number of connected devices as the drivers [41]. This electricity use equals 12.5 to 30% of the total electricity consumption of a country like Germany [42]. Hereby, Wi-Fi connected IoT devices contribute especially to this increase in energy consumption compared to low power consumption wireless networks [32]. Upstream energy use of the communications and data networks and the data centres was estimated at 327 TWh in 2019 with a decrease to 2810 TWh in 2030 [41].

## Including occupant behaviour and possible rebounds

Whereas EN 15232:2017 suggests that more automation leads to more energy savings [43], examples from practice show that occupants find ways around those fully automated solutions in order to serve their needs; for example by blocking lighting or occupancy sensors [44]. How the room automation technology is used, and which control algorithm is chosen may be determining factors for whether energy savings are achieved and lead to better user acceptance. For example, using manual-ON/vacancy-OFF control strategies for lighting may lead to 62% energy use reductions for lighting compared to automatic ON/vacancy-OFF function [45].

Therefore, unlike a conventional LCA for buildings, when assessing IoT for occupant-centric building operation, there are unknown IoT-induced behaviours of the occupants to consider. The application of room automation in buildings can lead to rebound effects due to for example the change in occupants' comfort expectation or in occupants' behaviour or due to conflicting goals in the automation programming of controls and the actual need of occupants. Potential negative effects of taking control away from occupants with regards to their satisfaction and prevalence of sick building syndrome symptoms were described in Hellwig, et al [46]. When conducting sensitivity analyses, researchers should always probe the influence of the assumed expected benefits from IoT.

## Conclusion and outlook

Legislation and standardisation (for example, in the EU: EN 15232:2017) proposes to apply more room automation using sensor and control technologies and at the same time reduce the amount of occupant control. This kind of approach aims to achieve reductions in energy use and lessen the gap between predicted and actual consumption. One perspective argues that IoT devices are always valuable if they can demonstrate tangible environmental advantages at a reasonable cost. On the other hand, there is another perspective that highlights the significant burden imposed by these devices during the manufacturing and disposal stages of their lifecycle. To account for both, we need a decision-support tool that accounts for the entire lifecycle, and moreover factors in uncertainties from occupant behaviours. Thus, along with the rapid adoption of IoT, we need the right assessment toolkit. LCA can be one of those tools (though not the only tool). This paper outlines such an adapted LCA framework: boundary selection, functional unit, lifespan, impact categories, and other assumptions regarding IoT benefits, each influence the conclusions drawn, diverging from those of a building LCA. Given the current lack of comprehensive studies and the speed of IoT deployment, we urge researchers and practitioners to conduct further critical evaluations. Moreover, we recommend digital sobriety wherever possible, to prioritise environmentally conscious design and solutions with individual system components - such as environmentally friendly wireless powered electronics [47]. Finally, as a systematic review was beyond the scope of this review, we acknowledge potential gaps in our argument and anticipate their resolution through future systematic approaches.

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