

## ANALYZING THE ENVIRONMENTAL SUSTAINABILITY OF SMART BUILDINGS

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### Abstract

Smart buildings are becoming increasingly important for the construction industry. They are associated with optimization potential for efficiency and therefore ecological sustainability. However, there are currently no studies that can scientifically prove this thesis. Through a comprehensive methodology involving literature reviews, analysis of smart buildings, and expert interviews, the study explores the complexities of achieving environmental sustainability in smart buildings. Emphasizing the importance of standardized definitions, data availability, and collaboration among stakeholders, the paper presents use cases and highlights their impact on the sustainability of a smart building. Furthermore, information for evaluating the environmental sustainability of smart buildings is defined.

### Introduction

According to the European Copernicus Climate Change Service 2023 will be the hottest year in the last 125.000 years. Oktober 2023 even sets a record as the warmest month ever recorded, with a global average temperature 1.7 degrees above pre-industrial levels (Schmid, 2023). This underscores the urgency of adhering to the goals of the Paris Climate Agreement, not only in limiting global temperature rise but also in reducing emissions and adapting to climate change (Europäische Union, 2016), (Bundesministerium für wirtschaftliche Zusammenarbeit und Entwicklung, 2023). The building sector, responsible for 40 % of final energy consumption in Europe (United Nations Environment Programme, 2022), plays a crucial role. In Germany, 35 % of total energy consumption goes to buildings, contributing to 30 % of annual CO<sub>2</sub> emissions, with 75 % of a building's carbon emissions occurring during operation (SmartScore, 2021).

To address this, there is a need to reduce energy consumption in existing buildings and enhance the sustainability of new ones. Innovative construction methods and materials, such as 3D printing, wood, clay, and CO<sub>2</sub>-reduced concrete, are being explored (Bäuerle & Lohmann, 2021), (Neef, et al., 2020), (Haist, et al., 2023). Simultaneously, the adoption of technological solutions, especially smart building applications, is increasing (Mordor Intelligence, 2023).

Despite the growing interest, there is a lack of comprehensive scientific studies on the ecological sustainability of smart buildings, particularly in terms of user and facility management practices. This paper aims to fill this gap by scientifically analyzing the environmental sustainability of smart buildings.

- Which applications and associated data are necessary for evaluating the ecological sustainability of a smart building?

- What data is available for use in a smart building that goes beyond a classic building atomization and what additional data is required?

This case study was carried out exclusively in the Smart office area, because smart homes have too individual a design, as well as other data protection difficulties. Furthermore, the smartness of other types of buildings has not yet been sufficiently further developed. It will assess optimization potential, consider stakeholders (project developers, owners, manufacturers, and facility managers), and scrutinize data flow within smart buildings, identifying potential interface problems and data losses. The paper concludes with recommendations on calculating the environmental sustainability of smart buildings based on practical experiences and expert insights.

### Literature Review and related work

#### Definition of a smart building

A clear distinction between buildings with classic building automation and smart buildings was drawn up with the help of a literature review. The literature and practical applications lack a uniform definition of a smart building, attributed partly to differing perspectives among project participants throughout a building's life cycle (SmartScore, 2021), (Monterioa Froufe, et al., 2020). As outlined in literature developers emphasize user experience for increased property value, while facility management (FM) focuses on safety and energy savings (Qolomany, et al., 2019), (Li, et al., 2020), (Pašek & Sojková, 2018). To sustain a smart building efficiently and ecologically, there is a need to network stakeholders and establish a unified definition.

Current consensus, based on literature and project analysis, describes a smart building as one equipped with diverse technologies (actuators, sensors, microchips) for data collection, storage, and analysis (Bosch & Deckert, 2023), (Plageras, et al., 2018). According to the (Fraunhofer-Allianz Bau, 2022), smart buildings use automation to enhance physical properties through holistic control concepts and suitable technologies. They integrate existing building automation systems or use autonomous sensor technology installed solely for smart building solutions (Graveto, et al., 2022).

There exist different perspectives on smart building applications. (Bosch & Deckert, 2023) focus on automated, energy-efficient, and sustainable building networking that positively impacts user experience, climate protection, and environmental conservation. (Moretti, et al., 2020) emphasizes optimizing maintenance services in smart buildings.

A comprehensive definition emerges from these perspectives that is shown in Figure 1: A smart building is a digitally connected building with diverse technologies and

systems. It aims to enhance user experience and positively impact the three pillars of sustainability. Smart buildings continuously collect real-time data through sensors of the facilities, systems and users. This data is transparently stored, processed, and evaluated, ideally in a cloud and made available to a building management platform. Considering data over the building's life cycle supports optimization, acting as a foundation for new building planning.

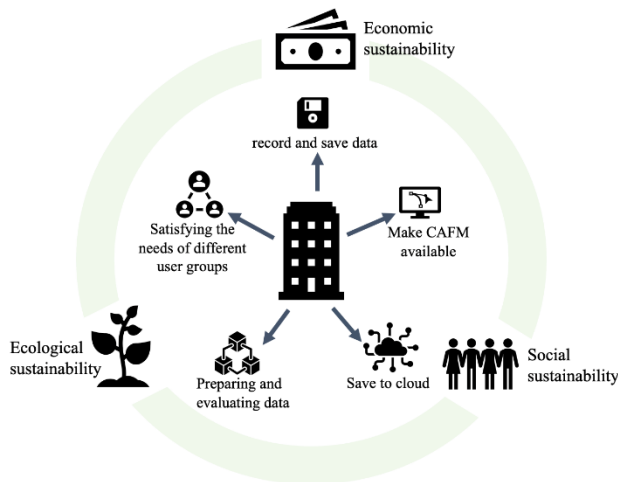


Figure 1: Definition of a smart building

### Influence of smart buildings on environmental sustainability

Research in the field of smart building is becoming increasingly important, especially in relation to environmental sustainability. Figure 2 shows the number of scientific publications on the keywords "smart building" and "sustainability" and a continuous increase on Scopus and google scholar between 2018-2023.

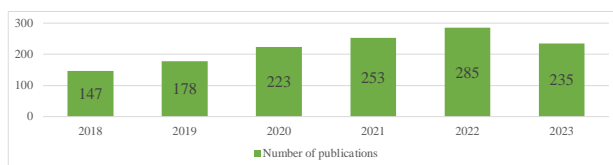


Figure 2: Publication in the area of smart buildings and environmental sustainability published in the years 2018-2023

With the Smart Readiness Indicator (SRI), the European Union provides a basis for assessing the readiness to implement smart components in buildings. However, this does not provide a basis for assessing the sustainability of the building (The European Commission, 2020). Rising energy costs and the need to meet the Paris climate targets (Koch, 2023) mean that companies want to reduce their consumption in office space through energy monitoring (Nulsch, 2023). ISO 52120-1:2021 deals with the influence of building automation and management on energy efficiency (DIN e.V., 2019). This shows a correspondence with the analyzed use cases of a smart building. The standard uses a factor-based method to estimate the influence of energy consumption based on the degree of automation

of various functions. Improving the energy efficiency standard according to the standard can lead to significant savings, although previous standards have listed similar factors. In literature it is stated, that smart buildings could save 10 % - 25 % in energy (Fraunhofer-Allianz Bau, 2022), (Fraunhofer-Allianz Bau, 2023), (Jacob & Kukovec, 2022). Annex 81 addresses the fact that the potential of digitalization for the energy efficiency of buildings has not yet been fully exploited. among other things, the project aims to develop software applications with the help of available cost-efficient data in buildings. Semantic standards are defined and an open data platform is required (International Energy Agency, 2023).

Manufacturers promote smart buildings as a driver for environmental sustainability in the building sector, focusing on reduced energy consumption, cost reduction and increased comfort through intelligent optimization systems that adapt energy consumption to occupancy and use. More efficient use of space saves resources and maximizes stakeholders' profits (Siemens Schweiz AG, 2020). In order to evaluate the savings and optimizations of environmental sustainability by smart buildings, an analysis of 23 manufacturers have been conducted in addition to the literature review. The information was taken from product catalogs, white papers, proof of concepts or the companies' websites. Eight of 23 companies indicate potential savings, that vary from 10 % up to 40 %. Some providers regard the energy in general, others differentiate between heating and lighting energy. A few put the savings in heating costs or operating costs at between 30 % and 40 %. One claims to achieve area savings of 30 %. The other 15 companies do not provide any information on savings. The analysis showed 5 major problems in defining the environmental sustainability for smart buildings:

1. No information is provided on the initial values (e.g., planning or previous years of operation) or the basis for calculating the savings,
2. predominantly no information on whether the savings relate to thermal or electrical energy,
3. the number given cannot be substantiated, as generalized statements about CO<sub>2</sub> savings are often made or an increase in the users' sense of comfort is suggested, as well as falling personnel costs due to a healthier environment,
4. the focus is on long-term savings potential rather than short-term added value and
5. changes in the use or operation of the property, deviating conditions in facility management and other relevant factors on the technical side are not mentioned.

None of these problems will be solved by special solutions in showcase buildings. In order to make the building sector more sustainable, solutions are needed for the building sector as a whole.

### Methodology

Based on the literature review (Literature Review and related work) on "smart building" and "environmental sustainability" keywords was conducted using databases like

Google Scholar and Scopus, the revision of the research gaps is carried out in three steps, that are shown in Figure 3.

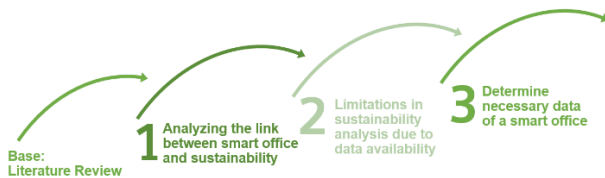


Figure 3: Methodology of this paper

Step 1 analyzed the current link between sustainability and smart buildings in Practice. Therefore, firstly 15 Case Studies of Smart Buildings in Central Europe were analyzed. Afterwards, the results were validated by guided interviews with 67 experts provided qualitative and quantitative insights. By doing so, the use cases, that affect the ecological sustainability of smart buildings, were evaluated.

Step 2 outlines limitations in sustainability analysis due to data availability. Hereby, the challenges highlighted in the expert interviews (e.g., data availability) were first summarized and discussed. Based on that, the data of 4 smart buildings, that were provided by the Facility Management and the building owner, were analyzed. In addition to that, the loss of data throughout the data processing from data collection to data usage is evaluated based on the case studies and further expert interviews.

Due to the lack of complete data, that could proof the sustainable impact of smart buildings, recommendations for necessary smart building data are made in a final step (Step 3).

### Step 1: Analysis of the environmental sustainability of smart buildings in practice

In order to evaluate the environmental sustainability 15 Case Studies were analyzed. Furthermore, 25 guided interviews were conducted with participants from 67 requested companies in asset and facility management (AM & FM), general contracting (GC), hardware and software manufacturers (manufactures) in building services, engineering, planning (P), project development (PD), and owners (O) (Figure 4) in order to validate the results of the Case Study analysis.

The companies were selected based on literature, project analysis, and smart building experience. Only 25 companies could provide insights into the link between smart buildings and sustainability, resulting in a 37 % response rate. Interviews took place between April 17 and June 30, 2023, either via Teams or on-site, with four companies also submitting written information.

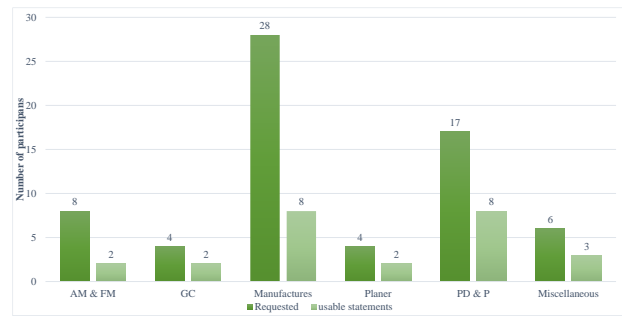


Figure 4: Participants' structure of the expert interviews

The expert interviews were based on the analysis from the basic analysis and the use cases of smart buildings, which were evaluated in workshops with experts. Drawing on existing knowledge, freely available content from implemented smart buildings, planning documents, and input from Central European smart building planners, use cases were clustered and evaluated for their environmental sustainability impact. A total of 64 use cases were evaluated.

### Evaluation of the use cases of smart buildings based on Case Studies and interviews

The analysis of 15 Smart Offices in Germany and Central Europe identified 64 use cases. Due to expert interviews those can be categorized into seven main areas. In addition, the potential influence of these on the three pillars of sustainability was identified. Examining the implementation rates of these use cases in smart offices, Figure 5 illustrates their distribution. The further out the use cases are placed, the more frequently they are implemented (Percentages in Figure 5). Notably, 34 % of all use cases impact environmental sustainability (shown in bright green), while 52 % influence economic sustainability, and 72 % impact social sustainability (shown in dark green).

The dominance of energy supply (82 % of use cases) and water supply (100 % of use cases) is evident in their substantial influence on the environmental sustainability of buildings. Only 36 % of the environmentally sustainable use cases were implemented in at least 50 % of the analyzed buildings, challenging the notion that smart systems are primarily implemented for environmental reasons. Most use cases affecting environmental sustainability (72 %) were implemented in less than 33 % of the smart buildings. Further examination highlights that use cases related to information management, user experience, and building security significantly impact social sustainability and user comfort. Over half (56 %) of these use cases were integrated into more than 33 % of the buildings, indicating a predominant focus on user satisfaction and experience rather than increasing environmental sustainability.

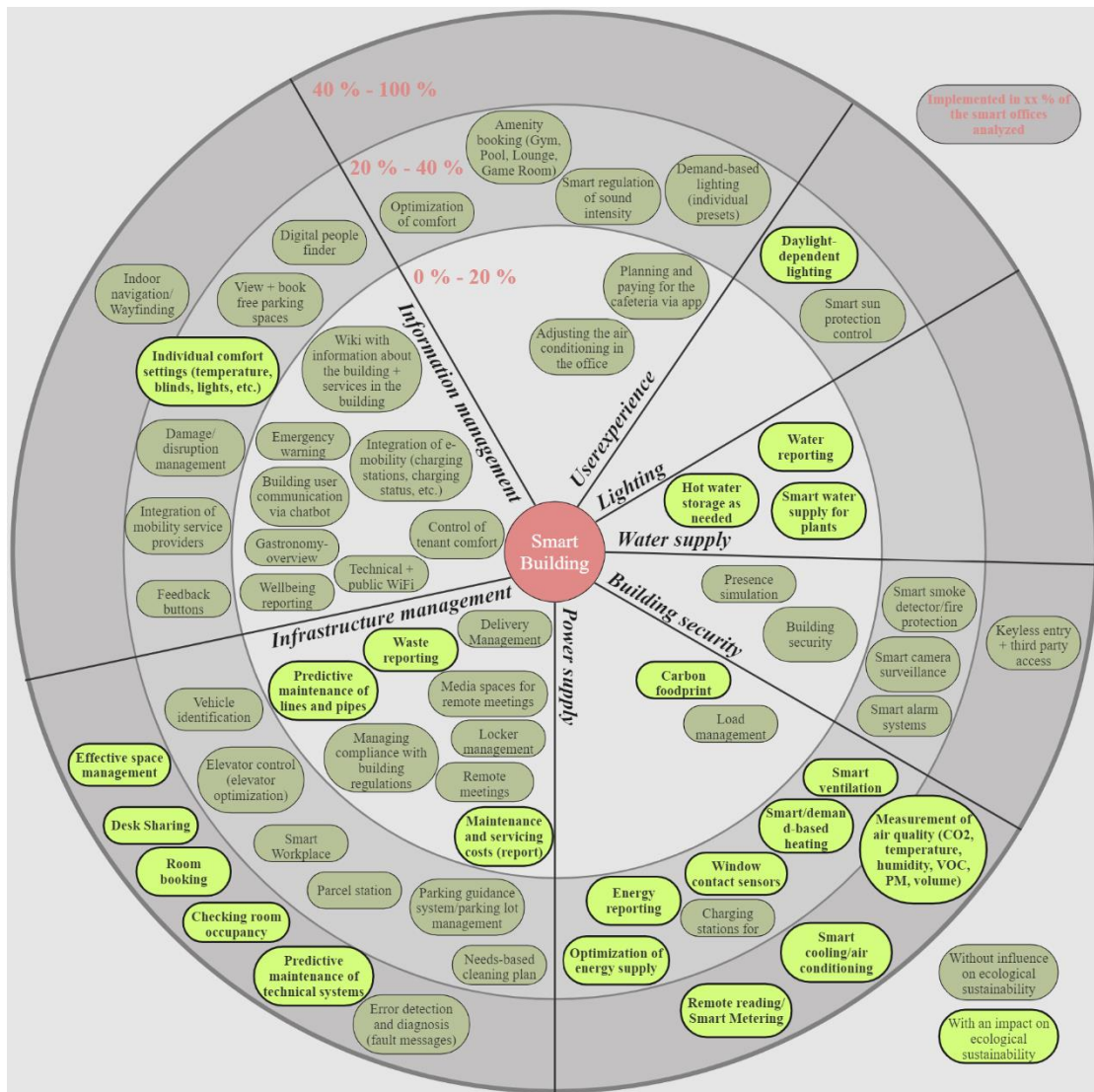


Figure 5: Illustration of the use cases of a smart building depending on the areas of application and illustration of the influence on environmental sustainability, as well as the frequency of use cases in realized smart buildings

Detailed expert interviews demonstrate that environmental sustainability is regularly not the primary objective of smart buildings but emerges as a by-product. Figure 6 the distribution of use cases impacting environmental sustainability, as well as their combinations with social and economic sustainability. Only 6 % of use cases exclusively impact environmental sustainability, while 61 % influence both environmental and economic sustainability. This dual impact is often due to the intention to operate buildings more cost-effectively, with reduced energy consumption correlating with improved ecological sustainability. Additionally, 33 % of use cases impact both social and environmental sustainability, reflecting the interconnected nature of these factors. This reiterates that the influence on ecological sustainability is typically a secondary outcome of smart building implementations.

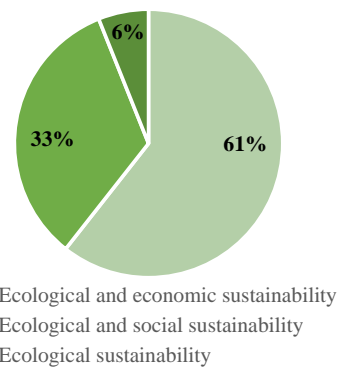


Figure 6: Percentage distribution of use cases with influence on the three pillars of sustainability

## Summary of the results and critical discussion

Based on the statements of the experts, 4 trends can be identified in which the use of smart buildings can lead to an optimization of ecological sustainability:

1. several experts confirm that the increase in mobile working that occurred during the Corona pandemic resulted in a high vacancy rate. This increased the importance of and interest in use cases that optimize the use of space, such as workplace booking or space management. This allows space savings to be achieved, which can reduce both grey energy and energy in operation, as space is used more optimally.
2. At the same time, these are aimed at environmental sustainability through side effects such as needs-based heating or air conditioning.
3. Sustainable management of buildings can also be achieved through the shared use of resources, such as meeting rooms, cars, workstations, etc.
4. an analysis of consumption values and the presence of people can contribute to optimized energy use (e.g., by reducing the use of space in the company).

Expert interviews reveal that smart building use cases can enhance environmental sustainability, but there is disagreement on whether smart functionalities are essential for sustainable construction and operation. Some argue that sustainable practices can be achieved through optimal design and material choices alone, while others emphasize the importance of needs-based regulation and suggest additional energy savings through sensor and hardware utilization. The following section provides detailed insights into these perspectives. The experts also assert that a building's operation can be made more ecologically sustainable through analyses and subsequent optimization of energy consumption or space utilization (Figure 7). This definition of the functionality levels can also be found in the definition of the SRI. However, insufficient information is available on the data basis for calculating these savings, with only one interviewee from the manufacturer group mentioning the starting point as the planned energy demand of the building. It is unanimously agreed among the experts that smart functionalities serve as optimizations rather than remedies for planning errors.

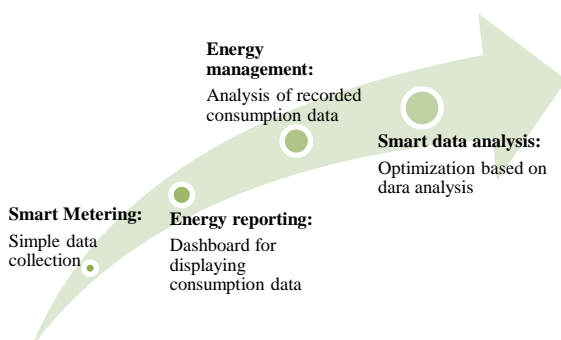


Figure 7: Exemplary optimization levels of the use cases

## Step 2: Analyzing limitations of the sustainable smart building due to data availability

This section summarizes expert assessments of the initial situation regarding data availability in the real estate sector. Afterwards, the data basis used by the experts in their own companies will be examined. Finally relevant building data from the study that can be used to measure and assess the environmental sustainability of a building is listed.

### Case Studies

6 % of the requested experts were able to provide data from their smart buildings. The remaining respondents referred to data protection or were unable to provide data for other reasons. The received data sets were incomplete or not meaningful. For two buildings, the data could only be provided monthly and for one building only annually. It was not possible to clearly identify the system boundaries to which the data refers. In addition, in three cases, information on the building was missing. Therefore, it was not possible to analyze the sustainable operation of an actually implemented smart building. As a result, the savings claimed by the experts cannot be validated. For this reason, data and their collection interval, which are necessary for the evaluation of the building operation, were identified and summarized in Table 1.

### Initial situation of the real estate sector regarding data availability according to the experts

A smart building requires the effective use of data stored in the cloud to promote environmental sustainability. It is necessary to capture data from the building management system, integrated use cases and the entire life cycle of the building. All data (e.g., building model, consumption data, attendance data, FM data, BMS data) from the building must be available over the entire life cycle in order to be able to derive optimization potential from the data. 20 % of experts emphasize that large FM companies often prioritize functionality and user well-being, while building sustainability is neglected. 50 % of manufacturer experts report impairments due to manual interventions in automated processes. Furthermore, two experts noted that the operators often do not have the necessary in-depth knowledge of all the processes and functions of the building and also do not have the capacity to operate a building in a technically professional manner. Another expert criticized the fact that the owners have no need to make the management of the building more sustainable, as the tenants bear the energy costs. Continuous optimization for sustainable operation moves into the background. Some owners have only shown an interest in sustainable building operation since the changes in the real estate industry, as tenants now bear the energy costs.

### Current data basis of the experts

Figure 8 shows the results of the expert interviews on the use of the data collected in smart buildings and highlights the data flows and losses. It was interrogated whether data on building operation is recorded and if this data is used

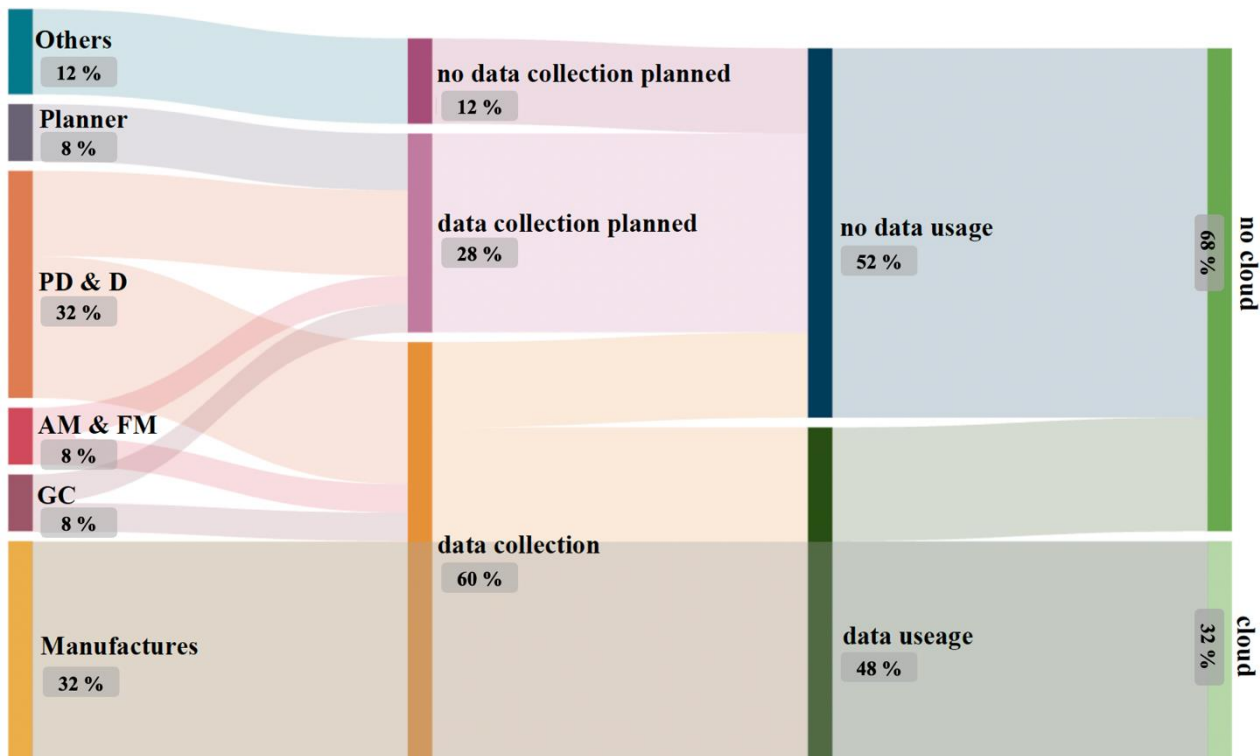


Figure 8: Illustration of the current data basis based on the expert interviews

for further purposes. The status of cloud solutions for data storage was also determined.

60 % of the companies surveyed collect building operating data (marked in orange), either directly by owners, FM or third-party providers. 28 % plan to collect data, while 12 % have no plans to do so.

Of the companies collecting data, 20 % do not use the data further and the storage locations are unclear. The remaining 80 % use the data for FM support, plant optimization or sustainable operational control. This corresponds to 48 % of all companies surveyed, with 75 % of these data-collecting companies being manufacturers. Only 62 % of the project developers and owners surveyed receive data from manufacturers, which is merged in PowerBI dashboards. A proprietary building operating system is rarely used. Over 50 % of experts do not use any building technology or energy-related data for optimization in their companies. Only 32 % of interviewed companies store data centrally in a cloud. However, they all belong to the group of manufacturers who sell the cloud as part of their portfolios. This means that it is not possible to draw any conclusions as to whether the relevant players (FM, building owners, etc.) use the data centrally for long-term analyses and evaluations of optimization scenarios.

#### Difficulties in data availability

The aim of this paper is to compile relevant data for the uniform assessment of smart buildings in terms of environmental sustainability. The following section presents the necessary data basis. In the validation phase following the interviews, only four companies provided data on their smart buildings, which was largely implausible and incomplete. Due to a lack of data quality, no conclusions

could be drawn about the operation and sustainability of the buildings. Data protection issues and concerns, particularly in relation to the General Data Protection Regulation (GDPR), also prevented 73 % of experts from releasing data. Works councils were against use cases that collect personal data, such as access controls, due to concerns about employees' privacy rights. The debate on data protection versus sustainability remains open. Two experts criticized the lack of availability of data for optimization and research purposes, while one manufacturer considered anonymized provision of customer data in the future but pointed to limited resources.

### Step 3: Definition of Relevant Data for assessing environmental sustainability

The results of the expert interviews and available data show the current problem in the building sector: data availability. Data is regularly not recorded and stored sufficiently over a long time by the building management system. Data failures go unnoticed and even existing data is not used optimally. A sufficient data basis is crucial so that the collected data can be automatically processed and made available to users, asset managers and other stakeholders in a clear and concise manner. Only in this way can the data be used for optimization and have a positive impact on environmental sustainability. The building management system often records various data over a period of time, including supply and return temperatures, control signals and status messages from technical components. This data can already indicate major errors in the regulation and control system.

To assess the sustainability of smart buildings, the experts listed implemented use cases and provided consumption

data for heating, cooling and electricity at quarter-hour intervals. The inclusion of occupancy data, such as the number and type of occupants, was considered crucial. The information requested included building area, type of use, number of employees, occupancy data, metering concepts, floor plans, heating/cooling systems, ventilation and sensor infrastructure. Based on these criteria, relevant data for the environmental sustainability analysis in smart buildings is compiled in Table 1.

Table 1: Data basis for the sustainability assessment of a smart building

Nature of the data	Description
<b>Energy consumption data (heating, cooling and electricity) of the building</b>	
Consumption data for the entire building, individual parts of the building or rental sections - General, technical and tenant electricity - Heating/cooling consumption of the respective rental areas, if applicable meeting and conference rooms recorded individually	Ideally, consumption data should be recorded on a quarter-hourly basis and broken down into individual building sections. Smaller-scale recording enables more precise monitoring and must be selected according to the type of use of the building. [kWh]
Emission factor of the respective energies	CO <sub>2</sub> -equivalent data for different energy sources according to the Law on Energy Efficiency. To compare the type of energy supplier in different buildings. [gCO <sub>2</sub> e/kWh]
Outdoor temperature	To classify the amount of energy consumed. Ideally every 15 minutes for consumption [°C]
<b>Planning documents</b>	
Average demand of Energy	Comparative value for checking the operation. This must not be exceeded. [kWh/m <sup>2</sup> a]
Building area or individual rental space	For consumption data of individual sections, in each case with details of the gross floor area. Allocation and comparison of the different areas. [m <sup>2</sup> ]
Type of use	List of the types of use in the building (office, canteen, daycare center, fitness studio, etc.). Relevant for assessing the energy consumption of the smart building as such. As well as for the comparison of other smart buildings by type of use.
Heating and cooling generation systems, air conditioning systems	Information on the type and output of the systems. To classify the energy requirement depending on the respective energy source. As well as for checking the control behavior. [e.g. kW]
<b>Building automation and smart building</b>	
Data points of the different systems	Type and number of data points of the technical building systems installed in the building
Individual room control	Zone size incl. number and type of connected data points
Fault message forwarding	Information on the process chain in the event of a fault message from a system or system component. Not directly for comparison or evaluation of ecological sustainability, but decisive for optimization potential of the systems.
Metering concept	Necessary for the allocation of consumption data.
List of implemented use cases	Incl. description, for assessment of smartization.

Data storage	Information on the duration of data storage and storage location to ensure data availability for the analysis of the building.
Sensor infrastructure	Type and number of sensors or concepts regarding the installed sensors (brightness, occupancy, temperature, air quality such as CO <sub>2</sub> , Bluetooth beacons), to assess smartization.
<b>Operation</b>	
Occupancy data	Information on m <sup>2</sup> per person, as well as time-related information on the use of the building area. Is required to assess the energy consumption. [m <sup>2</sup> /n; n/h]
Number of employees	For comparison with other smart buildings [n]
Evaluation of the use cases	Evaluation of the frequency of use of different use cases. To identify the optimization potential regarding the use of the building's Smartness.

The identified essential data for evaluating building operation provides a basis for analyzing smart buildings in terms of their sustainability. This database must be validated in further studies.

## Conclusion and recommendations for action

The analysis relies on the standardized definition of a smart building established in this paper across different building types. The clustering of use cases serves as a common foundation for assessing potential impacts on environmental, economic, and social sustainability. Currently, ecological sustainability is often considered a by-product of improved economic or social sustainability. To enhance ecological sustainability, more dedicated ecological use cases need implementation. It's important to note that technological advancements may introduce new use cases for smart buildings.

However, the analysis reveals the incompleteness and poor traceability of provided data, particularly concerning energy consumption. Technical and data protection reasons hindered obtaining further information on data classification, occupancy figures, outdoor temperatures, or measurement concepts, rendering the database unreliable. Consequently, results were supplemented with expert interviews, and strategies for future data collection were developed.

The study's limitations include the exclusive use of smart offices from Central Europe and a lack of representation from companies outside Europe. Additionally, the short lifespan of the smart buildings studied suggests that operators may lack a holistic understanding of building functions and processes. The study does not address the embodied carbon of components like sensors, actuators, and cables, posing a need for comprehensive assessments. The study highlights potential for further investigations, particularly regarding the embodied carbon of data storage throughout a building's life cycle.

The identified essential data for evaluating building operation provides a basis for analyzing smart buildings in terms of their sustainability. To validate the defined data basis, real buildings must be monitored over an extended period. Potential increase in CO<sub>2</sub> emissions from additional hardware and data storage should be considered. A comparison with similar buildings lacking smart implementations can provide valuable insights.

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