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Sociotechnical design of building energy management systems in the public sector: Five design principles ☆

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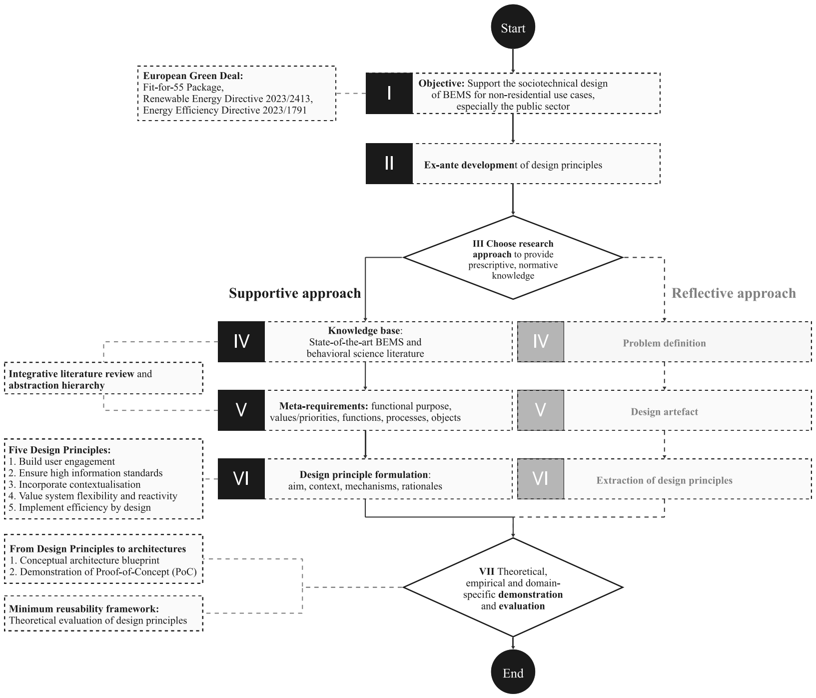
GRAPHICAL ABSTRACT



Own figure based on Design Principle Development Framework according to Möller et al. [1]

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ABSTRACT

Advocacy for energy efficiency solutions in non-residential buildings, particularly within the public sector, is part of the response to the climate crisis by the European Union (EU). Traditional building energy management systems (BEMS) focus primarily on technological advancements but often overlook the influence of occupant

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Design principles
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behaviour on energy consumption. This study develops a set of five design principles aimed at bridging this sociotechnical gap by integrating behavioural strategies with technical solutions. Following a design principle (DP) development framework, informed by an integrative literature review and the abstraction hierarchy (AH) method, the study proposes actionable guidelines for designing BEMS architectures. With the aim of supporting future BEMS blueprints, a conceptual architecture is created based on the design principles. A BEMS proof-of-concept (PoC) demonstrates how to apply the design principles and the architecture to potentially optimise the use of renewable energy sources in a public sector building. The minimum reusability evaluation framework is employed to evaluate the proposed principles theoretically. The novelty of this work lies in its interdisciplinary approach, which goes beyond previous studies by offering normative guidance that balances both technology and human factors. These findings suggest that a sociotechnical approach to BEMS design can significantly enhance energy efficiency, offering valuable insights for stakeholders, such as system designers and energy managers. Future research should focus on real-world implementation and empirical validation of the proposed principles.

1. Introduction

The European Union (EU) continues to increase its advocacy for greater energy efficiency and strategies to mitigate the adverse effects of climate change. This is part of its broader promotion of a clean energy transition [1]. Technological [2] and regulatory [3] initiatives have been developed to promote efficient energy practices and other measures designed to reduce carbon emissions.

The intermittent nature of renewable energy (RE) generation and green energy legislative targets (exemplified by the European Commission's 2050 targets [4–6]) highlight the need for innovative solutions [7]. These solutions should include the integration of renewable energy sources (RES) into the EU's energy mix [8] with a view to increasing energy efficiency and flexibility [9]. Regulatory frameworks, like the Energy Efficiency Directive 2023/1791, spotlight the public sector's pivotal role in driving the EU's transition to using RE. As part of the EU member states' obligation to participate in the clean energy transition, the Energy Efficiency Directive puts particular emphasis on the need for public sector buildings to act as role models of energy efficiency [10].

Technologies like building energy management systems (BEMS) are at the forefront of these efforts. Traditional BEMS strategies focus primarily on technological enhancements, such as predictive control strategies and the internet of things (IoT) [2]. These use sensors and optimisation tools to predict and manage energy consumption efficiently [11]. Such BEMS often overlook the role played by changing consumer behaviour in contributing to energy efficiency and flexibility goals [12]. There is growing evidence that behavioural strategies implemented alongside technological advancements contribute to the effectiveness of BEMS [13].

Incorporating human behaviour into the design of BEMS requires a comprehensive framework that addresses this sociotechnical challenge. Consideration should be given to the technical components, economic factors, and human-centred considerations, such as information asymmetries and technology acceptance [14]. It is acknowledged that user engagement in energy efficiency and flexibility initiatives has practical relevance [15]. Nevertheless, there is a lack of normative guidance regarding the alignment of technology and behavioural strategies with a view to creating positive synergies. The following two research questions were formulated to address this gap:

- **RQ1**: What normative guidance can support non-residential BEMS designers as they seek to enhance energy efficiency through the optimal use and balance of technical advancements and behaviour-influencing strategies?
- **RQ2**: How can system designers apply this normative guidance to blueprint and implement BEMS architectures?

To address the first of these questions, this paper proposes five design principles (DPs) for BEMS. These offer actionable insights to guide system designers, technology developers, and energy managers. This study contributes to the growing interdisciplinary literature on sustainable[2] energy management, by bridging the gap between theoretical research and practical application.

While this study offers valuable normative guidance for sociotechnical BEMS, it is important to note a few limitations. The proposed design principles DPs have not yet been implemented in real-world BEMS scenarios. The effectiveness of suggested mechanisms may vary depending on factors such as organisational culture, technological maturity, and regulatory environment. Practical implementation and empirical validation in diverse settings are needed.

To reflect the interdisciplinary complexity at the intersection of Information System (IS), energy research and behavioural science, this paper is structured as follows. Firstly, the concept of BEMS is introduced and related work is presented. To outline the fundamental motivation of this paper the relevant European policy landscape is also summarised in this section (see Section 2). This is followed by Section 3, where the methodological framework for deriving and formulating DPs for BEMS is outlined. The framework is based on two main pillars: the method of Möller et al. [17] for design principles development and the abstraction hierarchy (AH), a method that originates from the cognitive work analysis (CWA) [18]. Afterwards, a set of DPs for non-residential BEMS is proposed in Section 4.

To answer research question two, in Section 5 the paper illustrates how a conceptual architecture can be derived from the proposed design principles. This is followed by a demonstration of the DPs by applying them in a public sector context for a Sustainable Energy Scheduler proof-of-concept (PoC) [19] in Section 6. This section provides a practical example of how the DPs can contribute to real-world use cases, especially when used in a public sector context. The DPs are evaluated using the minimum reusability evaluation framework, according to Iivari et al. [20]. In Section 8, conclusions are drawn for the proposed BEMS DPs, limitations are recognised, and perspectives for future work are highlighted.

2. Related work and motivation

2.1. Building energy management systems (BEMS) and behavioural science

BEMS are studied widely [21], and are a crucial element in ensuring that Europe's buildings are equipped to contribute to the development of a clean energy future. The central aim of a BEMS is to improve the energy efficiency of buildings, without negatively impacting occupants' comfort [21]. The Energy Transition Expertise Centre (EnTEC)

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[2] The UN defines sustainability as meeting the "needs of the present without compromising the ability of future generations to meet their own needs" [16]. For the purposes of this paper, this means minimising resource waste and CO_2 emissions in energy use. Additionally, we use the Cambridge Dictionary definition: sustainability is described as "the ability to continue at a particular level for a period of time". This underscores the purpose of the BEMS designed according to DPs to create a long-lasting sustainability impact, while being easy to adopt by all building occupants and stakeholders.

defines BEMS as computerised architectures that consist of units which monitor and control the physical infrastructure of a building [22]. This classical engineering definition is predominant in the literature [21], highlighting a traditional perspective towards understanding the nature of BEMS.

There are many examples of how BEMS contribute to energy efficiency. Related studies often focus on a building's heating, ventilation, and air conditioning control (HVAC) system, as thermal energy consumption constitutes the primary source of a building's energy demand [23].

For example, Tien et al. [24] demonstrate technological advancements in a university building case study. They noted that vision-based deep learning frameworks can be used to monitor the activities of a building's occupants. An example is how the manual operation of windows can be monitored in real-time with the heating, ventilation, and air conditioning control (HVAC) system being informed. Frahm et al. [25] further elaborate on the economic optimisation potential of HVAC systems in their simulation-based work. They demonstrate that system designers can achieve better outcomes by considering novel occupant-centric multi-zone price storage control (PSC) and model predictive control (MPC) strategies, rather than traditional control strategies (such as simplified price control (PC), which focuses solely on the energy price as the control variable). Yang et al. [26] investigate a machine-learning-enabled predictive building model for controlling the air-conditioning and ventilation systems in university offices and a lecture theatre. Compared to the original BEMS proportional–integral–derivative (PID) control strategy, the machine-learning-enabled control system reduces cooling thermal energy consumption by 58.5% and 36.7% in the offices and lecture theatre respectively.

Chen and You [27] also use a machine-learning model predictive control framework for BEMS for renewable energies. This allows for compensation to be made for weather forecast errors in standard model predictive control frameworks. Zhuang et al. [28] present a data-driven predictive control approach for internet of things (IoT)-enabled HVAC systems using time-series forecasting and reinforcement learning. This led to improved HVAC operations with energy conservation of up to 17.4% and an increase in occupant comfort of 16.9%. In another simulation study, Silvestri et al. [29] investigated the potential of deep reinforcement learning (DRL) compared to conventional rule-based controllers. In this two-month building trial, their findings show that DRL leads to improved thermal control of the building, enhancing both energy efficiency and occupant comfort. Another example is provided by Ye et al. [30], who evaluate the energy-saving potential of presence-based and counting-based occupant-centric control schemes for HVAC systems in primary schools. Their study demonstrates conservation effects of up to 12.4%.

In addition to novel control strategies enabled through predictive analytics and machine-learning for BEMS, technological advances at the appliance-level are also investigated. For example, Pang et al. [31] quantify (in their nationwide simulation of households in the United States) the energy conservation potential of HVAC systems if equipped with smart home thermostats. Their results indicate the possibility of conserving up to 30% of thermal energy across different household types. Similarly, Wang et al. [32] adopt an appliance-based perspective, and propose an indoor stereo-camera-based occupancy monitoring system for a fresh air management system in public spaces. They demonstrate energy conservation effects of up to 67% through precise occupancy monitoring in a set of use case scenarios. While such studies exemplify the potential of BEMS in a specific context, other studies provide prescriptive knowledge on the general design of such systems.

For example, Körner et al. [33] develop a conceptual architecture and DPs to guide the design of advanced BEMS. These incorporate precise emission management and data-driven measures for buildings. Bartolucci et al. [34] introduce a design methodology for selecting optimal energy management strategies for multi-energy systems for each building. This results in lower system cost and higher emission efficiency. Cremi et al. [35] present a design methodology for a decision-support tool aimed at retrofitting commercial buildings. This tool identifies the most suitable technological options to optimise BEMS strategies, taking account of local policy requirements and potential for cost-efficiencies. Using this methodology in a commercial-building case-study in Italy resulted in cost and emission savings of up to 20% and 35% respectively. Zhao et al. [36] propose a data-driven energy management framework that facilitates the modelling of a building's thermal system. It takes account of both energy conservation and occupant thermal comfort to achieve optimal HVAC operations.

Beyond this engineering perspective, more studies are identified that refer to BEMS within a broader scope. Mariano-Hernández et al. [23] define BEMS (based on Bonilla et al. [37]) as a set of techniques to optimise energy efficiency in buildings. This includes targeting two different energy management methods: an active and passive approach to BEMS. The active BEMS is concerned with actively managing the building by applying rule- and optimisation-based techniques, leveraging sensor, controller and actuator infrastructure. The passive BEMS includes complementary behavioural strategies to raise end-users' awareness of their energy use, and to promote behaviour that would favour energy conservation [23].

The majority of studies focus on the application of complementary behavioural measures in the design of residential BEMS use cases [23]. Despite the residential focus, some behavioural strategies are also applied in non-residential environments to account for human factors. This paves the way for implementing combined passive and active BEMS strategies in public and commercial sectors.

An example is provided by Papaioannou et al. [38] who present an IoT-enabled BEMS enhanced by a gamification strategy to alter user behaviour to reduce energy waste in public buildings. This is also illustrated by Rafsanjani et al. [39] who introduce an IoT-based smartphone application that provides personalised energy feedback to occupants of a commercial building. The result of a twelve-week experiment is an average energy conservation effect of 34%.

The integration of BEMS and behavioural studies can create a synergistic effect, maximising energy savings and efficiency, while promoting lasting behavioural change. Jiang et al. [40] proposed a novel multi-agent BEMS. This system interacts with both occupants and the HVAC system to balance thermal comfort and energy demand, overcoming the limitations of traditional pre-set temperature control methods. In simulated environments, the multi-agent BEMS achieved energy savings of 3.5%–10% compared to conventional systems. Another example of this integration is the BizWatts system, introduced by Gulbinas et al. [41]. By providing network-level eco-feedback, BizWatts motivated commercial building occupants to reduce their energy consumption. The system also collected extensive data on user interactions, which can be used to improve interface design and enhance user engagement. Such integrated systems not only optimise energy management but also empower occupants to adopt energy conservation behaviour. Varlamis et al. [42] discuss in detail the advantages of sensors and actuators in BEMS for monitoring and consumer empowerment in universities. They emphasise the untapped potential of using sensor data to gain insights into occupant behaviour patterns, enabling the provision of personalised feedback and recommendations at the optimal time and in the appropriate format.

Further studies outside of dedicated BEMS research describe the potential of behavioural measures for energy efficiency purposes in non-residential buildings. Improving occupant behaviour can lead to substantial energy savings. But this must be implemented without compromising comfort. Amasyali and El-Gohary [43] proposed a data-driven method to assess the potential for achieving occupant-behaviour changes that would simultaneously reduce energy consumption and enhance comfort. This method includes machine learning models sensitive to occupant behaviour for predicting energy consumption and comfort, along with a genetic algorithm for optimisation. The experimental results showed potential energy savings in the range of 11%–22%, and significant improvements in occupant comfort. Another study, conducted by Gómez et al. [44] had a seven-year time horizon, between 2013 and 2019. It split a cohort of 2500 government workers into a control group and two treatment groups, with the latter subjected to inter-group competition and positive peer pressure. The study found that both mechanisms effectively promoted pro-environmental behaviour, thus providing a nuanced comparison of their differential impacts on behavioural change.

Behavioural interventions must be designed carefully, taking account of the context. Nilsson et al. [45] tested two behavioural intervention programmes designed to change energy-related behaviours in an office setting. Ninety-three office employees in a construction company were randomly assigned to one of three conditions: control, intervention programme, or intervention programme with group identity salience. The interventions included the provision of goal-setting, feedback, information, and behavioural prompts, with one condition designed to manipulate group-identity. Subjects assigned to experimental groups perceived that they changed their behaviours to a greater extent than the control group. Strikingly, energy consumption efficiency promotion measures led to a decrease within all three groups. This latter finding suggests that other factors may also contribute to the generation of energy efficiency savings.

Gamification and delivery of personalised feedback are additional strategies that can complement BEMS and behavioural interventions. Ruggiu et al. [46] highlighted the potential of gamification to improve organisational efficiency and productivity, though they also noted concerns about subjects' privacy and autonomy. Implementing privacy by design can address these concerns, thus supporting responsible innovation. Furthermore, Coleman et al. [47] explored the feasibility of the in-office delivery of personalised feedback about energy conservation. While personalised feedback raised awareness and increased energy-saving identification opportunities, the study noted that significant effort is required to produce such feedback.

The complementary advanced BEMS with behavioural interventions (such as gamification, personalised feedback, and optimised load shifting) is a comprehensive approach to energy conservation in non-residential buildings. These strategies can improve energy efficiency and also foster lasting behavioural changes that empower occupants to proactively contribute to increasing sustainability. The literature highlights that measures to induce behavioural change are not just an alternative means for fulfilling energy efficiency endeavours in buildings. They are also worth considering as a complementary measure for the design of residential and non-residential BEMS. This contributes to changes in the perception of BEMS, from these being mainly a classical technology concept to them being also a sociotechnical information system. While technical frameworks for blueprinting BEMS are addressed extensively, there is a lack of sociotechnical BEMS design guidance that aligns technical advancements with behavioural strategies [33].

2.2. European policy and the public sector as a role model

The 2020 EGD seeks to transform Europe into the first net-zero continent by 2050. One central energy-related principle of the EGD is that transition towards sustainability can be influenced by emphasising efficiency efforts in general, particularly in the buildings sector, and by progressing towards an energy system based on renewables. This is embodied by different EGD objectives, such as building interconnected energy systems and actively promoting sustainable empowerment of consumers [12]. The objective realisation of the EGD is targeted within the Fit-for-55 (FF55) policy package, a set of path-building actions designed to reduce greenhouse gas emissions by 55% by 2030. For the energy-related context of the EGD, the Fit-for-55 (FF55) package includes the revised RED 2023/2413 from November 2023, which states the goal of increasing the RE share in consumption to at least 40% by 2030. It also includes the revised EED 2023/1791 from October 2023, accentuating the Member States' obligation to improve energy performance in various contexts, including the public sector. This paper focuses on the targets and implications of the directives for the public building sector. This is particularly relevant considering that the public sector accounts for up to 10% of the Union's final energy consumption [9], and that 40% of European energy consumption and 36% of greenhouse gas production in the EU is due to the construction, use, renovation and demolition of buildings [48]. Three key subject areas were taken from the above-mentioned energy-related principle of the EGD [12]. These key subject areas are: buildings; energy efficiency; and RE. They were used to screen the identified directives (RED, EED) for implications for the public sector (see Fig. 1).

From the RED, one central implication is the complementary use of monetary and non-monetary incentives to promote sustainable energy demand patterns holistically across domains. An additional implication refers to the effort to digitise demand, linking final energy consumption with the actual availability of RE. The second implication emphasises, in particular, the need for well-designed BEMS. These implications are valid not just for the public and other non-residential sectors, but also for private households. They emphasise the role of BEMS to align consumption and RE availability.

Complementary to the RED is the EED, which underscores the importance of consumer behaviour. It promotes dynamic demand side instruments and measures for behavioural change. This adds further impetus to awareness that energy efficiency and flexibility (such as the renovation of buildings) are alternatives to technological and process-related strategies. The EED notes the potential exemplary role of the public sector as one aspect of how policy makers can consider technological options for working towards a net-zero continent. The directive also mentions the need to adopt holistic approaches, as well as purpose-built digital tools which can be implemented in a transparent fashion. Article 43 highlights active BEMS with automation and control aspects, mainly to implement energy efficiency in buildings. Since the public sector in particular must renovate buildings to reach energy savings of up to 3%, the pivotal role of BEMS becomes apparent for renovation and retrofitting activities [22].

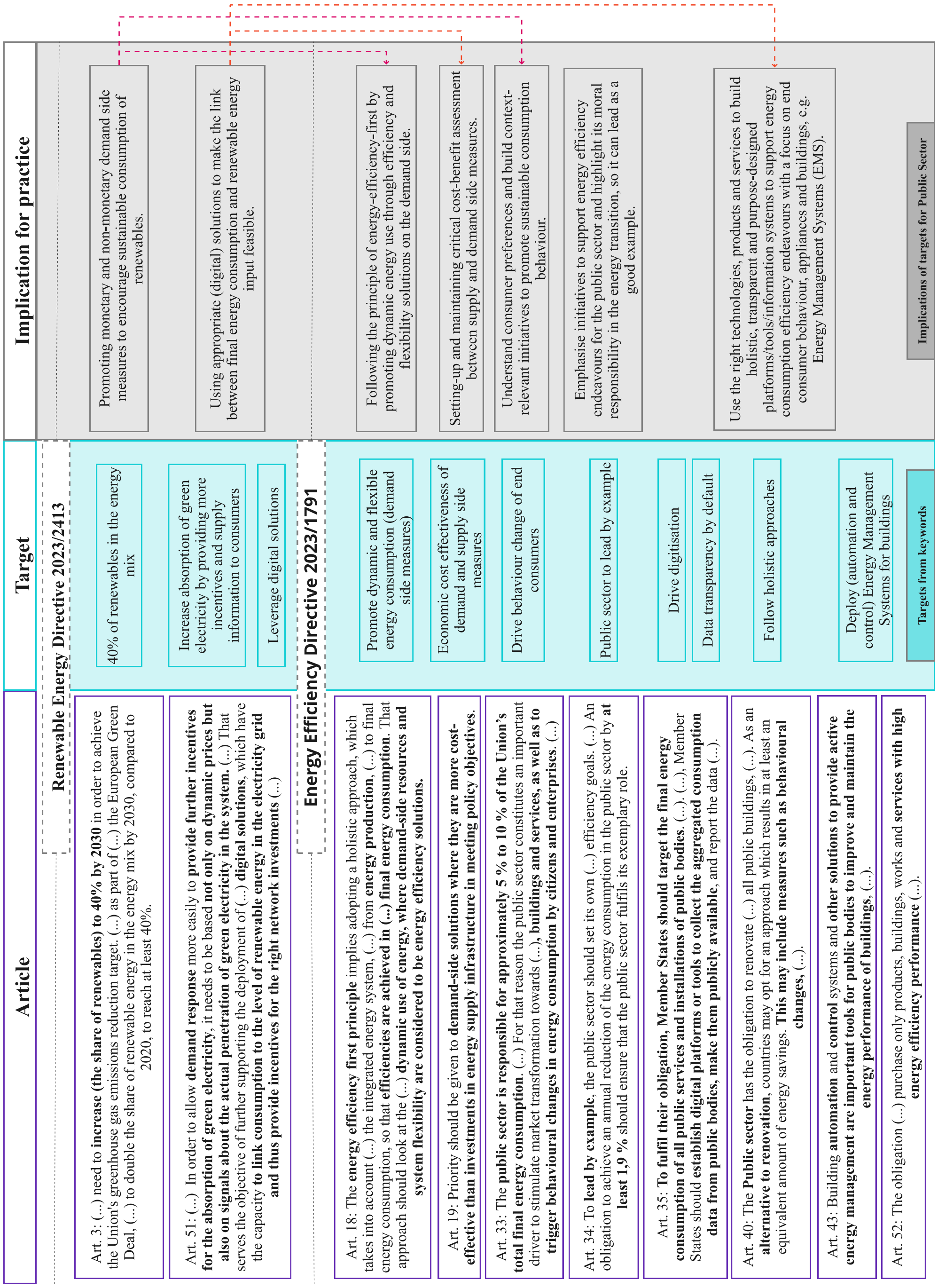
Even though each Member State is responsible for transposing the European directives into national law, the EGD, RED, and EED underscore the trend towards adopting behavioural-economics approaches in policy design in recent decades [49]. There is particular emphasis on the importance of taking account of the sociotechnical potential of BEMS.

3. Methodological framework

In this section, the methodological framework to derive DPs for the sociotechnical design of BEMS is described. In 3.1, a supportive approach towards DP development based on Möller et al. [17] is introduced. In 3.2, the cognitive work analysis (CWA), a framework for analysing complex sociotechnical domains, is described [18]. The abstraction hierarchy (AH), a specific analysis method of the CWA, is subsequently presented in 3.3 as a tool for deriving requirements and constraints for BEMS in the non-residential domain. The AH is then merged with the principle formulation framework by Gregor et al. [50], as described in 3.4 to distil clearly formulated DPs from the abstraction process.

3.1. Derivation of design principles

The method for DP development proposed by Möller et al. [17] was followed. It consists of a structured process of seven steps, as illustrated in Fig. 2. This method has been used to formulate DPs for comparable use cases like citizen-centric green Information System (IS) [51] and for distributed autonomous systems [52].



Article	Target	Implication for practice
Renewable Energy Directive 2023/2413		
Art. 3: (...) need to **increase (the share of renewables) to 40% by 2030** in order to achieve the Union's greenhouse gas emissions reduction target. (...) as part of (...) the European Green Deal, (...) to double the share of renewable energy in the energy mix by 2030, compared to 2020, to reach at least 40%.	40% of renewables in the energy mix	Promoting monetary and non-monetary demand side measures to encourage sustainable consumption of renewables.
Art. 51: (...) In order to allow **demand response** more easily to **provide further incentives for the absorption of green electricity**, it needs to be based **not only on dynamic prices but also on signals about the actual penetration of green electricity in the system.** (...) That serves the objective of further supporting the deployment of (...) **digital solutions**, which have the capacity **to link consumption to the level of renewable energy in the electricity grid and thus provide incentives for the right network investments** (...)	Increase absorption of green electricity by providing more incentives and supply information to consumers Leverage digital solutions	Using appropriate (digital) solutions to make the link between final energy consumption and renewable energy input feasible.
Energy Efficiency Directive 2023/1791		
Art. 18: The **energy efficiency first principle** implies adopting a holistic approach, which takes into account (...) the integrated energy system, (...) from **energy production**, (...) to final energy consumption, so that **efficiencies are achieved in (...) final energy consumption**. That approach should look at the (...) **dynamic use of energy, where demand-side resources and system flexibility are considered to be energy efficiency solutions.**	Promote dynamic and flexible energy consumption (demand side measures)	Following the principle of energy-efficiency-first by promoting dynamic energy use through efficiency and flexibility solutions on the demand side.
Art. 19: Priority should be given to **demand-side solutions where they are more cost-effective than investments in energy supply infrastructure in meeting policy objectives.**	Economic cost effectiveness of demand and supply side measures	Setting-up and maintaining critical cost-benefit assessment between supply and demand side measures.
Art. 33: The **public sector is responsible for approximately 5 % to 10 % of the Union's total final energy consumption**. (...) For that reason the public sector constitutes an important driver to stimulate market transformation towards (...), **buildings and services, as well as to trigger behavioural changes in energy consumption by citizens and enterprises**. (...)	Drive behaviour change of end consumers	Understand consumer preferences and build context-relevant initiatives to promote sustainable consumption behaviour.
Art. 34: To **lead by example**, the public sector should set its own (...) efficiency goals. (...) An obligation to achieve an annual reduction of the energy consumption in the public sector by **at least 1,9 %** should ensure that the public sector fulfils its exemplary role.	Public sector to lead by example	Emphasise initiatives to support energy efficiency endeavours for the public sector and highlight its moral responsibility in the energy transition, so it can lead as a good example.
Art. 35: **To fulfil their obligation, Member States should target the final energy consumption of all public services and installations of public bodies.** (...). (...), Member States should **establish digital platforms or tools to collect the aggregated consumption data from public bodies, make them publicly available**, and report the data (...).	Drive digitisation Data transparency by default	Use the right technologies, products and services to build holistic, transparent and purpose-designed platforms/tools/information systems to support energy consumption efficiency endeavours with a focus on end consumer behaviour, appliances and buildings, e.g. Energy Management Systems (EMS).
Art. 40: The **Public sector** has the obligation to renovate (...) all public buildings, (...). As an **alternative to renovation**, countries may opt for an approach which results in at least an equivalent amount of energy savings. **This may include measures such as behavioural changes**, (...).	Follow holistic approaches	
Art. 43: Building **automation** and **control** systems and **other solutions to provide active energy management are important tools for public bodies to improve and maintain the energy performance of buildings**, (...).	Deploy (automation and control) Energy Management Systems for buildings	
Art. 52: The obligation (...) purchase only products, buildings, works and **services with high energy efficiency performance** (...).		
	Targets from keywords	**Implications of targets for Public Sector**

Fig. 1. Own figure: European Policy Implications based on EGD, EED and RED.

The first step of the DP development method consists of formulating the solution objective, that is, the purpose of the DPs. In this work case, the objective is to guide the design of comprehensive BEMS, which considers advances in technology and consumer engagement strategies to pursue the policy objectives of the EGD concerning the public sector. In the second step, the research context is established by discerning whether the DPs form an integral part of a broader research process, or serve as the study's primary outcome. Since the latter holds, the DPs proposed are the centrepiece of this paper.

The third step involves deciding between a supportive or reflective research approach. In the supportive approach, DPs provide advanced knowledge to help design a BEMS before starting the design process. These principles are derived from various sources such as literature, core theories, case studies, and expert interviews. Conversely, the reflective approach entails reflecting on design actions already taken, extracting abstract DPs from these actions. The supportive approach is chosen as the DPs are intended to provide design knowledge to support the creation of a BEMS before its inception.

The fourth step consists of defining the knowledge base. It encompasses theoretical frameworks, literature, empirical data, and other sources relevant to understanding and deriving meta-requirements for DPs. The knowledge base comprises relevant European policies, sociotechnical literature on human behaviour and BEMS, and IS and behavioural theories.

As a fifth step, meta-requirements need to be determined before the functional system requirements can be identified. They are crucial in directing DPs towards the broader goals and standards for creating a sustainable BEMS. In this research, the meta-requirements were

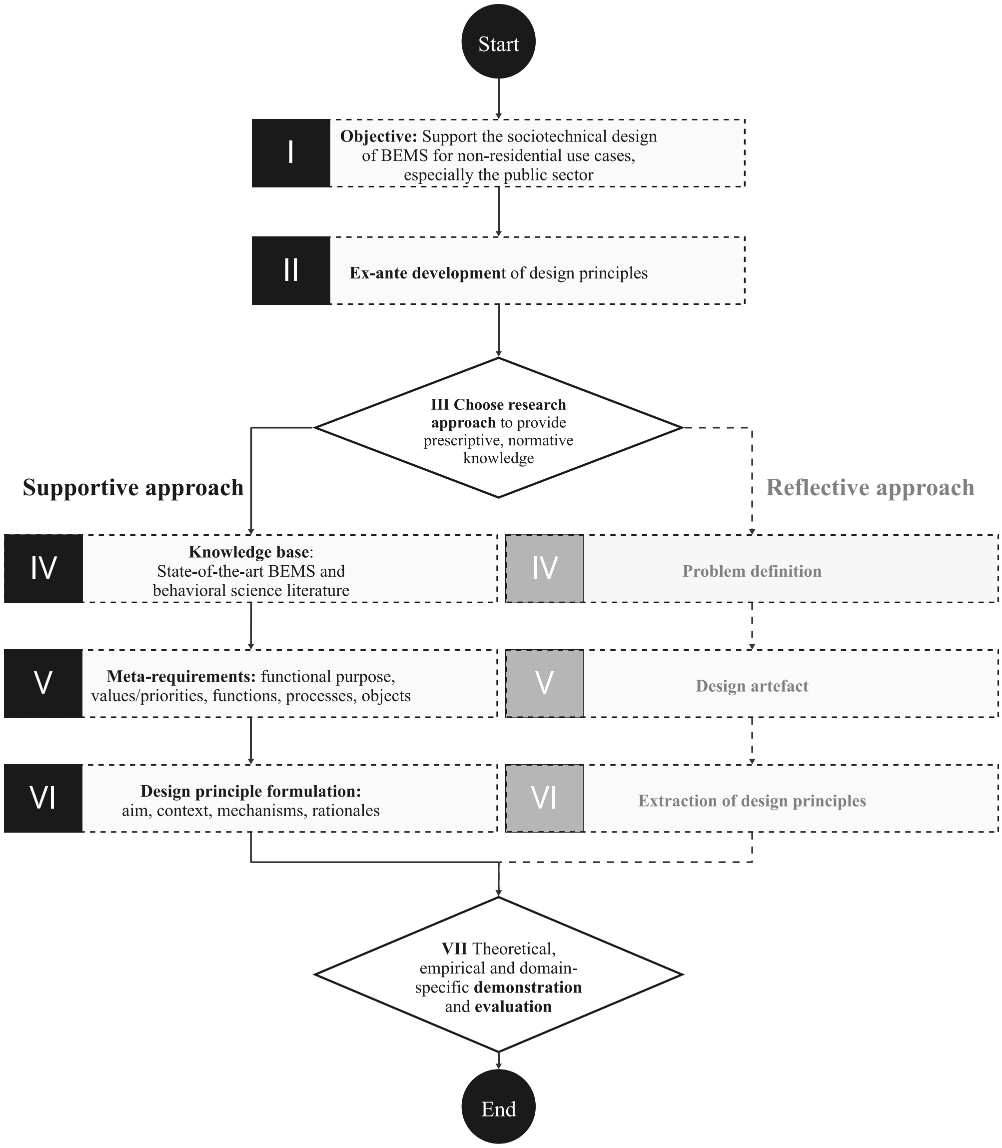


Fig. 2. Supportive design principle derivation framework adapted figure from Möller et al. [17].

identified through an integrative literature review. An integrative literature review aims to overview, critique, and potentially generate new theoretical knowledge on a topic [53]. This follows the methodology proposed by Torraco [54] as the guiding framework. Relevant literature was identified in the database SCOPUS by using the following keywords string: "("non-residential building" *AND* "energy consumption") *AND* ("energy conservation" *OR* "energy efficiency" *OR* "demand response" *OR* "energy management system" *OR* "renewable energy" *OR* "sustainability" *OR* "public sector")". Afterwards, a backward/forward literature search was conducted to identify further relevant literature. Then, the literature was coded individually. Subsequently, the created codes were merged independently and pooled into a standardised database through consensus agreement. An exploratory analysis was used to identify and map the information within the AH (see 3.3).

In the sixth step, the DPs are formulated by using the meta-requirements (see 4), which are organised in the AH. Building on this foundation, the elements that can be grouped together are carefully examined to ensure they are coherent and aligned with the overarching goals.

In the seventh and final stage, the DPs are evaluated. Through a series of internal workshops, a minimum reusability evaluation [20] was conducted (see 7). The framework ensures that the DPs are prescriptive, have practical relevance, and exhibit a level of generalisability. This means they suggest a precise particular action for blueprinting a BEMS by formalising design knowledge (as demonstrated in 5 and 6). They can be applied to a broad set of BEMS use cases, rather than being limited to a specific instance.

3.2. *Cognitive work analysis (CWA)*

Understanding that the European policy framework and insights from diverse BEMS studies puts substantial emphasis on developing sociotechnical measures to support Europe's green energy transition, the cognitive work analysis (CWA) was identified as a suitable framework for this paper. Rasmussen et al. [18] developed and introduced the CWA as a conceptual user-centric framework to support the design of sociotechnical information systems taking account of the complexity of cognitive activities and human attributes [18].

Rasmussen et al. [18] focus on the idea that the suitability and feasibility of an information system are subject to the system's design, factoring in the mental workload a user faces in a specific context. If it is known that when the mental workload is high, information

Table 1
Cognitive work analysis: Dimension and common approaches based on Burns [55].

Dimension	Common analysis approach
Work domain	Abstraction hierarchy
Tasks/activities	Control task analysis, decisional ladder
Strategies	Strategy Analysis
(Social) Organisation and cooperation	Functionality analysis, interaction analysis, social cooperation and organisation analysis
User resources, limits & values	

systems might relieve the cognitive burden if it is designed carefully, particularly by linking system attributes with human factors [55]. Results of the CWA are constraints that guide the design of the information system. These constraints are derived by analysing influential dimensions within a context. Dimensions of the analysis are defined as the work domain, the tasks or activities conducted, the strategies available, the (social) organisation and cooperation setting, as well as the individual user dimension focusing on constraints that result from human behaviour, mental resources, and preferences [56].

In the process of conducting a CWA, system designers apply different analysis approaches for each dimension (see Table 1). The exact analysis approach used per dimension can vary depending on the context and feasibility [55].

Despite the theoretical value of CWA, significant practical hurdles make it difficult to analyse all recommended dimensions. Hilliard and Jamieson [57] state (in their novel approach to using CWA to (re-)design energy efficiency monitoring and targeting systems (MTS) in companies) that some phases of the CWA are more useful than others. They state that some dimensions blur into one other, and that applying analysis in some of the dimensions of CWA is a very complex task due to the need to balance abstraction and granularity. The study highlights that these challenges depend on the context and inherent complexity of the environment [57].

Even though applying the CWA can be challenging, it has been applied several times over recent decades to design information systems approaches in a set of diverse use cases, *i.e.* enterprise social network technologies [58], safety in passenger transportation and vehicle occupancy optimisation [59], railway safety [60], mining operations [61], para-sports [62], sustainable emergency system development [63], cyber security [64] as well as in military and aerospace use cases [65].

For this paper, the CWA is used as an approach to consider human behaviour as a design requirement for BEMS in the non-residential sector. Given the objective of this paper, the multi-dimensional CWA approach is reduced to the work domain analysis (WDA), from which DPs for BEMS can be proposed (see Table 1). By concluding on DPs from the abstraction of a work domain within the work domain analysis (WDA) (see Section 3.3), the analysis process in BEMS use cases is facilitated. By managing the complexity inherent to a work domain, system designers benefit from assistance and orientation in the blueprinting phase of designing appropriate BEMS, with a focus on active and passive methods for increasing energy efficiency.

3.3. Abstraction hierarchy

In their research calling for a new approach to formulate effective DPs, Gregor et al. [50] highlight that DPs are conceptual guidelines that work towards a defined purpose. This describes a means-end relationship within a sociotechnical system - a system consisting of human and non-human actors. Gregor et al. [50] point out that many studies do not take sufficient consideration of human actors' role and nondeterministic behaviour when proposing DPs. Based on previous research by Gregor et al. [66] as well as Lee et al. [67], Gregor et al. [50] emphasise the abstraction of a domain to theorise about generally applicable DPs that consider relevant human and non-human actors. The abstraction is a process to derive generalised concepts for a problem-solution relationship within a domain by reducing the problem context to its key factors [67]. In this paper, the method of the AH is applied. This assists this paper's objective of highlighting the key concepts shaping the sociotechnical design of BEMS in public sector buildings. The AH is structured into five levels [18,59] (see Table 2).

Table 2
Abstraction hierarchy: Levels and descriptions.

Level	Description
Functional purpose of the system	This level defines the overall purpose of the sociotechnical system.
Values & priority measures	This level refers to the values and priorities inherent to the overall goal and influences its fulfilment.
Purpose-related functions	Items on this level describe the strategies and approaches that impact the fulfilment of values and priorities.
Object-related processes	Processes defined in this level explain how purpose-related functions can be deployed and achieved.
(Semi-) Physical objects	This hierarchy level declares objects needed to perform processes fulfilling the system's purpose.

The first level defines the functional purpose of the system within the chosen domain — in this case, the public sector. The functional purpose describes the absolute objective of the system and directly correlates with the problem identified in the domain. This is followed in level two by declaring values and priorities influencing this functional purpose. The third layer contains purpose-related functions embodying approaches and strategies to achieve level two's predefined values and priorities. Level four defines object-related processes, including clear processes to implement and achieve purpose-related functions from level three. Level two, three and four represent the meta-requirements (see 3.1). The fifth and last level of the hierarchy informs about (semi-)physical objects, which can be described as human and non-human actors within the superordinate functions and processes. Each level includes multiple items, known as nodes. Higher-level nodes provide the rationale or goals, while lower-level nodes detail the specific actions or processes to achieve those goals. The nodes of each level stem from an integrative literature review (see 3.1).

3.4. Formulation of design principles

This paper draws an analogy between the AH and the DP formulation framework by Gregor et al. [50] to distil DPs, as depicted in Fig. 3. The proposal by Gregor et al. [50] to formulate DPs based on decomposing principles into different components matches the hierarchic structure of the AH implemented in this paper. They define five components for the formulation of DPs: the aim of the principle; the context; the mechanisms; the actors; and the rationales that theoretically or empirically justify the DPs. While the aim and context are already outlined as part of the functional purpose and defined through values and priorities, mechanisms are covered by the narrative of the purpose-related functions and object-related processes. This narrative is illustrated in Fig. 3 by black, vertical arrows. Horizontal, dark blue lines visualise relations and synergies within the levels of the AH. (Semi-)Physical objects from the AH embody the principle's actors, like hardware, software, and human stakeholders and are presented in Section 5. To fulfil the formulation requirement of a rationale, the conclusions from the AH are built upon existing IS theories and insights. This approach is built explicitly for the DP derivation and formulation exercise in this paper.

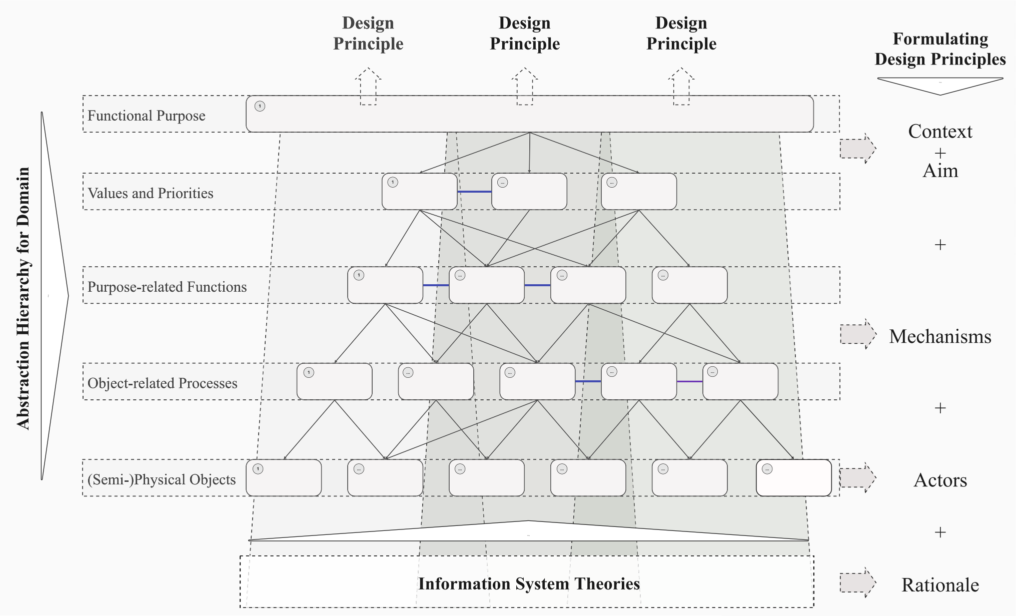


Fig. 3. Own figure based on the AH [59] and the DP formulation framework [50].

4. Design principles for BEMS

The paper from Körner et al. [33] about guiding the development of building energy emission management systems (BEEMS) highlights the need for prescriptive support for the design of BEMS. The authors developed a conceptual architecture based on a structured literature review and derived six DPs in the intersection of BEMS and emission management. Even though the proposed DPs share the same format approach from Gregor et al. [50], their research focuses specifically on the emission efficiency of building operations. This paper builds upon their research and broadens the scope towards energy efficiency and flexibility within buildings with an increased recognition of the sociotechnical components of BEMS. Fig. 4 depicts these results. As described in Section 3.3, the values reflect the aims and context of a DP. The identified functions and processes constitute the mechanisms. BEMS design can employ several mechanisms to advance towards the aims. These examples are not exhaustive but indicate that each principle can be approached in multiple ways, inspiring and suggesting various options. Among the mechanisms, nudges play a significant role for multiple DPs. They employ psychological mechanisms such as loss aversion, social comparison, and social norms to influence human behaviour through heuristic decision-making pathways, rather than solely relying on rationality [68]. Not all of these mechanisms can be integrated into BEMS design, but the most relevant ones are described in the related DP. Lastly, the level of (semi-)physical objects encompasses all involved human and non-human actors. Those actors create the implementation baseline, which can be attributed to multiple mechanisms.

The following subsections outline the functional purpose, which defines this study focus. It is followed by five DPs. For each DP, the respective rationale, aims and mechanisms are outlined. The rationales are displayed through existing Information System (IS) literature to validate the DPs.

4.1. Functional purpose

The functional purpose of BEMS design is to support sustainable energy use in non-residential buildings, taking account of active-technical and passive-behavioural measures. Technical and behavioural measures are now given greater emphasis since the European Green Deal (EGD) explicitly promotes their important complementary role as part of efforts to make energy use sustainable (see 2.2). Sustainable energy use requires the realisation of different perspectives: First, it refers to efforts in energy conservation manifested through the various energy-saving objectives within the directives of the Fit-for-55 policy package (see 2.2). Second, it stands for increasing load-shifting capabilities and flexible consumption behaviour, particularly as set out in the Energy Efficiency Directive (EED) in Section 2.2. Third, it represents an effort towards the optimised use of renewable energies, as demanded in particular by policymakers through the Renewable Energy Directive (RED) in Section 2.2. This multi-faceted functional purpose can be influenced and achieved through a set of values, functions and processes identified using an integrative literature review.

4.2. DP1: Build user engagement

4.2.1. The rationale

The first DP focuses on *building user engagement*, which is crucial for the consistent and long-term use of BEMS. Research has demonstrated that user engagement is essential for the sustained adoption and effectiveness of technological products [72]. This principle concerns technology adoption, which refers to the initial uptake and acceptance of BEMS within an organisation, and continuous engagement, which goes beyond the initial adoption phase and focuses on maintaining user interaction with the BEMS over time.

User engagement is closely associated with the technology acceptance model (TAM), developed by Davis [14]. The author posits that perceived usefulness and perceived ease of use are the primary factors influencing an individual's intention to engage with a system. This intention, in turn, is a critical mediator for actual system use. According to the TAM framework, perceived usefulness can be influenced by perceived ease of use. Therefore, BEMS designed to be more intuitive and user-friendly tend to be perceived as more useful.

4.2.2. The aim

Multiple goals were identified that BEMS designers should consider achieving to build user engagement. First, the BEMS should respect the priorities within each domain. For example, its use must not compromise the workers' productivity by distracting them from their standard daily tasks. Secondly, a user-centred approach can foster sustained engagement and acceptance of BEMS [73]. Hence, user satisfaction must

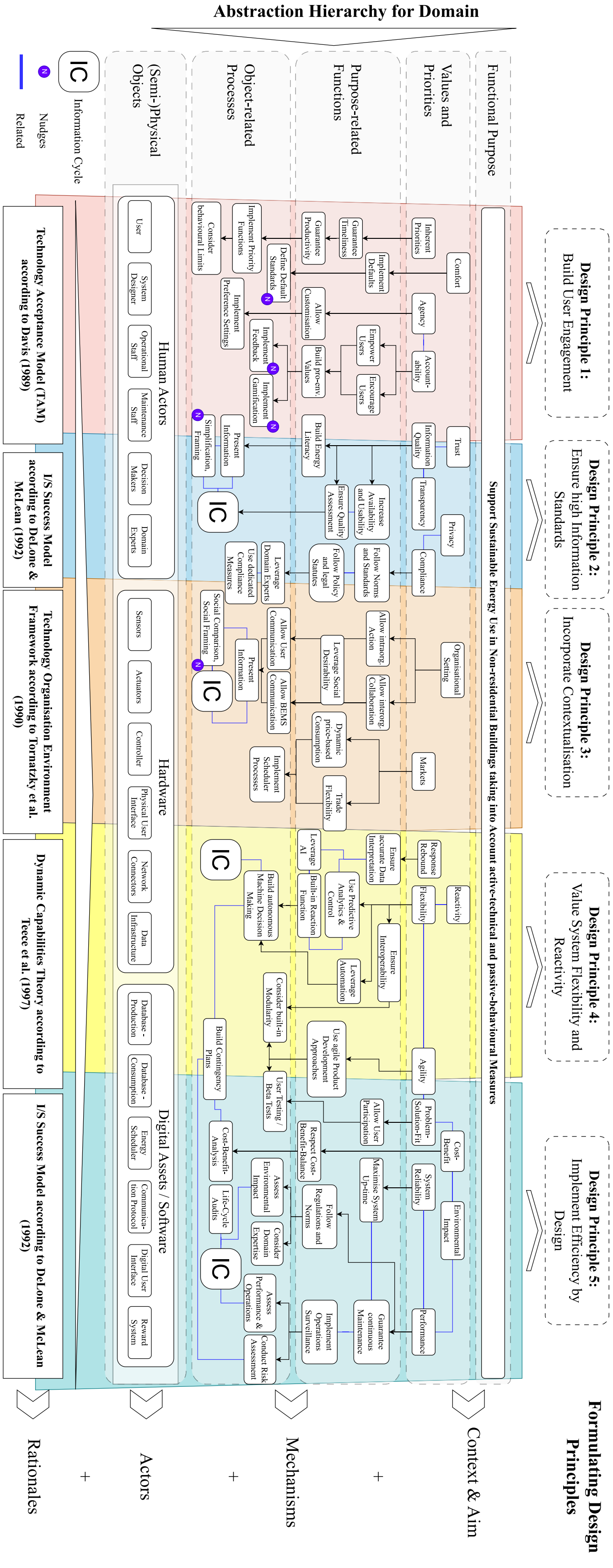


Fig. 4. Own figure based on the AH [59], the DP formulation framework [50], the technology acceptance model [14], the I/S success model [69], technology-organisation-environment framework [70], and the dynamic capabilities theory [71].

be prioritised [74]. For example, it includes maintaining perceived thermal comfort without requiring significant changes of habit or additional tasks. Third, users should have agency [15,75]. It refers to the capacity of individuals to act independently and make their own choices, and it involves having control over one's actions and decisions [76]. In this context, agency means allowing users to have control over their energy consumption and be able to adjust according to their preferences. The concept of agency leads to the fourth aim: accountability. This implies that users feel responsible for their energy consumption. Accountability ensures that users are not only engaged over the long term, but also committed to achieving the goals of the BEMS [38,77]. The system designer should account for response fatigue, where consumers grow tired of constantly tracking incentive tariffs and adjusting their energy consumption accordingly [78], ultimately leading to avoidance of the user's agency [47] and perceptions of a lack of recognition for effort being made. Finally, to ensure long-term engagement, users must trust the system [47], and high information quality must be guaranteed. Since these last two aims are intertwined with DP2, more details are provided in Section 4.3.

4.2.3. The mechanisms

Maintaining a balance between engagement and productivity is essential to ensure respect for domain priorities. While BEMS should encourage active participation, it should not become a source of distraction for workers. The system should integrate seamlessly into the workplace without hindering employee focus, work efficiency, timeliness and productivity. Consequently, BEMS designers should implement priority functions and, when necessary, consider behavioural limits, such as defining minimum and maximum temperatures in the work environment.

Default nudges are seen as crucial tools for facilitating behavioural change to achieve sustainable energy consumption while maintaining comfort [79]. The default nudge involves designating a desirable option as the default choice, with users retaining the freedom to opt-out if they prefer an alternative [68]. This enables building consumption to meet BEMS recommendations, which minimise energy consumption while favouring the use of renewable energy sources (RES). Its main advantage is that building users are only required to expend minimal effort for achieving the goals, with their comfort and productivity not affected. Previous studies, such as Loock et al. [80] or Brown et al. [81], show that setting a default temperature or saving goal can lead to significant energy savings in office workplaces. If the BEMS designers decide to implement default nudges, some of the processes they must implement include defining the default standards (*i.e.* temperature settings and time schedules) and considering the implementation of necessary automation processes.

The third aim dealt with in this section is agency, which can be fostered by, amongst other things, customisation options, (such as personalised temperature settings) or customisable apps. Usability and tailored interfaces for different user types give agency to users, enhancing their more control and influence over the system's effectiveness and adoption [33]. When individuals or groups have agency, they are empowered to make decisions and take actions [15]. With this empowerment comes the responsibility to be accountable for the outcomes of their decisions. Thus, environmental awareness [82] is crucial for promoting sustainable behaviour. By enhancing users' understanding of energy systems and their environmental impacts, they are equipped with the agency required to make informed choices [83]. Implementing personalised feedback is one of the processes that can foster environmental awareness and a sense of agency and accountability in users [47]. By tailoring feedback to individual characteristics, the system can provide relevant and meaningful insights, enhancing the perceived value of the system. For example, personalised energy-saving tips or specific data on how individual actions impact energy consumption can create a stronger connection to the BEMS itself and the functional purpose of the system introduced in Section 4.1 [42].

4.3. DP2: Ensure high information standards

4.3.1. The rationale

The second DP is fundamental to every information system — *Ensure high information standards*. To ensure high information standards, this paper underlines the role of information as a qualitative product of the BEMS. This principle is divided into three information standards values: trust, transparency, and privacy. Although these dimensions are worthy of differentiated consideration, together, they affect one of the cornerstones of the IS Success Model by DeLone and McLean [84] based on DeLone and McLean [69]. The authors conclude on three success categories, with this achieved by harmonising success variables from existing studies about information systems and categorising the variables. The first category of the IS Success Model refers to the system quality, which includes measures of success including efficiency and resource utilisation. This more technical category is subject to DP 4 and 5. The second category refers to the effectiveness and influence of an information system measured through ease of use and user satisfaction. This creates a link to the DP 1 [14]. Based on the argumentation of DeLone and McLean [84], information quality is the third pillar of the IS Success Model and is measured through context-dependent success attributes. These success attributes define the qualitative state of information provided to system users and are the pivotal point of this DP. Within the domain of non-residential energy consumption, the following information attributes are the most relevant:

- Individual relevance, as presented by Coleman et al. [47] in their research about the effectiveness of personal energy feedback in offices.
- Accuracy, as shown by Ornaghi et al. [85] that precise information, embodied in feedback or social nudges, shows more positive effects on actual consumption patterns.
- Timeliness, highlighted as fundamental success variable of information initiatives towards consumers [86].
- Clarity, as introduced by Paone and Bacher [87] in their work on reviewing the state-of-the-art on how to influence the energy consumption behaviour of building occupants through increased transparency and comprehensiveness.
- Credibility, as a catalyst accepting and acting upon provided information. This is presented in the work of Ozawa-Meida et al. [86], in which the occupants of public-sector buildings see their energy literacy improve when information originates from a trusted source.

4.3.2. The aim

These information attributes define the user's demand for transparency and trust, rooted in high information quality success attributes. At the same time, privacy requires compliance when processing information [2]. Privacy is a value for high information standards shared by both users and policy designers. System designers must meet two primary aims: ensuring information quality, fostering transparency and trust; and securing policy compliance through relevant privacy standards.

4.3.3. The mechanisms

To work towards these aims, a set of mechanisms was defined. Firstly, to satisfy the policy and user privacy requirement, system designers and decision makers must consider applicable data protection norms and legal requirements. All consumption-related data, such as behavioural data, is covered by the General Data Protection Regulation (GDPR) within Europe [88]. To take account of this, domain legal experts should be involved in designing the sociotechnical BEMS. Data protection measures like the pseudonymisation of behavioural data should be implemented to ensure regulatory compliance [88]. The value of privacy can create a degree of tension with the different nudge approaches introduced in this paper. For example, system designers considering gamification nudges for a BEMS use case should choose the optimised implementation approach in alignment with data privacy statutes [46]. System designers can implement functions that ensure continuous information quality assessment as a secondary mechanism. This supports data availability and the usability of relevant energy and consumption-related information.

Processes designed to enable values like trust, transparency and privacy are based on a cycle of continuously acquiring, organising, processing, analysing and providing information in an optimal fashion for the intended user. Each step allows decisions to be taken on the extent to which the information provided through the BEMS fulfils high-quality standards. The timely availability of accurate and complete information requires the integration of suitable databases and techniques to enable the precise processing and analysis of data. This is in line with the work of Körner et al. [33], which accentuates, amongst other aspects, the importance of information reliability. Behavioural measures can contribute to the perceived relevance and comprehensibility of information. BEMS can leverage nudges, like simplification and framing, since they influence how users experience information. Simplification refers to reducing the complexity and increasing the salience of energy-related information. It consists of building comprehensible statements from which users can derive strategies towards more sustainable behaviour [89]. In comparison, framing uses specific presentation strategies to make information more tangible, relevant, and potentially more attractive [90]. This set of nudges, which target how information is presented, offers additional advantages in the intersection of DP 1 and 2. By considering the most appropriate tools to make energy consumption data more understandable, the energy literacy of building occupants can be improved. While increased energy literacy contributes to user engagement objectives, as outlined in the previous subsection, it can also impact the perceived transparency of complex energy-related information [91].

4.4. DP3: Incorporate contextualisation

4.4.1. The rationale

The third DP focuses on *incorporating contextualisation*. It is a crucial factor in the adoption and engagement of BEMS, and in general of IS research [92]. This principle is grounded in the technology-organisation-environment (TOE) framework by Tornatzky et al. [70], which provides a comprehensive approach to understanding the adoption and use of technology. Within the technology-organisation-environment (TOE) framework, two pillars are under consideration:

- The organisational context focuses on the internal environment, including collaboration and communication within and between organisations. This ensures that BEMS align with organisational priorities and workflows, fostering user acceptance and engagement.
- Environmental context looks at external factors, such as market dynamics and regulatory environment. BEMS must respond to external market conditions, adapt consumption patterns to dynamic pricing, and participate in energy trading markets.

4.4.2. The aim

The aim of incorporating contextualisation encompasses both internal and external aspects. Internal contextualisation involves adapting BEMS to the organisational setting, while external contextualisation includes taking advantage of energy markets.

4.4.3. The mechanisms

To adapt to the organisational setting, BEMS should facilitate both inter- and intra-organisational collaboration [41]. This can be achieved by enabling robust communication channels within and between organisations. Such communication ensures that the BEMS can integrate smoothly with existing workflows and support collaborative energy management efforts. One effective mechanism for fostering collaboration is through social comparison and desirability, leveraging social framing nudges. By presenting information that allows users and facility managers to compare their energy consumption with peers, BEMS can promote a competitive yet cooperative environment as shown by Siero et al. [93] and Dwyer et al. [94].

Social nudges find a practical application within office environments, characterised by compact communal dynamics. Empirical studies by Wong-Parodi et al. [95] and Ornaghi et al. [85] validate this assertion: their research underscores the efficacy of providing office personnel with feedback regarding their energy consumption *vis-à-vis* their colleagues. This approach capitalises on the psychological impact of social norms and peer pressure to drive energy-efficient behaviours. From a more technical perspective, human decision-making can be considered through context-specific diverse occupancy profiles, as demonstrated by Happle et al. [96]. Diverse occupancy profiles have shown to be a pivotal parameter for correct demand forecasts and appropriate energy model designs.

Externally, BEMS should be designed to adapt consumption patterns in response to dynamic pricing models. Organisations could reduce their energy expenditure by aligning energy use to price signals. This is feasible if the variations in electricity price are sufficient to generate savings exceeding the additional operation costs [97]. This requires advanced scheduling processes that can predict and respond to price fluctuations. BEMS should support energy trading flexibility in different flexibility markets. This provides a financial incentive for the decision-makers, and contributes to the stability of the energy grid [98]. Implementing these capabilities involves forecasting electricity prices and automating control systems to adjust energy use dynamically in response to market signals. In addition to market signals, context-specific regulations and policy conditions form a essential design factor for energy management in buildings. While policies can embody motivations, they also present obligations which can vary within contexts like countries or regions. Choosing the right energy management strategies for buildings based on the specific policy regulations should be part of early design phases for BEMS [35].

4.5. DP4: Value system flexibility and reactivity

4.5.1. The rationale

System flexibility and reactivity are the focus of this DP. Flexibility in this context is about the system being able to evolve through integration with current and emerging technologies and solutions [33]. On the other hand, reactivity focuses on the system's capability to adjust rapidly to varying environmental conditions and user demands. Reactivity is also connected to DP 3 as the system's ability to respond to various situations and environmental conditions that affect the BEMS, such as natural disasters, political or regulatory changes, and seasonal behavioural shifts. These factors, internal or external to the BEMS, interfere with the controlling and monitoring system, and previous reviews revealed that incorporating them increases engagement success, not just by the BEMS designer and the utility manager but also by the end-users in the resilience and disaster recovery system [16,99].

Contingency plans ensure resilience and adaptability and correlate with the DP5: Implement Efficiency by Design. One example of a contingency plan is incorporating watchdog mechanisms and backup systems. Watchdog mechanisms continuously monitor the system for anomalies or failures, triggering predefined responses or switching to backup components to maintain system functionality [100]. Redundancy is another critical concept in contingency planning, involving duplicating critical components or systems to ensure uninterrupted operation in case of failure [101]. Cold standby redundancy is a widely applied design strategy to achieve high system reliability in various applications [102]. The appropriate redundancy design must consider a cost–benefit analysis for each use case, balancing the added protection against the associated costs. Yet, standby arrangements are wildly adopted solutions given their cost–benefit [103]. Here, the system operates with primary and backup components on standby, ready to take over if a primary component fails. This strategic approach to system design enhances the BEMS's ability to respond to environmental changes and user demands swiftly, ensuring operational continuity and user satisfaction.

This DP is closely connected to both the dynamic capabilities theory (DCT) [71] and the system quality pillar of the IS success model by DeLone and McLean [84]. DCT highlights the importance of an organisation's ability to integrate, build, and reconfigure internal and external competencies to address rapidly changing environments. Additionally, reactivity is one of the factors that DeLone and McLean [84] highlights as being crucial for achieving high system quality, which is essential for user satisfaction and overall system success. This DP is considered important to ensure that BEMS are technologically equipped, agile, and responsive to user needs and environmental shifts.

4.5.2. The aim

Pursuing system flexibility and reactivity, this DP aims at adapting BEMS dynamically to user behaviours and external changes. Yet, BEMS should address response rebound [78]. Response rebound refers to the phenomenon where users adjust their energy consumption to compensate for reductions or increases during previous energy management initiatives. This results in either higher or lower energy use in current time slots, highlighting how response power affects consumer behaviour. Response rebound can occur when users accept BEMS setting changes, generating discomfort, but more energy ends up being used due to previous load changes, such as variations in heating temperatures. This sort of response correlates to the importance of engaging users for the long term, as discussed in the first DP.

4.5.3. The mechanisms

Designers should leverage automation to achieve the BEMS's dynamic adaptation. Digitisation for sustainable control solutions across internal systems such as heating, lighting, and cooking domains has been reported to improve energy efficiency by 20% to 30% [104]. Adaptation usually leverages automation and predictive analytics to enhance energy efficiency significantly. It is particularly important to design BEMS that act autonomously, execute workflows and processes automatically, perform complex analyses to calculate energy and emission key performance indicators, and derive a thorough basis for emission-related actions [33].

Plug-load flexibility allows for easy assignment to specific plugs and individuals in a building, and they can be reassigned without interfering with other building systems. This type of system enables remote control of connected appliances and collection of high-resolution energy-use data, which facilitates the determination and prediction of additional measures, such as building occupancy and occupant energy-use efficiency [41].

In light of addressing response rebound, integrating artificial intelligence (AI) for predictive controls has enhanced energy management, enabling savings of up to 40% in non-residential BEMS [105].

The integration of a comprehensive BEMS poses challenges such as data accuracy, regulations (*e.g.*, GDPR), and system interoperability [99]. Ensuring the reliability of data and the seamless functionality of integrated systems is crucial to building trust and effectively implementing BEMS [106]. Priorities for BEMS have focused on fault detection, building control, and facility management [106]. Thus, robust data-sharing capabilities allow aggregating and analysing data from various sources to optimise energy use and predict future needs.

For successful data aggregation, BEMS integrate seamlessly with existing and future technologies, both internal (*e.g.*, HVAC, lighting) and external (*e.g.*, smart grids, renewable energy sources) [107]. Existing monitoring systems, such as SAP and CRM, if compliant with standards like CRREM, BACnet, Modbus, IoT protocols, or ISO 50.001, may ensure that other commercially available systems remain interoperable and modular [33]. Nevertheless, challenges remain in implementing integral controls for BEMS, including interoperability issues between buildings and software tools, deficiencies in data accuracy and consistency, and difficulties in accurately modelling as-built systems due to the lack of specification data [106].

Those challenges can lead to mistrust regarding the use of transmitted data, which can be mitigated effectively if BEMS not only fulfil the fundamental task of providing energy-related data but also autonomously manage energy data and corresponding action to reduce the reliance on human operations, enhancing the overall efficiency of the system [108]. Thereby, well-integrated BEMS can adapt to new technologies and regulatory changes, maintaining system effectiveness over time.

4.6. DP5: Implement efficiency by design

4.6.1. The rationale

The last DP originates from agile product and project management concepts, and correlates with the values of flexibility and reactivity. It is formulated as *implement efficiency by design*. This DP relates to the success category of system quality within the IS Success Model [69]. For this category, the success model empirically defines success attributes, which include the realisation of user requirements, resource utilisation, system reliability, technical efficiency and human factors involved in building and maintaining the system. Existing BEMS literature reveals (within the pursued abstraction process) a set of values and priorities that match the success attributes defined for the system quality. First, the value of fulfilling the requirement of being an appropriate problem-solution-fit for the use case [109] was identified. This value emphasises the importance of considering the problem context when defining a solution and ultimately designing the BEMS. Considering the problem context in detail allows system designers and decision-maker (such as facility managers) to define user requirements and constraints that can address the problem precisely [109]. Uncertainty about the relationship between problem and solution can lead to greater bias when defining system requirements. This can cause inefficiencies within the BEMS. The second value centres on balancing cost and benefit. This refers mainly to the idea of efficient resource allocation when designing and running a BEMS. The design and development of BEMS is principally a technical project that uses resources [109]. Evaluating costs is crucial to make the system's operation economically feasible and use case efficient. This highlights a strong relationship to the value of the BEMS being an appropriate problem-solution-fit. The third value is defined as performance, which strongly relates to additional values like environmental impact and system reliability. The value of performance embodies system efficiency and operability. System reliability refers to ensuring that the BEMS operates correctly when needed. The relevance of environmental impact is closely related to the work of Körner et al. [33], which specifically develop DPs to account for emission efficiency as part of the BEMS architecture and operations.

Altogether, the values of this DPs focus mostly on the operational state of the BEMS but can already be anticipated in the design phase [109].

4.6.2. The aim

These values aggregate into the principle's aim: system designers should account for the BEMS being a cost-efficient problem-solution fit and considering measures that will ensure reliable and sustainable performance.

4.6.3. The mechanisms

Mechanisms that can be applied to design a problem-solution fit include approaches that allow for the accurate scoping and framing of the problem context and requirements. Purpose-related functions, such as user participation in the design process, are essential to ensure that a system works towards its intended purpose and is accepted by the users [110]. For example, in their research on investigating user perspectives through user feedback in a non-residential BEMS use case in Indonesia, Chin and Lin [110] concluded with design suggestions for BEMS from user perspective. This contributes to a higher success probability for BEMS in similar use cases. Mechanisms enabling cost-efficiency include cost–benefit analyses and life cycle audits in design and operation phases, which build upon the continuous monitoring as well as assessment of the performance and requirements of BEMS [111]. A well-designed information processing cycle enables monitoring and the assessment of cost information. In their literature review on energy savings improvements in hospitals, Rahman et al. [112] emphasise the importance of low-cost-high-efficiency measures to contribute to the balance of cost-minimisation and reaching health and sustainability goals. Körner et al. [33] also consider the importance of cost-optimised measures by proposing highly autonomous system components in a distinct DP for emission-focused BEMS. This underscores, in particular, the potential of automation techniques and AI.

To consider system performance and reliability, maintenance approaches and strategies to maximise the system's up-time need to be outlined. These rely on continuous surveillance of the system's key performance indicators and the operability of its assets to detect operational anomalies and deviations from operational targets [109]. An example of a potential performance indicator of automated BEMS (such as RE schedulers) is the effective consumption share of renewable energies [19] while operational anomalies can be hardware malfunctioning [109]. Measures to react to technical and project management-related challenges in operations, which can be accounted for in the design, include risk assessments and contingency plans [109]. This can be accomplished, for example, by implementing redundant systems, which can be activated when the primary system fails due to a technical error (see Section 4.5). Additional quantitative key performance indicators in BEMS (besides occupant's comfort levels) (see Section 2.1) focus on the environmental impact through energy and emission savings [113]. As introduced in 2.2, these indicators are of special interest to policymakers when it comes to auditing buildings' energy performance. To consider this, it is recommended that system designers implement compliant environmental assessment structures and reporting functions as part of their buildings' energy management digitisation efforts [33,114].

5. From design principles to a conceptual architecture of sociotechnical BEMS

This section discusses the last level of the AH as outlined in Section 3.1 - the (semi-)physical objects. The first Section 5.1, discusses the (semi-) physical objects, which form the foundation of BEMS, integrating both human and non-human actors such as hardware, digital assets (*e.g.*, software) and stakeholders within the system. These actors constitute the backbone of a sociotechnical BEMS, enabling the system-side implementation of the proposed design principles. Section 5.2 suggests how the design principles could be addressed through the different objects within a system. The third Section 5.3 introduces an exemplary BEMS conceptual architecture. The architecture translates the design principles, facilitated by the (semi)-physical objects, into a conceptual design for sociotechnical BEMS consisting of four pivotal subsystems. This illustrates how the principles allow designers to consider sociotechnical design components in comprehensive system designs and how this research can contribute to the design phase of practical solutions.

5.1. (Semi-)Physical objects for sociotechnical BEMS

In the context of sociotechnical BEMS, both human and non-human actors play crucial roles in fulfilling the system's overall aims and functional purpose [50]. Alongside human participants, these actors (also called (semi-)physical objects within the AH in Section 3.3) include non-human system components such as IoT sensors and actuators, user interfaces, data access objects, and rule-based decision-making systems [115]. These technical components inform and control energy management strategies within the building and enable the proposed mechanisms of each DP within the AH.

Within BEMS, these objects can be broadly categorised into autonomous and non-autonomous systems. Autonomous systems, such as IoT sensors and actuators, operate independently, performing tasks without human intervention. They also serve as key access points for human-system interaction. Non-autonomous systems, on the other hand, require human interaction or decision-making, such as augmented manually operated light switches [116] or user interfaces designed to facilitate decision-making processes [115,117]. While autonomous systems reduce the cognitive load on users and ensure long-term engagement [75,118], non-autonomous systems involve stakeholders directly in the energy management process.

To accommodate the normative character, clusters of objects are defined and assigned to the design principles. Object clusters are linked to their purpose-related functions and related processes.

These clusters include the database management and fusion cluster, the scheduler and smart recommendation cluster, the actuation system cluster, and the rewarding/reinforcing human-interactive cluster.

The database management and fusion cluster is classified to handle diverse data sources, ensuring that the information used by the system is properly accessible. This is essential for informed decision-making and optimal energy management. Technologies employed may involve structured or unstructured databases, with commonly deployed technologies such as SQL and NoSQL databases [119]. Many BEMS integrate database management and fusion techniques responsible for processing, storing, organising, and analysing various data sources [99,120]. These include building systems, weather conditions, energy production metrics, market prices, and user behaviour [121]. The effectiveness of a BEMS largely depends on its ability to manage data efficiently.

The scheduler and smart recommendation cluster provides optimised consumption schedules and recommendations based on data-driven insights [121]. This cluster differs from traditional control systems by considering both external data (like weather) and behaviour patterns of building occupants to optimise internal device operation.

Actuation system cluster refer to traditional IoT objects such as sensors, actuators, and control-and-command software. For example, this includes automated temperature control in HVAC systems. Actuation systems are typically categorised into centralised or distributed arrangements. Centralised actuation systems in BEMS, such as lighting or those controlling HVAC, regulate indoor temperature, humidity, and air quality, thus significantly impacting energy consumption [122]. In contrast, decentralised systems, which often use wireless sensor and actuator network (WSAN), offer greater flexibility and scalability by enabling localised control and energy management within the BEMS [123].

The rewarding/reinforcing human-interactive cluster represents any object in the system that uses data to offer building occupants actionable insights and recommendations via intuitive interfaces. The hardware and software components of such a human machine interface (HMI) are essential for facilitating communication between humans and machines, enabling users to access information, control appliances, and monitor processes [117]. They can display historical energy consumption data, including emissions, and provide users with key performance indicators and further decision support metrics.

5.2. *From DPs to architectural objects*

Table 3 proposes, based on the AH from Section 4, how functions and processes from each DP can be considered through the object clusters in BEMS designs. Within the Sections 5.2.1 to 5.2.5, further descriptions and details are given on how each DP can be addressed through hardware and software.

5.2.1. *(Semi-)physical objects that build user engagement*

DP1 suggests the optimisation of BEMS operations to sustain long-term user engagement by rewarding and reinforcing interactions with the system. This involves providing actionable insights and recommendations, enabling effective energy management through personalised suggestions and automated scheduling.

User engagement can be supported by designing HMI components that present intuitive information [14,117]. Reward mechanisms for energy-efficient behaviour [13], information feedback [19], and gamification elements [124] further strengthen involvement. Success is highest when users are rewarded for specific behaviours rather than merely for interacting with the system [125].

A goal management component aligning user goals with system objectives facilitates efficiency efforts [125]. Customisable information provision supports decision-making [117]. Other examples also include further integration with rewarding/reinforcing human-interactive components using blockchain solutions to distribute immediate rewards to users [13] or leveraging trust and notarisation functionalities within the solution's context [19].

5.2.2. *(Semi-)physical objects that ensure high information standards*

DP2 underscores the importance of maintaining data accuracy, reliability, and timeliness to ensure the provision of relevant and correct information to both occupants and automated BEMS functionalities. Database management and fusion subsystems fulfil this requirement by aggregating and processing internal and external data, while adhering to regulatory standards like the European GDPR. Integrating open-source platforms and secure access control for third-party applications further enhances data integrity and reliability [126]. Moreover, implementing quality assessment mechanisms within databases improves the availability, usability, and quality of information processed and communicated within the building. This enables customised and context-relevant gamification and feedback elements for interactions between occupants and the BEMS.

5.2.3. *(Semi-)physical objects that incorporate contextualisation*

DP3 suggests integrating external data, such as weather, policy context, and energy prices, with internal data like user behaviour patterns. This enables customised energy management strategies tailored to building needs and conditions, such as policy regulations and cost structures [35]. Complete and reliable data sources support the generation of actionable insights and daily or weekly schedules for energy users [127].

BEMS use smart schedulers and optimisation algorithms to efficiently manage energy based on variable and context-dependent user demand [128]. Timely, contextually relevant recommendations are more likely to be adopted by users [33]. BEMS require different user interfaces that assign energy consumption to independent user profiles [117]. This allows energy behaviour to be tailored to individual consumption preferences and building profiles (*e.g.*, factories, schools, and offices).

5.2.4. *(Semi-)physical objects that value system flexibility and reactivity*

DP4 is mostly addressed through the actuation systems' capacity to respond rapidly and effectively to changing conditions, both internally (*e.g.*, occupancy changes) and externally (*e.g.*, weather variations). Implementing actuation systems' and schedulers' strategies for HVAC and lighting systems within buildings has been reported to improve energy consumption by 20% to 30% [104]. This adaptability can positively influence building performance and aligns energy use with dynamic user preferences and fluctuating environmental conditions.

BEMS adapts dynamically to user behaviour and preferences, utilising energy data across the entire energy flow. By integrating data and providing personalised information [116,127], the system empowers informed energy decisions.

Table 3
Object clusters for the DPs of sociotechnical BEMS.

DP	Purpose-related function	Object-related process	Object cluster
Build user engagement	Empower and encourage users	Implement feedback and recommendations	Scheduler and smart recommendation objects
		Implement gamification and reward elements	Human-interactive objects
	Allow customisation	Implement preference settings	Scheduler and smart recommendation objects
	Implement defaults	Define default standards	
	Guarantee timeliness and productivity	Implement priority functions and consider behavioural limits	
	Build energy literacy	Present simplified and relevant information	Human-interactive objects
Ensure high information standards	Increase availability, usability, and quality of information	Information cycle	Data base management and fusion objects
	Follow norms, standards, policy and legal statutes	Leverage domain expertise and dedicated compliance measures	Data base management and fusion objects
Incorporate contextualisation	Allow intra- and inter-organisational action and collaboration	- Allow user and BEMS communication - Present information - Information cycle	Scheduler and smart recommendation objects
	Leverage social desirability	Implement social comparison and social framing	Human-interactive objects
	Dynamic price-based consumption and trade flexibility	Implement scheduler processes	Scheduler and smart recommendation objects
Value system flexibility and reactivity	- Ensure accurate data interpretation - Leverage AI - Use predictive analytics and control - Built-in reaction function - Leverage automation	- Build autonomous machine decision making - Information cycle - Contingency plans	Actuation system objects
			Scheduler and smart recommendation objects
	Ensure interoperability	Consider built-in modularity	Actuation system objects
			Human-interactive objects
			Data base management and fusion objects
	Use agile product development approaches		Human-interactive objects
Implement efficiency by design	Allow user participation	User testing/beta tests	
	Respect cost–benefit balance	- Cost–benefit analysis	Data base management and fusion objects
			Scheduler and smart recommendation objects
	- Maximise system up-time - Guarantee continuous maintenance - Implement operations surveillance	- Assess performance and operations - Conduct risk assessment	Actuation system objects
	Follow regulations and norms	Information Cycle	Scheduler and smart recommendation objects
		- Assess environmental impact - Life cycle audits - Consider domain expertise	Data base management and fusion objects

Recent advancements in schedulers and smart recommendations align with DP4, emphasising interdisciplinary exchange platforms and simulations like digital twins [106]. Protocols like Modbus and advancements in IoT protocols [129] and web applications, such as If This, Then That (IFTTT) [19], enhance machine-to-machine communication, improving actuation systems' efficiency and interoperability.

5.2.5. (Semi-)physical objects to implement efficiency by design

DP5 recommends optimisation algorithms and intelligent schedulers to ensure efficient energy use and promote behavioural changes [130]. By leveraging data fusion techniques and decision support systems, the actuation system can be guided by calculated metrics and key performance indicators. This allows control of individual actuators, such as lighting appliances, power plugs, and HVAC systems [13].

DP5 suggests that traditional control strategies, such as hybrid PID-fuzzy schemes, to adjust actuation parameters based on real-time data [131]. It also highlights the potential of AI methods in HVAC control [132]. Thereby, the modularity of BEMS allows for the reassignment of plug-load flexibility, which enables remote control of appliances and collecting energy-use data for building occupancy and energy efficiency [41]. Information monitoring and diagnostic systems as part of the actuation system are supporting operational performance, identifying control issues and equipment malfunctions [133]. Fault

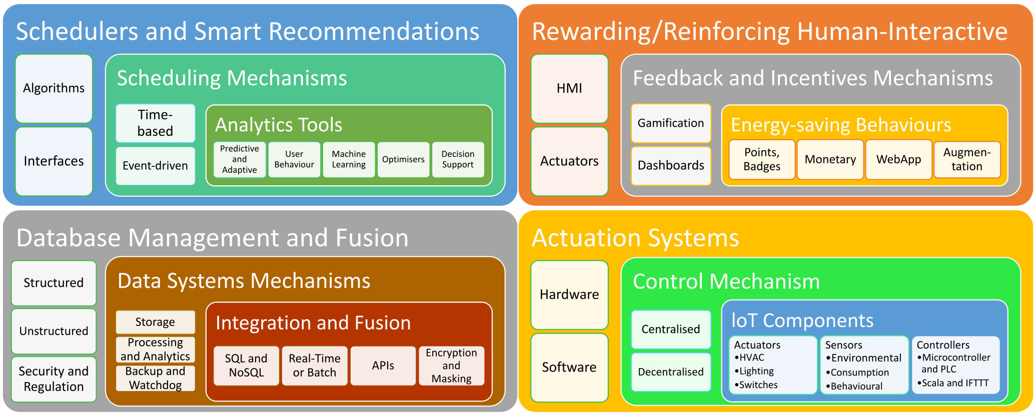


Fig. 5. BEMS conceptual architecture: demonstrating the integration of (semi)-physical objects and adaptive functionalities under the influence of the DPs.

detection algorithms are used to support maintenance activities and maximise system's up-time [134].

5.3. BEMS conceptual architecture

The BEMS conceptual architecture, illustrated in Fig. 5, comprises four distinct clusters that interact with each other. Studies by Rafsanjani et al. [39] and Li et al. [98] provide additional insights into optimal energy management strategies for BEMS.

1. The **Actuation system** cluster collects data from multiple IoT sensors distributed throughout the building. These sensors capture real-time environmental data, such as temperature, occupancy, and lighting levels. This data can either be processed immediately to refine operational parameters or sent as raw input to the database management and fusion subsystems for deeper analysis and flexibility in data handling. It also responds to scheduler commands to adjust in real-time operational conditions within the building, aligning energy use with the latest data insights.
2. The **Database management and fusion** cluster serves as the central hub for data aggregation and processing. They receive raw data from actuation systems within the building [42] and allow the combination with data from external sources like weather forecasts and energy production [19]. The processed information is then fed into the schedulers and smart recommendation cluster. Based on predictive and prescriptive analytics of the available real-time data, IoT actuators receive commands to adapt energy-related operations within the building. Aggregated and analysed data can further support the design of personalised feedback and recommendations [42].
3. The **Scheduler and smart recommendation** cluster uses the integrated data from the database management and fusion cluster to make optimised decisions about energy usage [26,27]. Schedulers optimise the timing and execution of automated energy-consuming activities by aligning them with user preferences, building needs, and external factors like energy prices or peak load periods [99]. The smart recommendation cluster further refines these decisions by providing actionable consumption feedback to users. This cluster dynamically interacts with both actuation systems to adjust real-time operations and with human-interactive objects to inform and engage users.
4. The **Rewarding/Reinforcing human-interactive** cluster leverages the responses from the scheduler and smart recommendation objects, providing users with clear, actionable insights and rewards for energy-saving actions. These human-machine interfaces reinforce desired behaviours and align user actions with sustainable system objectives.

Design strategies may employ multi-functional objects to streamline operations. In such a way, one technology can fulfil more than one functionality at once. For example, blockchain technology can act as both a database for notarising data storage and rewarding objects, enhancing system integrity and simplifying the BEMS architecture [19]. Similarly, digital twins can merge data analytics with user interaction to enhance decision-making processes [106]. Furthermore, AI can synchronise actuation and scheduling, optimising control over IoT devices by adapting in real-time to changes in the environment or user settings [104]. Such design options should be evaluated and adapted to individual BEMS needs, use case requirements, and context characteristics.

This architecture serves as a practical demonstration of the reusability of the identified DPs. Section 6 further assesses and demonstrates the reusability of this architecture by applying it as a blueprint of an energy scheduler application in a public sector building.

6. Demonstration

In this section, the application of the DPs is showcased based on the BEMS PoC as described in Lima Baima et al. [19]. This BEMS PoC exemplifies the integration of external low-carbon energy scheduling data, applying IoT and blockchain technologies to enhance sustainability, awareness, and operational efficiency in a public sector setting. While Section 6.1 contains a short description on the functions and architecture of the BEMS PoC, Section 6.2 evaluates the PoC against the DPs.

6.1. PoC description

Lima Baima et al. [19] integrated an approximation from Zhang et al. [135] to optimise the use of RE in their BEMS PoC. Their BEMS maximises renewable generation consumption with electric heat pump (EHP) operational resolution to renewable generation at a three-hour interval. It processes forecasts for RE production [136] and combines them with information on energy use in public buildings. The data are fed into the scheduling system, which optimises the energy use model considering the settings input of public sector buildings users, such as desired temperature, building construction year, living space, basement availability, and roof insulation. The energy consumption profile is composed of a three-hour resolution, allowing for the capturing of thermal dynamics of the heating system and dwellings. The model generates the load profile from three demand types: space heating, lighting, and appliances. Space heating demand is flexible, depending on the dwelling occupants' satisfaction level.

6.1.1. PoC Architecture

This BEMS PoC leverages predictive analytics to synchronise energy-intensive operations, mainly focusing on EHP, such as temperature

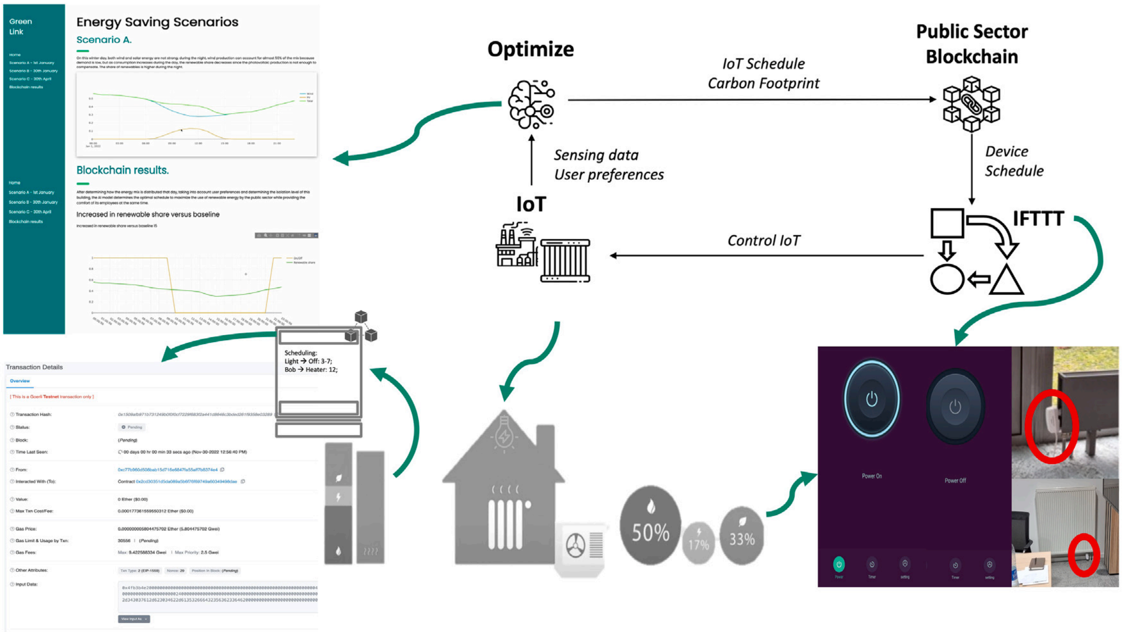


Fig. 6. Overview of the BEMS PoC architecture from Lima Baima et al. [19].

adjustments in public buildings, with periods of low-carbon energy production availability in the grid. This synchronisation is facilitated by integrating real-time weather and forecasts of energy production data, thereby optimising the balance of the building's demand and the available RES supply in the grid. Lima Baima et al. [19] use educational tools and information awareness to incentivise and promote energy-saving habits among users, facilitating the adoption of low-carbon energy-saving practices through educational and informative operational graphs [137]. The BEMS takes advantage of a PSB [138] and an optimised low-carbon energy scheduling approach [135] to support the BEMS design. The PSB provides the intrinsic trusted features of a governmental consortium. Meanwhile, the low-carbon energy scheduling optimisation is employed to IoT device control.

The BEMS PoC employs IoT for measuring and monitoring public entities' energy use, with data being logged directly into the chosen PSB via smart contracts [139] to increase energy awareness and user behaviour compliance to the optimised energy-savings strategy.

Lima Baima et al. [19] integrated smart contracts register IoT devices' use into the PSB and push the optimised schedule control into the IoT devices. The smart contracts were developed using *Solidity*, a statically typed programming language, and back-end operations were handled using *JavaScript*, which interfaced with the blockchain via the *ethers.js* library. While the current functionality of the employed components is acknowledged, the design is modular and adaptable, allowing for ongoing refinements based on user feedback and system performance metrics.

6.1.2. Services and functions

The work leverages the If This, Then That (IFTTT) service to control and supervise EHP operations based on RE projections and user input. The author used IFTTT's applet functionality to program *webhooks* to trigger the IoT devices' operational time via *HTTP* requests. Despite potential drawbacks, including the system's internet reliance and privacy concerns, the interoperability and automation capabilities aligned well with the project's engagement goals, making it the most suitable option.

The intersection of comfort and energy efficiency is most pertinent for indoor temperature regulation. For most buildings, heating and cooling systems account for up to 55% of the total energy use [140]. Due to its considerable energy footprint, the BEMS employs a heuristic formula to determine EHP operating hours. While the architecture can be adapted for other IoT devices within the IFTTT environment, the energy implications of EHPs demand a more tailored approach. Drawing from the utility analysis model [135,140], the formula incorporates the current building temperature, the target temperature, and the building load coefficient (BLC). The BLC refers to the building structure and its capacity to retain heat [140].

The following refers to the implemented solution components and methods:

- Temperature Difference $|T - 20\ ^\circ\mathrm{C}|$: Calculates the heating or cooling requirement by contrasting the current temperature with a target (averaged to 20 °C). Based on the concept of building recovery time, which is the time a building takes to recover from its setback to its occupied set point.
- BLC: This variable evaluates energy efficiency by comparing power use to ambient temperature, indicating how effectively the building retains energy.
- Max and min EHP operating hours (min_{ehp_num} and max_{ehp_num}): The outcome is adjusted according to the minimum and maximum number of hours the EHP must function in a day. Additionally, it is combined with the specific hours the grid has the most significant share of electricity generated by renewables, which optimises the start times and operation of heating systems during those periods. The heuristic approximation aligns with optimising heating system operations based on the current and target temperatures and the BLC cap.

The formula to estimate EHP operation is given by:

$$EHP_{hours} = max\left(min_{ehp\_num}, \left\lceil max_{ehp\_num}\frac{\alpha\frac{|T-20\ ^\circ\mathrm{C}|}{20\ ^\circ\mathrm{C}}+\beta(1-BLC)}{\alpha+\beta}\right\rceil\right) \quad (1)$$

$$\alpha, \beta, BLC \in [0,1] \text{ and } T \in [0\ ^\circ\mathrm{C}, 40\ ^\circ\mathrm{C}]$$

$$min_{ehp\_num} \le max_{ehp\_num} \in \{0, 1, \ldots, 24\}$$

Where T is the current temperature, BLC is the building load coefficient, α and β are the normalisation factors, and max_{ehp_num} and min_{ehp_num} are the maximum and minimum daily EHP operation hours.

The implemented system also calculates the proportion of RE in total energy generation to promote energy efficiency and sustainability. The implemented heuristic integrates the proportion, considering it as total energy generation:

$$RE_{share} = \frac{RE_{gen}}{TE_{gen}}$$

Where RE_{gen} is the RE generation, and TE_{gen} is the total energy generation. The optimised hours for the EHP to operate to maximise the use of RE is determined by:

$$EHP_{on} = \begin{cases} True, & \text{if } i \in sorted\ indices\ of\ RE_{share}[-ehp_{hour\_num}:] \\ False, & \text{otherwise} \end{cases} \tag{2}$$

The increase in the share of RE when the EHP is operational is calculated by:

$$RE_{share\_increase} = \frac{\frac{1}{EHP_{hours}} \sum_{i=1}^{24} RE_{share}(i) \times EHP_{on}(i)}{\frac{1}{24} \sum_{i=1}^{24} RE_{share}(i)} - 1 \tag{3}$$

Where RE_{share} is the share of renewable energy, and EHP_{on} is a binary variable indicating the electric heat pump state.

6.2. Evaluation against the DPs

Fig. 6 illustrates the architecture of the BEMS PoC, designed to control IoT devices, which are supported by several components, with each playing a role in the system's functionality, thus enabling the processing of more complex operations. This subsection elaborates on the conformity with the DPs for each of the main BEMS components:

- **User Interface**: Public sector institutions can set up their environment-centric parameters via the Flask interface, composed of temperature, construction year, dimensions, and basement and roof insulation. This feature aligns with DP1: *Build user engagement* by providing an intuitive interface that enhances user interaction and perceived system usefulness.
- **Data Collection and Reprocessing**: Parameters are collected from public entities' inputs and external datasets, supporting DP2: *Ensuring high information standards* through accurate and credible data management.
- **Energy Consumption Prediction**: Based on public entities' inputs and the dataset, the BEMS anticipates energy consumption patterns normalised between a 0 and 1 range. This predictive capability facilitates dynamic adaptation as part of DP4: *Value system flexibility and reactivity*.
- **Optimisation and Scheduling**: The system interfaces with the external service, acquiring an optimised schedule for the IoT devices per the predicted energy consumption trends. Here, the focus is determining the ideal operation windows to boost energy efficiency and RES use, enhancing DP5: *Implement efficiency by design*.
- **Real-time Management of IoT Devices**: With the optimised schedule, directives are sent to the IoT devices via the IFTTT platform, ensuring operations during intervals of highest energy efficiency and RES use, thus implementing DP3: *Incorporate contextualisation* by adapting to external data inputs like weather conditions. The nature and interoperability of the IFTTT to control IoT devices also addresses DP5: Implement Efficiency by Design and DP4: *Value system flexibility and reactivity*.
- **Performance Metrics**: The system retrieves and presents on the interface three core metrics for increased public entity engagement:
  (a) Operational status visualised across 24 h
  (b) The percentage of RE consumption over the previous day
  (c) The augmentation of renewable-generated electricity use as a system optimisation outcome

This feedback mechanism is part of sustaining DP1: *Build user engagement* by providing users with actionable and meaningful insights about their energy use.

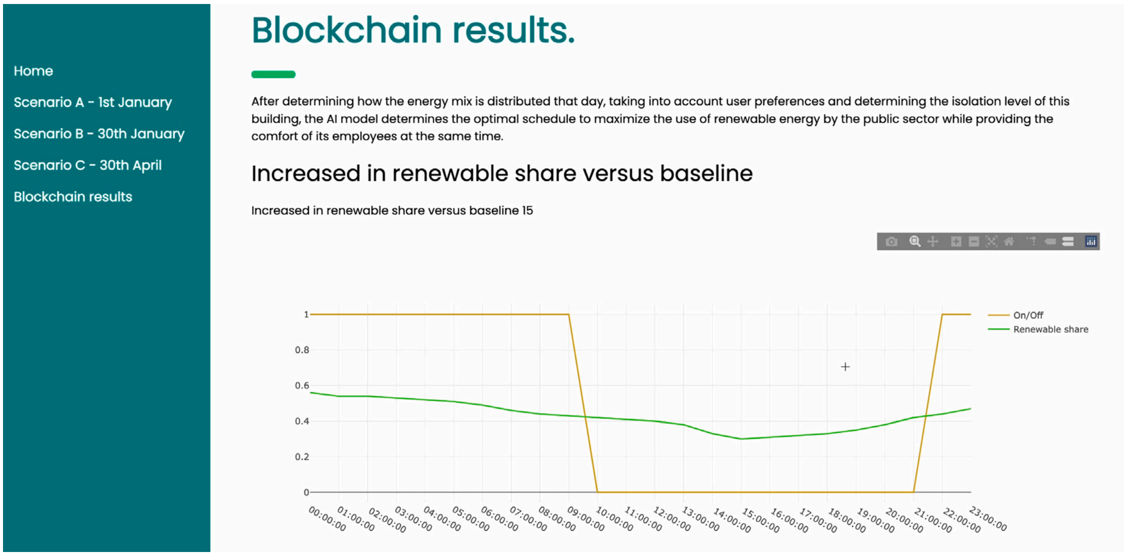
6.2.1. BEMS output: Visualisation of renewable energy consumption

The BEMS PoC underwent evaluation by scenarios testing based on real-world weather data and the precision in controlling IoT devices to validate its effectiveness, addressing DP5: *Implement efficiency by design*. Lima Baima et al. [19] compared each scenario's anticipated EHP operation with RE production on random days in 2022. Fig. 7 depicts three different day scenarios on the left side tab, with a graphical representation displayed in the centre, informing the user of the BEMS operation. As a result, there is a 15% increase in RES use compared to no scheduler use, a significant increase, particularly under favourable conditions. The interface then emphasises this increase in RE proportion relative to the baseline, reinforcing DP2: *Ensuring high information standards* by providing transparent and credible reporting of performance outcomes.

6.2.2. Opportunities for improvement

Despite the system aligning with all DPs to a certain extent, there are still opportunities for improved enhancement of engagement according to strategies previously discussed, including:

- **Build user engagement (DP1)**: The BEMS PoC provides an interface for setting parameters, but may not fully engage users beyond the initial setup. There is a need for more dynamic and interactive features to promote regular user interaction, feedback, and adjustment, ensuring sustained engagement. One solution is implementing dynamic dashboards that allow users to visualise real-time energy consumption, to set goals, and to track progress. Incorporating social comparison and gamification elements such as rewards, challenges, and leaderboards can motivate continuous interaction and engagement with the system.
- **Ensuring high Information Standards (DP2)**: The BEMS currently uses data collection and predictive analytics, but there is room for improvement in data accuracy, timeliness and overall information quality provided to users. It is not always clear how individual accountability for energy use is connected in this arrangement. While blockchain is used for transparency and notarisation, the consortium characteristics of a PSB can be seen both as an advantage and a disadvantage. Implementing transparent reporting and real-time updates could enhance trust and reliability in the system's outputs. At the same time, each consortium has its characteristics, but if all participants trust each other as in a PSB, the notarisation can still be leveraged. For example, advanced real-time data analytics tools could process data in real-time, providing users with up-to-date and accountable information.
- **Incorporate contextualisation (DP3)**: The BEMS currently incorporates external data for optimisation, but there is potential for deeper integration with internal organisational data and processes. Tailoring the system more closely to specific organisational workflows and external energy demand conditions could improve its adaptability and effectiveness in various scenarios. One possible solution is to use adaptive learning algorithms to dynamically adjust the system's operations based on internal preferences and external market changes. Another strategy involves rebalancing customisable grouping profiles to adapt different workers and their work settings to compatible energy use. For example, the BEMS can explore social nudges by comparing similar work setups (*e.g.*, making a distinction between office and hospital workers).
- **Value system flexibility and reactivity (DP4)**: Although the BEMS PoC was designed to adapt to changing conditions, im-



Blockchain results.

After determining how the energy mix is distributed that day, taking into account user preferences and determining the isolation level of this building, the AI model determines the optimal schedule to maximize the use of renewable energy by the public sector while providing the comfort of its employees at the same time.

Increased in renewable share versus baseline

Increased in renewable share versus baseline 15

Fig. 7. Visualisation of renewable energy consumption in PSB [19].

plementing more proactive measures to enhance its reactivity to unexpected changes, such as extreme weather or spikes in energy demand, could improve its resilience and responsiveness. Disaster recovery systems are valuable tools for supporting such situations. Incorporating predictive maintenance capabilities greatly enhances the ability to forecast and address system issues before any period of downtime.

- **Implement efficiency by design (DP5)**: The system focuses on optimising energy use, but there could be a greater emphasis from the outset on the integration of cost-effective design strategies. This includes leveraging advanced analytics to predict and mitigate inefficiencies before they occur. This ensures a cost-efficient operation that aligns with sustainability goals. Although the work already leverages readily available tools such as IFTTT for interoperability with IoT devices, it does not mention integration with the dataset input. Another aspect is conducting life-cycle assessments to evaluate the environmental impact and ensure the system's design minimises resource use and maximises energy savings.

Enhancing these aspects could further align the BEMS with established DPs, ensuring the system meets technical requirements and effectively adapts to user needs and environmental changes. By integrating these actions and tools, the BEMS can significantly improve its usability, efficiency, and effectiveness, leading to better adoption and sustainability outcomes.

7. Minimum reusability evaluation approach

This section presents the evaluation of DPs described in Section 3.1 with the minimum reusability framework according to Iivari et al. [20], which was achieved by carrying out a series of workshops.

Iivari et al. [20] define five criteria which embody the minimal requirements for an actionable DP: accessibility; importance; novelty and insightfulness; actability and guidance; and effectiveness. The definitions are outlined as follows [20]:

- **Accessibility**: refers to the criteria of comprehensibility of the DP. Since DPs are generated from a very generalised point of view, and that they can be short and abstract in their formulation, this ensures the importance feature that researchers and practitioners alike can use it. To ensure this, it is necessary to choose the right language and potentially to add extra explanations to increase transparency.
- **Importance**: represents the current relevance in science, society, and business. DPs are considered to be important if they contribute to the design of a feasible solution to a current problem.
- **Novelty and insightfulness**: relates to the criteria of adding new knowledge to existing theory and practice.
- **Actability and guidance**: actability refers to the DP needing to allow for practitioners to act on these principles. Guidance is defined by the orientation given through the options and restrictions imposed by the DP.
- **Effectiveness**: this relates to the impacts which result from the DP, and whether these meet the requirements outlined within the scope of any problem.

This approach was chosen as a way to validate the practical applicability of the DPs in supporting real-world BEMS use cases. This is also called a light evaluation since it does not involve field testing nor validation through expert interviews. The evaluation was achieved through workshops with fellow researchers. They followed workshop standards, as outlined by Thoring et al. [141] to ensure research rigour. The insights were distilled and summarised from the discussions and workshop notes and are presented in Table 4.

As highlighted in Table 4, the evaluation criteria are met due to the chosen research approach for deriving and formulating DPs. Even though there will be a need to evaluate the DPs in a naturalistic way in the future, for example in a field test, this evaluation (together with the conceptual architecture (see Section 5) and demonstration (see Section 6)) foresees the likelihood of a positive tendency for the applicability of the DPs.

8. Conclusions and future work

The EU's advocacy for a clean energy future features greater emphasis on the need for more efficient energy consumption, and strategies to mitigate the adverse effects of climate change. The EU understands that the non-residential sector – particularly the public sector – needs to be a positive benchmark and role model for energy efficiency. BEMS are a crucial part of these efforts as they improve electricity efficiency and provide flexibility. This is essential given that energy use in buildings significantly impacts overall energy demand.

Recent advancements in the field tend to focus predominantly on the technical aspects of BEMS, but pay insufficient consideration to the preferences and behaviour of the people who work and live in buildings. The majority of studies on BEMS focus on the contribution

Table 4
Minimum reusability evaluation according to [20].

Criteria	Evaluation
Accessibility	The meta-requirement of the DPs are derived as means-end-relationships from the AH process. Sections 4.2 to 4.6 translate the abstract means-end-relationships of Section 4 into a comprehensible format. By building an explicit narrative for each DP and shedding light on the rationale, aims, mechanisms, and actors, the DPs become accessible.
Importance	The derivation of the DPs is based on the motivation and needs expressed in current European policies (see 2.2). The promotion of efforts to combine technological measures and behavioural insights into a holistic approach towards BEMS was a centrepiece of this work.
Novelty and insightfulness	Given the dominance of the traditional technical view on BEMS, we do not know of any work which proposes to this extent insights for the sociotechnical potential of BEMS. While some research, like the studies of Körner et al. [33], proposes DPs for BEMS, we extend this scope and incorporate additional aspects which lead to new and complementary outcomes.
Actability and guidance	As part of this work formulation approach, mechanisms are offered explicitly as potential options for acting towards the aims defined for each DP. We provide insights about chances and constraints for each DP in sections 4.2 to 4.6.
Effectiveness	The DPs are derived from applied research and use cases. By using a literature review, we focused on knowledge that offered clear insights into the impacts of chosen measures. By incorporating those into the DPs, they were built upon mechanisms and design options that have shown effectiveness in the field.

of deep learning, predictive analytics, and IoT to building better systems. Attention also needs to be paid to research that is exploring how behavioural interventions can reduce energy consumption in the non-residential sector.

BEMS that feature insight from advances in engineering and behavioural sciences could optimise energy use while maintaining and potentially enhancing occupant comfort. However, there was a lack of normative guidance on how to approach this interdisciplinary challenge. This paper addresses two research questions:

- *What normative guidance can support non-residential BEMS designers as they seek to enhance energy efficiency through the optimal use and balance of technical advancements and behaviour-influencing strategies?*
- *How can system designers apply this normative guidance to blueprint and implement BEMS architectures?*

To answer the first research question, this paper introduces five DPs for building energy management systems (BEMS). These principles provide practical guidance for information system designers, technology developers, and energy managers, with a strong emphasis on promoting more efficient energy consumption in the non-residential building sector. In particular the public sector is used as a reference point. Through the combination of an integrative literature review, abstraction hierarchy, and Möller et al. [17]'s method for design principle development, five principles to guide the design of BEMS to support sustainable energy use in non-residential buildings are formulated:

- DP1: Build user engagement
- DP2: Ensure high information standards
- DP3: Incorporate contextualisation
- DP4: Value system flexibility and reactivity
- DP5: Implement efficiency by design

In an effort to answer the second research question, the article describes how to apply the design principles in the design of BEMS. For this purpose, a conceptual architecture is illustrated and a BEMS PoC architecture for an Energy Scheduler in the public sector is demonstrated. The results obtained with the system are described, its conformity with the identified DPs is evaluated, and it is highlighted how the PoC can be improved according to the DPs. The DPs are evaluated by applying Iivari et al. [20]'s minimum reusability evaluation framework.

This paper contributes to the normative guidance of designing and implementing BEMS that integrate renewable energy sources, comply with regulatory requirements, engage users, and optimise energy efficiency. The insights from the practical demonstration of the BEMS PoC not only address real-world energy management challenges, but also illustrate how to apply design principles to develop both conceptual and use-case-specific architectures. This paper highlights the synergistic potential of technical, economic, and human-centred system components to design more effective BEMS. By integrating behavioural strategies with technological advancements, the proposed DPs aim to ensure that BEMS can respond adaptively to user behaviour and environmental conditions. This facilitates the widespread adoption of energy-efficient practices among building occupants and stakeholders. In practice, stakeholders can benefit from this paper's guidance and architectural demonstrations on incorporating a behavioural perspective when designing a BEMS. Public sector institutions can use the DPs and how they are demonstrated here to enhance energy management practices, meet regulatory requirements, and advance sustainability objectives. Energy industry players can leverage the insights to develop innovative energy management solutions, while building owners and managers can optimise energy use and improve sustainability performance in their properties.

While the present study provides normative guidance for sociotechnical BEMS, it is essential to acknowledge certain limitations and areas for future research. A notable limitation is the absence of an actual implementation of the proposed DPs in a real-world BEMS scenario. Although the proposed DPs are based on documented best practices, the suitability of the identified mechanisms may vary depending on contextual factors such as organisational culture, technological maturity, and regulatory environment. A PoC analysis was presented, and it was demonstrated how system designers could leverage the DPs for blueprinting sociotechnical BEMS. Practical implementation and empirical validation in diverse real-world settings remain pending. Future work could focus on conducting field trials or case studies to evaluate the effectiveness and applicability of the DPs in the public sector and general, non-residential buildings. Further research could also explore the long-term impact and reusability of the proposed DPs, taking account of evolving technological advancements, regulatory frameworks, and user behaviour dynamics in the energy management domain.

In conclusion, while acknowledging the limitations and scope for further research, this work employs an iterative approach that integrates previous research findings and DPs. The methodology pursued seeks to establish that the design principles are both theoretically sound and practically relevant, with the goal of supporting continuous improvement and refinement in future iterations.

CRediT authorship contribution statement

Laura Andolfi: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Conceptualization. **Renan Lima Baima:** Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Conceptualization. **Lorenzo Matthias Burcheri:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Conceptualization. **Ivan Pavić:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Gilbert Fridgen:** Writing – review & editing, Supervision, Resources, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Renan Lima Baima reports financial support was provided by Fonds National de la Recherche. Gilbert Fridgen reports financial support was provided by Fonds National de la Recherche. Laura Andolfi reports financial support was provided by Creos Luxembourg SA. Lorenzo Matthias Burcheri reports financial support was provided by Fondation Enovos. Ivan Pavic reports financial support was provided by Creos Luxembourg SA. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used Grammarly and ChatGPT to improve readability and language. After using this tool/service, the authors reviewed and edited the content as needed and took full responsibility for the publication's content.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.apenergy.2024.124628.

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