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Assessment of Building Automation and Control Systems in Danish Healthcare Facilities in the COVID-19 Era

Jeanette Maria Pedersen [1], Farah Jebaei [2] and Muhyiddine Jradi [1,*]

[1] Center for Energy Informatics, The Maersk Mc-Kinney Moller Institute, University of Southern Denmark, Campusvej 55, 5230 Odense, Denmark; jeape17@student.sdu.dk
[2] Medical Laboratory Technologist, 5220 Odense, Denmark; jbfarah6@gmail.com
* Correspondence: mjr@mmmi.sdu.dk; Tel.: +45-6550-8210

Abstract: A well-designed and properly operated building automation and control system (BACS) is key to attaining energy-efficient operation and optimal indoor conditions. In this study, three healthcare facilities of a different type, age, and use are considered as case studies to investigate the functionalities of BACS in providing optimal air quality and thermal comfort. IBACSA, the first-of-its-kind instrument for BACS assessment and smartness evaluation, is used to evaluate the current systems and their control functionalities. The BACS assessment is reported and analyzed. Then, three packages of improvements were implemented in the three cases, focusing on (1) technical systems enhancement, (2) indoor air quality and comfort, and (3) energy efficiency. It was found that the ventilation system domain is the best performer in the three considered cases with an overall score of 52%, 89% and 91% in Case A, B, and C, respectively. On the other hand, domestic hot water domain scores are relatively low, indicating that this is an area where Danish healthcare facilities need to provide more concentration on. A key finding indicated by the assessment performed is that the three buildings score relatively very low when it comes to the impact criteria of energy flexibility and storage.

Keywords: smart buildings; building automation and control system; BACS auditing; EN15232 standard; initial commissioning; technical domains; indoor air quality; energy efficiency

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1. Introduction

1.1. Background

The emerge and fast expansion of COVID-19 has imposed new measures and requirements in all life domains [1–4], exerting enormous stress on the healthcare system worldwide [5]. Enhancing the level of hygiene and sanitation in healthcare facilities and hospital buildings turns to be a priority in the fight against the fierce pandemic. On the other hand, and due to the nature of the new pandemic in terms of fast transmission and spread through air, the importance of the establishment of high levels of indoor air quality and thermal comfort within healthcare facilities is nowadays eminent. In this context, a proper-designed, installed and operated building automation and control system is pivotal to attaining an energy-efficient operation and optimal indoor conditions in such facilities.

In recent decades, buildings design and construction auditing and performance evaluation has been a very hot topic, both in terms of theoretical studies and experiential implementations [6,7]. The largest block of such investigations and studies was concentrated on the holistic building level aiming to evaluate the overall performance, as well as the energy consumption of the different building domains [8–11]. In this regard, studies targeted building constructions and envelope [12], building services and systems including heating, ventilation, and air conditioning (HVAC) units [13], equipment and devices [14], with a holistic aim of improving the quality of design, enhancing the operation and reducing energy consumption and cost. On the other hand, the building automation and control

(BACS) system is the heart of modern smart buildings. It is the component allowing effective interaction and integration between various energy systems, services, controls, sensors, and meters [15–17]. Moreover, it is the major driver of every single decision-making process in the facility with advanced management and control strategies and capabilities. In recent years, major advancements have been presented in the field of BACS, both on the level of design and operation with new devices development [18], smart meters and sensors [19], and digital components integration [20]. However, and compared to other building components and specifications, very limited investigations and studies have been presented dealing with auditing and commissioning of such BACS, to ensure a proper design and optimal functionalities considering automation and control advancements and regulations.

As we are heading towards an expansion in the digitalization of the building sector with the principles of smart and grid-connected buildings, we are going to see more and more BACS installed in such buildings. Recent studies highlighted that the lack of initial auditing and design evaluation of BACS in smart buildings has led to large energy performance gaps, and correspondingly to a building not meeting its design requirements and systems that are not optimally controlled and drifting from the initial design standards [21,22]. While in many countries, regulations and standards are already established to carry out performance testing and initial commissioning on the whole building level; there is still a lack of such requirements for initial auditing and design evaluation for the building automation and control component in such newly built or retrofitted energy-efficient buildings.

1.2. BACS Auditing Schemes

In terms of overall building performance auditing methodologies and evaluation criteria, schemes on national and international levels have been developed and presented in the last years dealing with whole-level building certification, including DGNB [23], LEED [24], and BREEAM [25]. Nevertheless, very few similar schemes are discussed and presented when it comes to the specific building automation and control systems auditing and evaluation. In this context, one of the very popular BACS design evaluation schemes presented recently is the 'eu.bac System' methodology [26]. This BACS auditing and evaluation methodology have been implemented in multiple countries in Europe, with a drastic increase in the buildings being audited and commissioned. It is the product of the European Building Automation and Controls Association (eu.bac) which represents a large group of leading building automation and control equipment manufacturers and traders in Europe [27]. The eu.bac methodology in BACS evaluation is based on the very well established European standard EN15232 "Energy performance of buildings—the impact of Building Automation, Controls and Building Management" [28], which classifies buildings into multiple classes associated with the corresponding level of automation and control, ranging from A (best) to D (worst). The eu.bac methodology thus evaluates multiple building services, including various domains and technical aspects. Figure 1 shows a caption of multiple services listed under the heating system domain as part of the eu.bac system methodology. While the eu.bac methodology has demonstrated plenty of positive impacts in terms of evaluating BACS design, it only considers the impact of the design with respect to a single criterion, energy efficiency.

Recently, a first-of-its-kind instrument, 'IBACSA' for building automation and control systems auditing and smartness evaluation, was developed and launched to serve as a basis for initial and retro-commissioning of the BACS in various buildings and facilities [29]. The instrument is also driven by the requirements and regulations set by the European standard EN15232 for building automation and control but with a more holistic approach in terms of the impact criteria considered. IBACSA methodology employs a hybrid quantitative-qualitative multi-criteria assessment framework and aims at evaluating the BACS design on the level of eight different building domains. Such multi-criteria assessment frameworks have been employed in various studies in the literature and shows major positive impacts in terms of evaluating and assessing building automation systems design and overall building performance [30–32]. The considered domains are as follows: Heating, Hot Water, Cooling, Ventilation, Lighting, Dynamic Envelope, Electricity and Monitoring and Control. Thus, as part of the building automation and control system evaluation and assessment, IBACSA evaluates a list of services under each of the eight domains mentioned, summing up to 60 services in total. The services evaluation is a functionality selection process, where the user will select for each service, the level of control functionality associated with a list of choices provided by the tool. The higher the service functionality selected, the larger the number of points accrued for that service.

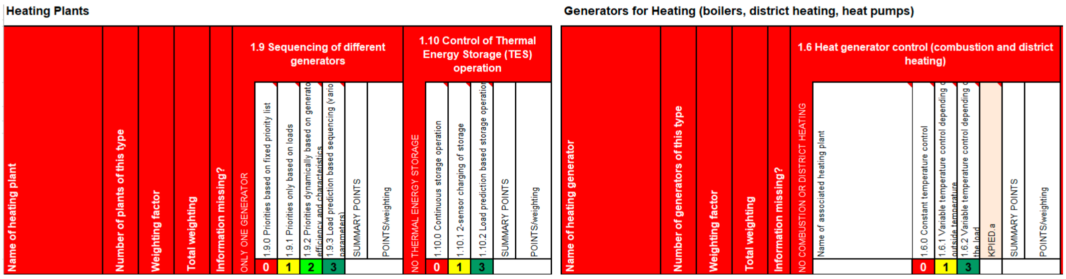


Figure 1. Caption of some services associated with the heating system domain in eu.bac system [26].

As the user selection of the corresponding services is completed, the instrument will provide a comprehensive assessment of each of the eight building domains against five impact criteria, (1) energy efficiency, (2) maintenance and fault prediction, (3) energy flexibility, (4) comfort and (5) information to occupants [29]. A points-based grading score is used to quantify the effect of functionalities on the five considered impacts. The number of points claimed for each functionality level are determined by a scale ranging from 0 to 3 points.

1.3. Aims and Objectives

Generally, the trend in building initial commissioning is that this process is carried out on the holistic building level, in order to evaluate if the envelope is living up to the standards and assess if the predicted consumption is in line with the building regulations. However, when it comes to evaluating and assessing the design and operation of the BACS, then it is either not considered or carried out with minimal resources and a limited level of detail. Obviously, this will lead to missing on evaluating and testing the brain of the building, which connects all different systems and establish a proper interaction of the diffident controls and operation patterns. This highlights the importance of having a user-friendly and comprehensive tool to aid in the decision-making on the energy effective and optimal design and installation of BACS and facilitate the process of auditing and evaluating various building services and the corresponding building smartness. One of the major building domains where an optimal design and operation of the BACS is crucial in the healthcare sector. In this regard, the majority of the healthcare buildings in Denmark are built before the year 2005, and therefore are limited when it comes to the features and functionalities of building automation and control systems [33]. However, the largest share of such buildings is expected to be retrofitted soon [34]. This study is an original initiative dealing specifically with Danish healthcare facilities building automation and control design and functionalities in light of the huge stress exerted by the COVID-19 pandemic on such buildings. The work aims at evaluating and auditing the level of BACS functionalities and capabilities, mainly in providing proper indoor air quality and thermal comfort for staff and patients. To evaluate the BACS levels and functionalities, three case study buildings will be considered, located in different Danish healthcare facilities. Each building is unique in terms of age, use, design, systems, schedules and services. Data about the BACS design and functionalities will first be collected. Then IBACSA instrument will be used to audit the level of automation and control in various building domains in the three buildings and evaluate the impacts against five impact criteria. Based on the base case scenario assessment results, three BACS improvement packages are suggested and implemented in IBACSA for each of the three case study buildings. The technical and economic impacts are then reported and assessed, and overall conclusions and notes on the building automation and control levels in the Danish healthcare system are drawn and analyzed.

This work is the first study carried out in Denmark, shedding light on the current status of building automation and control systems in the healthcare sector to evaluate its capabilities to satisfy proper indoor air quality and thermal comfort requirements. This study is carried out as part of the 'Automated Auditing and Continuous Commissioning of Next Generation Building Management Systems' (BuildCOM) research project, which aims at developing and demonstrating innovative tools for automated building management system auditing and continuous building commissioning [35], providing a basis for a methodical auditing and evaluation process for the design of next generation building management systems.

2. Methodology

In this work, the building automation and control systems auditing and smartness evaluation tool IBACSA will be employed and implemented in three case study buildings in Denmark, aiming to assess the current design and functionalities of the BACS in the three buildings and evaluate improvement scenarios considering multiple criteria. The three selected buildings are healthcare facilities situated in three hospitals in different regions in Denmark. Due to the sensitivity of working with healthcare buildings and to preserve privacy and confidentiality, we have chosen not to name the three buildings and just refer to these as a case name: Case A, Case B, and Case C. Although the three case study buildings are healthcare facilities, they are of a different type, use, size, location, and age. This diversity of case studies selection will ensure that the study will deal with various building domains within the Danish healthcare sector and will allow generalization and scaling up of the results and recommendations. Thus, the general results of this work will give to some extent a good assessment level of the building automation and control system design situation in Danish healthcare buildings in general.

The three case study buildings are as follows:

- Case A: Healthcare building constructed in 2001, with some later extensions and upgrades to the ventilation system design.
- Case B: Healthcare building constructed in 2000, undergone a deep energy retrofit in 2020/2021, including new ventilation and cooling systems and BACS design.
- Case C: Healthcare building constructed and opened in 2019.

IBACSA BACS evaluation matrix is highlighted in Figure 2, where the intended approach aims at evaluating each technical domain separately. This provides the capability of quick identification of poorly performing domains with respect to all impact criteria. Thus, each of the eight domains is evaluated and scored against the five impact criteria in addition to a total score provided for each domain, presented in the vertical line on the right of the matrix. The domain scores are referred to as domain assessment scores (DAS), where each DAS is calculated for each domain as the sum of the total impact points attained out of the maximum number of points available, expressed as a percentage. In addition, the matrix allows rating of the BACS with one overall score against each of the five impact criteria considered in the horizontal line at the bottom. These impact scores are referred to as the individual assessment scores (IAS) within each domain as shown in the figure below. The IAS is calculated for each of the five impact criteria considered and is the sum of impact points attained out of the maximum points available, expressed as percentage. The equations for calculating the individual DAS and IAS are shown by Equation (1) and Equation (2) respectively. In addition, the total IAS shown at the bottom of each impact criterion column in Figure 2 is defined as the overall impact of the BACS design and functionalities on each of the criteria. The total IAS is calculated by summing all the individual impacts of each domain with respect to the criterion in question, as shown in Equation (3). I is the single impact criterion score, I_{max} is the maximum impact criterion score obtained by summing up the single impact score for services within a specific domain, d is the specific technical domain among the eight domains considered, ic is the impact criterion among the five impact criteria considered.

$$DAS\ (d) = \frac{\sum_{ic=1}^{5} I(d,ic)}{\sum_{ic=1}^{ic=5} I_{max}(d,ic)} \times 100\% \quad (1)$$

$$IAS\ (d,ic) = \frac{I(d,ic)}{I_{max}(d,ic)} \times 100\% \quad (2)$$

$$IAS_{\ total}(ic) = \frac{\sum_{d=1}^{8} I(d,ic)}{\sum_{d=1}^{8} I_{max}(d,ic)} \times 100\% \quad (3)$$

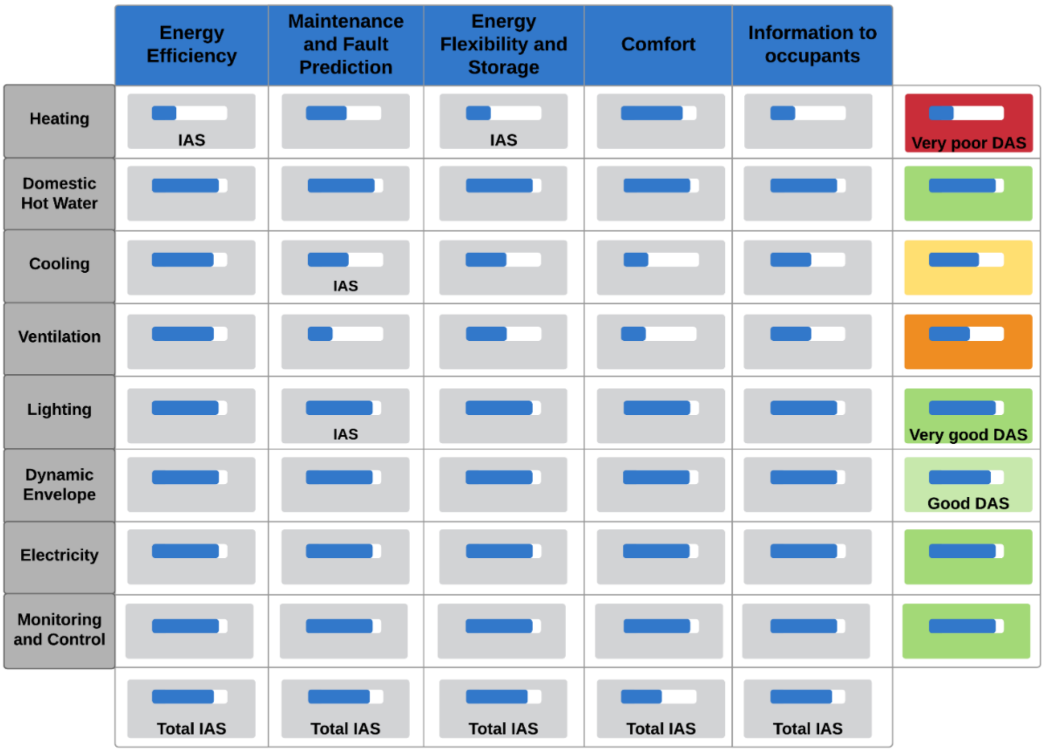
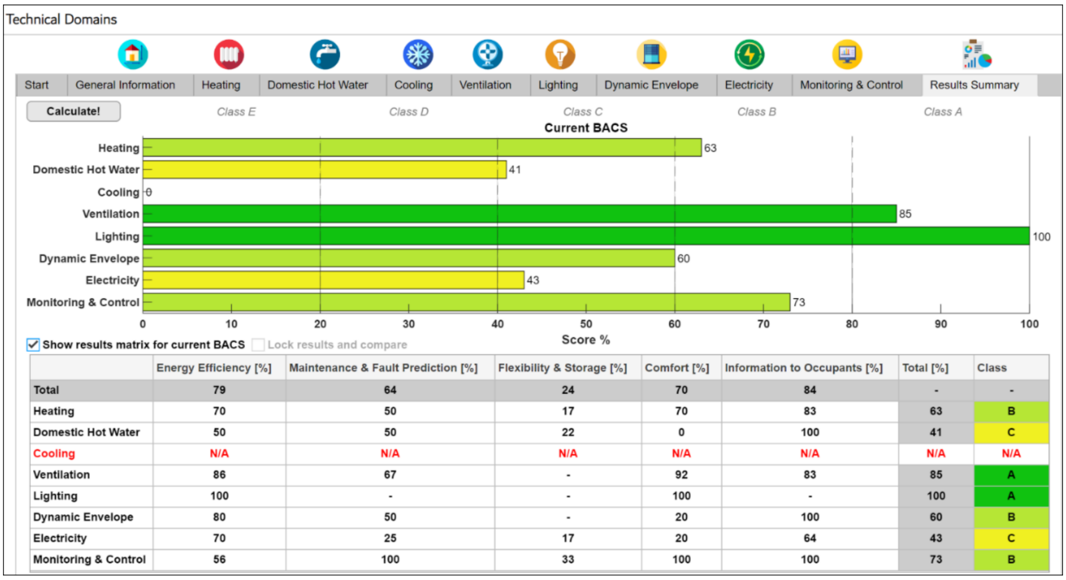


Figure 2. IBACSA evaluation matrix [29].

A screenshot of IBACSA 'Results Summary' tab is provided in Figure 3, showing all the evaluation results and highlighting clearly in colors the good and bad performing technical domains as well as the impact criteria which are satisfied the most and the least.

The overall work methodology with the various phases is summarized in Figure 4. The work will start with the first phase of information collection. At this stage, all information required to assess the building automation and control system will be collected and reported. This includes all relevant documents, drawings, maps, technical reports, retrofitting reports, interviews with the technical managers and feedback from building staff and users. This stage will be followed by the BACS baseline scenario evaluation in IBACSA. Thus, all information related to building automation and control functionalities is inserted in IBACSA, including various building domains and services. This will allow evaluation and auditing of the current BACS in the three buildings, and the scores are reported. Considering the results of the base case BACS auditing, three packages of BACS design and functionalities improvements are implemented for the three case studies, focusing on (1) technical systems enhancement, (2) indoor air quality and comfort, and (3) energy efficiency. The technical and economic impacts are then reported.



	Energy Efficiency [%]	Maintenance & Fault Prediction [%]	Flexibility & Storage [%]	Comfort [%]	Information to Occupants [%]	Total [%]	Class
Total	79	64	24	70	84	-	-
Heating	70	50	17	70	83	63	B
Domestic Hot Water	50	50	22	0	100	41	C
Cooling	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Ventilation	86	67	-	92	83	85	A
Lighting	100	-	-	100	-	100	A
Dynamic Envelope	80	50	-	20	100	60	B
Electricity	70	25	17	20	64	43	C
Monitoring & Control	56	100	33	100	100	73	B

Figure 3. Screenshot of IBACSA 'Results Summary'.

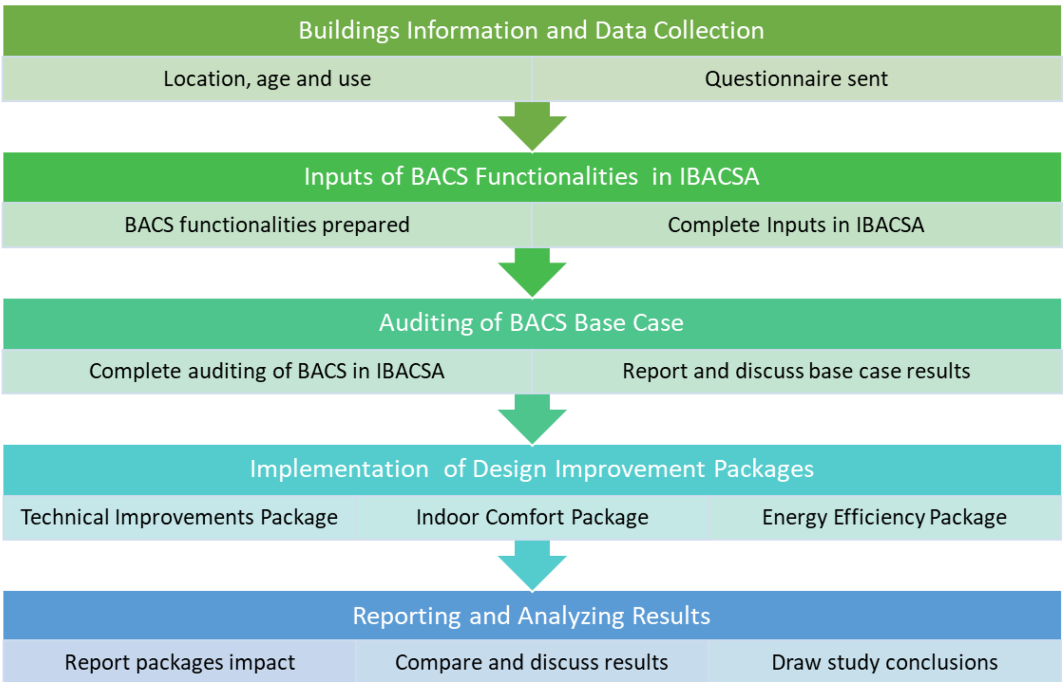


Figure 4. Overall work methodology.

3. Selected Case Study Buildings

In this section, a short introduction to each case study considered will be presented. Also, overall information on the BACS system design, building services, control and management functionalities and automation functions are summarized and reported. In each of the three cases, overall information regarding the BACS design and evaluation is collected and documented. This includes information reported as part of the building management system design, specifications of the active energy supply systems including heating, cooling and ventilation units, mechanical and electrical drawings and building maps and characteristics. In addition, a questionnaire, included in Supplementary Materials (This aincludes a copy of the questionnaire which was sent to each of the technical managers in the three case study healthcare facilities to inquire about the various functionalities corresponding to each of the building domains and services (In Danish)), was sent to each of the technical managers in the three healthcare facilities to inquire about the various functionalities corresponding to each of the building domains and services.

3.1. Case Study A

Case A is a healthcare building that was constructed in 2001, housing the hospital's emergency room, offices, on-call rooms, storage, etc. The building is located in the Capital region of Denmark. Certain information was unavailable and has therefore been assumed based on the technical manager's feedback and responses. This includes some information about the domestic hot water units as well as certain elements of the heating and ventilation system. The heating demand is covered by district heating, and the supply is controlled on an individual room level, with a thermostatic valve. The supply temperature is based on automatic central control, which depends on the filtered outside temperature. The pumps running the system have multi-stage control. The operation of heating system is based on a fixed time schedule. There is no reported thermal energy storage (TES) in this building. For reporting of heating system performance, a central reporting of current performance is in use where less than 50% of the relevant heating loads are metered. For domestic hot water, there is automatic on/off control of the charging of the storage, as well as automatic control of the temperature. The pump providing the flow employs a demand-driven control. This means that temperature and flow sensors are implemented, allowing variable pumping rates based on the demand. There is no reporting on domestic hot water usage.

The cooling provided in the building has similar controls as the heating, the only difference being that it has an automatic central control, instead of individual room control. The associated pumps have multi-stage control, the distribution is time scheduled, while the reporting is only central, and there is less than 50% of the cooling loads being metered. For the ventilation system, there is a central level control which is based on information from air quality sensors such as CO_2 and humidity. The supply airflow rate depends on occupancy, meaning that the rate increases when occupancy is detected. The airflow control is automatic and based on air pressure, and there is overheating control, making sure the supply air is not overheated. There is no icing heat recovery control, meaning that if there is high humidity and low outside temperature, the exhaust air is not protected against freezing. The setpoint is constant and can only be changed manually. There is no control of the use of outside air to cool down the internal fabric or inside air. Reporting of the indoor air quality is in real-time using CO_2 sensors, and the performance of the ventilation system have central reporting of current performance. The lighting system uses predominantly manual on/off switches, and there are no adjustments of intensity based on the daylight levels. In terms of the dynamic envelope, the blinds control is manual, the windows are manually opened, and no windows have the possibility to change transparency as smart windows. This also means that there is no control of the building's dynamic envelope performance at any level.

There is some locally produced electricity on the premise with installed PVs, though due to the legislative constraints, this electricity produced is not allowed to be stored, and the consumption is not optimized since it is a public healthcare building. If there is the availability of electricity production, it will be used onsite. In case of excess production, it will be fed to the grid, with no payment for the hospital. The current generation of locally generated electricity is reported, together with historical data, and the electricity consumption of the building is given as real-time feedback. Less than 50% of relevant electricity loads are metered. It is possible to charge EVs on the premise but with no reporting for the occupants. For the overall monitoring and control in the building, some general areas are covered. For example, it is not possible to heat and cool at the same time.

In addition, management for both heating and cooling setpoints are adapted from a central room and the HVAC system runs on a predefined time schedule. There is no control of thermal exchanges in the building and no fault-detection and diagnostics platform in place.

3.2. Case Study B

Case B is a healthcare building constructed in 2000 and has undergone a deep energy retrofitting process in 2020/2021. The building is expected to be fully in use by the end of 2021 and the beginning of 2022. The building is located in the Funen region of Denmark. It houses both plasmapheresis, blood donor units, screening facilities, cancer treatment units, offices, and laboratories. The retrofitting process has led to new ventilation and cooling units being installed, new sensors and meters implemented, a brand-new building management system implemented, and a whole retrofitting of the interior envelope. Most of the information was provided by the technical manager of the building, present in the building on a daily basis, so very little information has to be assumed. The heating supply is controlled individually for rooms, with communication between controllers and BACS, and uses occupancy detection. The thermally activated building systems (TABS) have advanced central automatic control, which self-regulates room temperature while maintaining a comfort range and keeping the heating demand low. It also includes some temperature feedback for control. In addition, the building utilizes the outside temperature to regulate the heating setpoint, and the associated pump operates with variable speed. The heating system has an implementation of reporting with fault detection and predictive maintenance as well as sub-metering for over 50% of the relevant heating loads. Demand side management is implemented to some extent being controlled by a scheduled operation. Domestic hot water has no storage charging control, nor storage temperature control. The circulation pump is operating based on demand and the reporting includes fault detection and predictive maintenance.

For cooling, the supply is controlled by the individual room; there is communication between sensors and BACS as well as occupancy detection. The temperature is controlled based on outside conditions, and the distribution pump has variable speeds. On the other side, the cooling units in the building have multi-stage control depending on demand and the storage of the cooling is operating with a time schedule. The cooling system is equipped with advanced fault detection and predictive maintenance as well as submetering for over 50% of the relevant cooling loads. Demand-side management is implemented to some extent, being controlled by a scheduled operation. The ventilation is controlled by occupancy detection, where the airflow rate increases if someone is present in the room considering the CO_2 level. There is automatic flow and pressure control with both overheating and icing protection. The setpoint for supply air temperature depends on the outside temperature, and the building utilizes outside air for cooling parts of the building naturally. Thus, night ventilation is also implemented as an option. Reporting includes real-time air quality measurements, historical data as well as warnings on maintenance or occupant actions. The performance of the ventilation is reported with fault detection and predictive maintenance capabilities. In terms of lighting, the building has both automatic motion detection and daylight sensors for the lighting system control. The dynamic envelope includes motorized blind operation with control using sensor data, detection on windows state (open/closed) and there are smart windows with integrated control with other systems such as heating and lighting.

There is no locally produced electricity, and therefore no storage or reporting for it either. It is not possible to charge EVs, though the electricity consumption of relevant loads is sub-metered with more than 50% of the installed capacity. Regarding the overall monitoring and control in the building, it is not possible to simultaneously heat and cool, and the heating and cooling setpoints are scheduled while also including unoccupied times into the system. All occupied areas have management of heat/cold, and the run time for the HVAC system is based on demands as well as predictive control or external grid signals. There is a fault detection and diagnostics platform implemented within the building management system, but there is no smart grid integration. The occupancy detection features are also used to control several systems in the building, including ventilation, cooling and lighting units.

3.3. Case Study C

The building in Case C is a new building where the construction was finished in 2019 and since then has been in full use. The building is located in the Jutland region of Denmark. It houses a large portion of the hospitals bed wards, divided into several floors, with associated functionalities. It also houses the hospital's blood bank, auditorium, and technical rooms. It is built in compliance with the low energy class of 2020, as well as indoor climate class A based on the latest Danish regulation for buildings [36]. For this case, a large sum of information was collected from documents and specifications, and the rest was informed by the building technical managers and users. The heating demand in the building is provided by district heating and controlled individually for each room, being able to deviate a couple of degrees from the automatic central control. The distribution pumps are multi-stage, and the heat distribution is automatic with start/stop. Control of the generators are dependent on the outside temperature, affecting the setpoint of the generator. The reporting of the heating includes current data, historical data, and forecasting, while less than 50% of the relevant heating loads are covered by meters. There is no storage of domestic hot water, and therefore no control of the storage or storage temperature. The circulation pump is demand-controlled, while the generators are run based on a fixed priority list. The reporting of the heating includes current data, historical data, and forecasts. There is no reported thermal energy storage (TES) in this building. This is typical for such hospital buildings to avoid the growth of legionella bacteria in the water supply.

Regarding the cooling system, the supply is controlled for the individual room, with communication between the controllers and the BACS system, and the supply temperature is controlled by demand. The pump has variable speeds, and there is no cooling storage in the building. The control of the cooling generator is dependent on demand, and the generators are on a fixed priority list. The information is reported with fault detection and predictive maintenance capabilities, while more than 50% of the relevant cooling loads are monitored. Ventilation is controlled on a room/zone level, with automatic flow based on pressure control in the air handling units, including protection against overheating and icing. The exhaust airflow rate and the supply temperature have variable control, including load compensation. The reporting of air quality is in real-time, and the ventilation system performance is equipped with fault detection and predictive maintenance capabilities. There is occupancy-based control for the lighting system, including scheduled off times, and the light intensity adjusts according to the daylight in the specific room. The dynamic envelope includes blind control combined with light/HVAC control, but there are no automatic operable windows or skylights, no smart windows, and no reporting of the opening/position.

There is the on-site generation of electricity from an integrated PV system on the roof, where the excess production is fed into the grid. Current and historical electricity production data are reported, where the general electricity consumption is reported with real-time feedback. It is possible to charge EVs in the facility, but there is no reported information to occupants. The submetering is installed on more than 50% of the relevant electric loads, and the interaction with the grid has optimized controls, based on external grid signals and local predictions. In terms of the overall monitoring and control in the building, there is partial building fault detection process, and occupancy detection is used for individual functions, such as lighting. It is not possible to simultaneously heat and cool the rooms, and both the heating and the cooling setpoints are managed from a central location, taking periods of no occupancy into account. Management of the HVAC system has an on/off control for heating and cooling generators based on building loads.

4. Current BACS Auditing

For each case of the three health care buildings, all the information presented in the previous section regarding the BACS design and the corresponding controls and functionalities, was collected, validated and introduced as inputs to the eight domains and 60 various services in IBACSA, aiming to audit and evaluate the current design of the BACS system. In this section, the results of the auditing of the BACS base case scenario in each of the buildings considered will be presented and summarized, along with an analysis and discussion on the scores and ratings. The results are given as a summary, reporting a total score within each technical domain. Besides looking at a total score within each domain, IBACSA tool also provides a scoring matrix, dividing the scores within each domain into the area of performance. This can provide detailed information about which impact criteria are lagging behind. It is important to evaluate each case individually since the building age, use, type, and the corresponding energy systems and services all impact the auditing of the BACS.

4.1. Case Study A

Introducing the data and services functionalities information for Case A into IBACSA, the overall auditing results of the BACS in the building are shown in Figure 5. Overall, it is noted that the building BACS evaluation is not rated that high, with all the initial scores suggesting a low level of control functionalities in the majority of the domains. The relatively best performing domains are the ventilation system control with 52%, monitoring and control with 45% followed by the heating domain with 29%. On the other hand, both lighting and dynamic envelope domains score zero, supported by the fact that the building lighting control is absent and there are no daylight or motion sensors implemented in rooms.

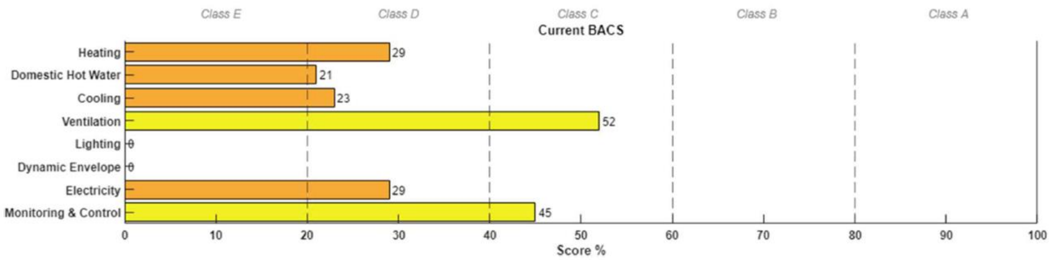


Figure 5. BACS auditing results for case study A along with domains assessment classes.

To increase the score of the lighting domain, it will require a basic implementation of occupancy detection or motion sensors along with daylight sensors. If both are automatically implemented so that the lights turn on/off depending on movement, as well as adjust light intensity based on the amount of natural daylight in the room, the score will increase to 100%. In the case of the dynamic envelope, it would require automatic blinds or better window designs to be installed. The latter is an expensive option to increase the score. The performance matrix generated by IBACSA for Case A is shown in Figure 6, depicting the overall results of each of the domains against the five impact criteria. It is noted that the impact criteria in which the building is scoring high are comfort, information to occupants and energy efficiency, though these still score relatively low, 39%, 33%, and 32% respectively on average. The impact criterion in which the building is scoring very low is flexibility and storage, with a score of 10%. In terms of the evaluation of the single building domains with respect to the criteria, it is highlighted that the ventilation system domain has the highest score in terms of the impact on energy efficiency (52%) and especially comfort (69%). On the other hand, all the other domains score very low against the criteria considered, generally less than 50%.

	Energy Efficiency [%]	Maintenance & Fault Prediction [%]	Flexibility & Storage [%]	Comfort [%]	Information to Occupants [%]	Total [%]	Class
Total	32	22	10	39	33	-	-
Heating	29	25	0	40	33	26	D
Domestic Hot Water	33	0	11	33	0	21	D
Cooling	25	25	0	33	33	23	D
Ventilation	52	33	-	69	33	52	C
Lighting	0	-	-	0	-	0	E
Dynamic Envelope	0	0	-	0	0	0	E
Electricity	40	25	8	20	45	29	D
Monitoring & Control	50	20	43	57	40	45	C

Figure 6. IBACSA performance matrix for Case A with domains and criteria impacts.

4.2. Case Study B

The data and services functionalities information for Case B were also introduced in IBACSA, and the overall auditing results of the BACS in the building are shown in Figure 7. Overall, it is evident that the building scores high in the majority of the domains, with some exceptions. The highest scoring domains are the lighting with 100%, ventilation with 89% and monitoring and control with 89%, all classified as class A. The worst scoring domains are the electricity with 17%, domestic hot water with 38% and dynamic envelope with 47%. Considering that the building has a new energy management system and building automation platform, it is not a surprise to see that the majority of the technical domains, especially the lighting, ventilation and heating along with monitoring and control system record-high overall score. This shows the positive impact of the retrofitting process on the BACS design and functionalities. On the other hand, the reason for the low electricity domain score (17%) is the absence of onsite electricity generation and storage and the limitation of the connection to the grid.

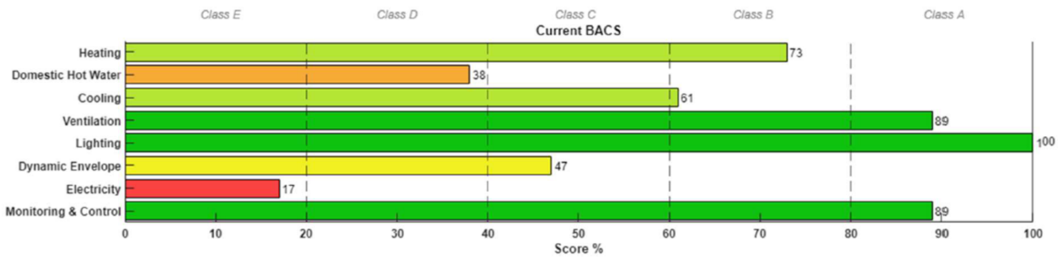


Figure 7. BACS auditing results for case study B along with domains assessment classes, the greener the bar color the higher the rating.

In addition, Figure 8 shows the performance matrix for Case B as evaluated by IBACSA with assessment of the different domains against all the impact criteria. Generally, it is noted that the building domains lead positive impacts with high scores in the majority of the criteria considered, with an average impact score between 72 and 80%. In addition, four of the eight building domains score the highest mark (100%) with respect to information to occupants and maintenance and fault prediction criteria, where the lighting and monitoring and control domains score 100% against the comfort criteria. The very high scores attained by the building domains in the majority of the impact criteria comes with an exception which is the flexibility and storage criteria, scoring a mere average of 17%. This is majorly due to the absence of any connection to the grid, no onsite electricity generation and no storage units integrated.

	Energy Efficiency [%]	Maintenance & Fault Prediction [%]	Flexibility & Storage [%]	Comfort [%]	Information to Occupants [%]	Total [%]	Class
Total	73	80	17	72	73	-	-
Heating	78	100	0	80	100	73	B
Domestic Hot Water	42	100	0	33	100	38	D
Cooling	68	75	20	67	83	61	B
Ventilation	81	100	-	92	100	89	A
Lighting	100	-	-	100	-	100	A
Dynamic Envelope	88	0	-	33	0	47	C
Electricity	29	0	0	0	25	17	E
Monitoring & Control	93	100	57	100	100	89	A

Figure 8. IBACSA performance matrix for Case B with domains and criteria impacts.

4.3. Case Study C

The data and services functionalities information for Case C were also introduced in IBACSA, and the overall auditing results of the BACS in the building is shown in Figure 9. Considering that the building is relatively new, opened in 2019 with a new energy management and automation system installed, the results reported by IBACSA for the different domains are to some extent acceptable. These results show that the building is scoring low in the domains of the dynamic envelope (26%), domestic hot water (34%), and heating (47%). In the case of the dynamic envelope, the score could be improved by implementing smart windows or automatic opening of windows, as well as reporting the performance of the dynamic envelope. None of these was highlighted to be suitable for this building, as informed by the technical manager who claimed that there had been no talk about using smart windows when the building was initiated in 2016, and it would require a large investment to implement either smart windows or automatic windows. Since the only dynamic envelope specification which is in use is the blind control, and this is the only parameter reported, this might not be worth the effort. The reason for a low domestic hot water domain score is the absence of onsite storage, which was also highlighted as being a no option by the technical manager due to healthcare legislation about water storage and legionella bacteria. The best performing domain is the ventilation system again with 91%, followed by monitoring and control with 68% and electricity and cooling with 62% for each of them.

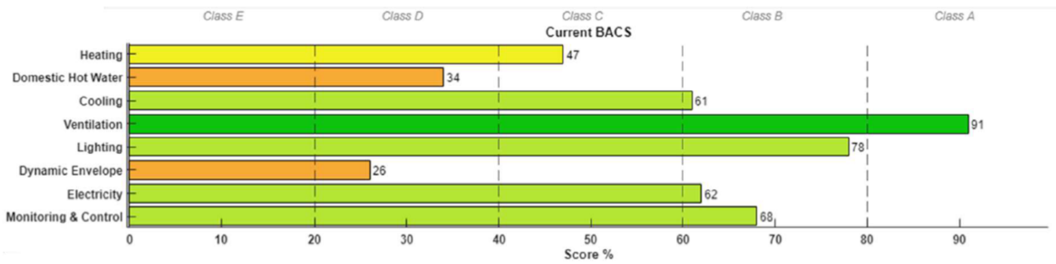


Figure 9. BACS auditing results for case study C along with domains assessment classes, the greener the bar color the higher the rating.

In addition, Figure 10 shows the performance matrix for Case C as evaluated by IBACSA with an assessment of the different domains against all the impact criteria. Generally, it is noted that the building domains return acceptable scores in the majority of the criteria considered, with an average impact score between 55% and 71%. The lighting system scores 100% when it comes to comfort, but the standout performer is the ventilation domain which scores high in the majority of the criteria with 100% for energy efficiency, 83% for maintenance and fault prediction, 92% for comfort, and 67% for information to occupants. The lowest scoring criteria is again the flexibility and storage with an average score of 27%, although some domains have a relatively good score in this regard, mainly electricity domain (42%) and monitoring and control (43%).

	Energy Efficiency [%]	Maintenance & Fault Prediction [%]	Flexibility & Storage [%]	Comfort [%]	Information to Occupants [%]	Total [%]	Class
Total	68	56	27	71	68	-	-
Heating	57	50	0	60	83	53	C
Domestic Hot Water	42	50	0	33	100	34	D
Cooling	61	75	40	67	83	61	B
Ventilation	100	83	-	92	67	91	A
Lighting	67	-	-	100	-	78	B
Dynamic Envelope	38	0	-	33	0	26	D
Electricity	80	50	42	80	64	62	B
Monitoring & Control	86	40	43	86	60	68	B

Figure 10. IBACSA performance matrix for Case C with domains and criteria impacts.

5. BACS Improvement Scenarios

Based on the results reported in the previous section on the base case BACS assessment and auditing in IBACSA for the three case study buildings, it is evident that there are some domains that need to be improved in terms of functionalities and control and automation capabilities, aiming to improve the performance against the different impact criteria. Some cases might have physical or legislative limitations and will score low in one or a few specific domains. Two cases, both scoring low in the lighting domain, might have completely different reasons behind the low score. Thus, the recommendations for each case will also consider the legislations and regulations in place along with the technical impacts of the improvements suggested. In this work, three types of improvements to the BACS are investigated depending on the improvement driver. Technical improvements focus on low-scoring technical domains, with intentions of improving specific domains or introducing certain systems which affect multiple domains. Comfort improvements, driven by the fact that this impact criterion is vital in health care facilities, and finally, energy efficiency improvements, aiming to enhance the rating of the building from an energy efficiency perspective, with a direct impact on both the technical and economic performance. In the next sections, we will present three BACS improvement scenarios for each of the case study buildings based on the drivers mentioned above.

5.1. Technical Improvements Package

The results for the different technical domains functionalities assessment and auditing have led to highlighting the low-performing domains in the three case study buildings. The technical improvements package will aim to improve the performance of the low-scoring technical domains against the different considered impact criteria. Through focusing on the technical possibilities, improvements suitable for the specific case are implemented. This could be system capabilities and units that are in plan to be installed in the near future based on communications with the technical managers, or systems that are easy to be upgraded from the technical point of view and also being affordable. Overall, an improvement to the low-performing technical domains scores is the goal.

5.1.1. Case A

To improve Case A's technical domains scores and to consider the base case evaluation results, it is recommended to implement an extensive reporting system to domains such as heating, domestic hot water, cooling, ventilation, and electricity, increasing the amount of sub-metering to more than 50% of the loads as well as implementing a fault detection and diagnostics platform. Table 1 shows the results of the different technical domains scores after implementing the modifications with the new functionalities and capabilities.

It is obvious that the implementation of the technical improvements package has lifted the scores of the majority of the domains, majorly monitoring and control from 45 to 66%, ventilation from 52 to 67% and domestic hot water from 21 to 41%. One note made by the technical manager of the building is that in the very near future, the plan is to upgrade the building energy management system and implement additional submeters and sensors on different levels. This fits very well with the suggested technical improvement package. On the other hand, the package implementation does not increase the score of flexibility and storage, since no storage units to provide flexibility are added. All other impact criteria increase energy efficiency by 5%, maintenance and fault prediction by 34%, comfort by 9% and majorly information to occupants by 42% to reach a new score of 75%.

Table 1. The results of the different technical domains scores after implementing the modifications of the technical improvements package in Case A.

in	Old Score (%)	New Score (%)	Assessment Class
	29	38	D
	21	41	C
	23	32	D
	52	67	B

Table 1. *Cont.*

Technical Domain	Old Score (%)	New Score (%)	Assessment Class
Lighting	0	0	E
Dynamic Envelope	0	0	E
Electricity	29	38	B
Monitoring & Control	45	66	D

5.1.2. Case B

When it comes to the technical domains, the situation is different for Case B, as the majority of the technical domains score high in the base case scenario as highlighted by IBACSA. This is to a large extent expected as the BACS was recently upgraded, and optimal functionalities and capabilities were added on different levels. The only low-scoring domain is the electricity domain with only 17%. To improve the automation and control systems for Case B, the score in electricity can be increased significantly if locally produced electricity by PVs or similar units were implemented, increasing the flexibility and storage. The day-to-day technical manager in the building informed that even though this would be recommended; physically, there was no room for PVs on the roof of the building due to the huge new ventilation and cooling units installed. So, since the building is situated is in a high-density part of the city, no nearby placement is possible either. A possibility for increasing the electricity score would be to implement EV charging, which would increase the score from 17% to 21%. Also, the addition of information for the occupants regarding the EV charging would bring it to 29%. Another possibility to improve the electricity score is the implementation of reporting real-time electricity consumption on a building level. This would increase the score further to 42%.

Increasing the score for domestic hot water would require some storage and control of hot water used for various services, majorly the temperature levels. This is, however, not possible since the hospital has strict requirements regarding the risk of legionella bacteria, and therefore it is not allowed to have such storage onsite. The score for the dynamic envelope can be increased by implementing reporting with historical data and predictive maintenance and implementing a light/blind/HVAC control. This would result in an increase for the dynamic envelope score from 47 to 84%, reaching class A.

5.1.3. Case C

Also, in the case of the BACS for Case C, the initial evaluation results are satisfactory, with acceptable scores in the majority of the domains. The dynamic envelope score is relatively low but as informed by the technical manager, there is no intention of upgrading the building in this regard due to the high cost of such measure. In terms of heating, additional control regarding heat supply and fluid temperature would be a probable improvement, which would increase the heating score. Combining that with a load or demand-based control for heat generators (in this case, district heating), would increase the score further from 47 to 73%. In terms of the impact criteria, the improvements suggested for the heating system control upgrade would lead to a 17% increase on the score of flexibility and storage for the heating domain. The reason for this increase is that the building would be able to adjust the heat generator capacity based on demand, introducing additional flexibility to the system.

5.2. Comfort Improvements Package

Within the healthcare system, indoor comfort and air quality are one of the top priorities, especially in light of the COVID-19 new measures and impacts. This is mainly the reason why in all three cases, the ventilation system is the top performer domain. The National Board of Health in Denmark highlights that the comfort of people includes temperature, lighting, static electricity, and humidity [37]. In terms of IBACSA auditing and assessment methodology, all technical domains have the possibility to be upgraded and improved against the comfort criteria. In this section, improvements targeting enhancing the overall building comfort criteria score are aimed at. The basic BACS evaluation against the comfort criteria in the three buildings has reported a score of 39%, 72%, and 71% in Case A, B and C, respectively.

5.2.1. Case A

With an overall comfort score of only 39%, Case A is the lowest-performing among the case studies in this regard and appears to be the case with the largest effort needed to establish an acceptable comfort level. Therefore, aiming to enhance the indoor comfort levels, improvements targeting the heating domain are suggested, including improvements to the heat supply control, TABS heat supply control, heat fluid supply temperature control, heat distribution control, and heat generator control, along with introducing the use of demand-based supply and feedback control. This improvements package is able to increase the total comfort score from 39 to 46%. This also affects all other impact criteria since an increase in the control level and functionalities will increase the score of energy efficiency, flexibility, maintenance, and fault prediction and information to occupants.

Implementing similar improvements to all other domains increases the total comfort from 39% to 64%, as highlighted in Figure 11a. This also includes introducing icing control to the ventilation units, automatic detection, and control of the lighting. However, no improvements in relation to the dynamic envelope were made, along with no changes to the storage of domestic hot water or electricity due to the legislative requirements. Comparing these results to the base case, all impact criteria have had an improvement. Total score of energy efficiency increases by 25%, maintenance and fault prediction by 22%, flexibility and storage by 5% and information to occupants by 5%. Looking at the classes of the domains, the heating and cooling have increased by one class, ventilation increased by two classes, while lighting have increased by four classes, going from 0 to 100% in the average score.

5.2.2. Case B

Case B has already scored high with respect to the comfort criteria in the base case BACS assessment using IBACSA. An overall comfort score of 72% limits how much can be done in terms of enhancing the BACS functionalities, and improvements could be seen as an addition rather than being a necessity. If the same improvement measures implemented in Case A are also employed in Case B, this will increase the comfort score of the building from 72% to 81%. The results of the upgrades can be seen in Figure 11b. For this, higher levels of demand-control were introduced, as well as a combined light/blind/HVAC control on the blinds in the building. For Case B, control within areas such as domestic hot water, electricity production/storage have not been employed for the same reason as Case A. Comparing these upgrades to the base case results, energy efficiency has increased by 12%, maintenance and fault prediction by 4%, flexibility and storage by 5% and information to occupants by 3%. Besides this, the heating and cooling domains have both been enhanced in overall and moved from class B to class A.

	Energy Efficiency [%]	Maintenance & Fault Prediction [%]	Flexibility & Storage [%]	Comfort [%]	Information to Occupants [%]	Total [%]	Class
Total	57	44	15	64	38	-	-
Heating	64	75	10	80	50	57	C
Domestic Hot Water	33	0	11	33	0	21	D
Cooling	64	75	10	78	50	56	C
Ventilation	71	67	-	92	33	72	B
Lighting	100	-	-	100	-	100	A
Dynamic Envelope	0	0	-	0	0	0	E
Electricity	40	25	8	20	45	29	D
Monitoring & Control	57	20	43	57	40	47	C

(**a**)

	Energy Efficiency [%]	Maintenance & Fault Prediction [%]	Flexibility & Storage [%]	Comfort [%]	Information to Occupants [%]	Total [%]	Class
Total	85	84	22	81	76	-	-
Heating	96	100	17	90	100	86	A
Domestic Hot Water	42	100	0	33	100	38	D
Cooling	93	100	30	89	100	82	A
Ventilation	90	100	-	100	100	96	A
Lighting	100	-	-	100	-	100	A
Dynamic Envelope	100	0	-	50	0	58	C
Electricity	29	0	0	0	25	17	E
Monitoring & Control	93	100	57	100	100	89	A

(**b**)

	Energy Efficiency [%]	Maintenance & Fault Prediction [%]	Flexibility & Storage [%]	Comfort [%]	Information to Occupants [%]	Total [%]	Class
Total	80	67	30	80	73	-	-
Heating	83	100	17	80	100	78	B
Domestic Hot Water	42	50	0	33	100	34	D
Cooling	82	100	40	100	100	81	A
Ventilation	100	83	-	92	67	91	A
Lighting	100	-	-	100	-	100	A
Dynamic Envelope	38	0	-	33	0	26	D
Electricity	80	50	42	80	64	62	B
Monitoring & Control	86	40	43	86	60	68	B

(**c**)

Figure 11. Performance matrix results of Comfort Improvements Package in (**a**) Case A, (**b**) Case B, and (**c**) Case C.

5.2.3. Case C

Similar to Case B, a score of 71% for comfort in Case C is very much acceptable, and thus, improvements on the level of automation and control would be deemed as an addition rather than necessary. However, a suggestion package to improve the comfort level further is designed and implemented, including the introduction of demand-based control, communication between controllers and BACS, as well as feedback control. The control of lighting has been upgraded to automatic detection instead of manual use. For Case C, the automation level of the following domains: domestic hot water, ventilation, dynamic envelope, electricity, and monitoring and control have not been changed either because of legislative requirements or the fact that the systems are already at the highest level of automation in the base case. The improvements package results are shown in Figure 11c, with an increase in comfort from 71% to 80%. The scores for the other impacts are also increased as follows: energy efficiency by 12%, maintenance and fault prediction by 11%, flexibility and storage by 3%, and information to occupants by only 2%.

5.3. Energy Efficiency Improvements Package

In the guidelines provided by the European standard for building automation and control EN15232, it is estimated that an increase in the BACS score of energy efficiency by 10 points is associated with an approximately 5% reduction in the building's overall energy consumption [28]. Of course, this is an assumption, as each building has its specific age, type, use, systems, envelope and BACS. However, the estimated energy savings could provide a preliminary assessment on the impact of certain improvement measures from an energy consumption perspective. As IBACSA point scoring system for energy efficiency follows the scoring system and recommendations of the EN15232, implementing improvements in the tool can be translated into an increase in energy efficiency points and, as a consequence, an estimation of the predicted energy consumption savings. In this section, an energy efficiency improvement package is implemented in each of the case study buildings aiming to attain a higher score of energy efficiency across all the technical building domains. Some of these improvements are similar to those of the comfort improvements, the main difference being, e.g., control of distribution pumps in the network or sequencing of heat generators which doesn't contribute to an increase in comfort levels, but only the energy efficiency score.

5.3.1. Case A

Focusing on energy efficiency, it can be noted from the base case BACS assessment that the technical domains of heating, domestic hot water, cooling, lighting, and dynamic envelope all score relatively low (less than 40%) against energy efficiency compared to the rest of the domains. Because of the constraints, no changes are made to storage of domestic hot water or the dynamic envelope. Implementing changes with the goal of increasing the energy efficiency has led to the results in terms of points for each domain presented in Figure 12a. This is a very deep retrofit of the functionalities of the BACS aiming to enhance the level of energy efficiency in general. The mentioned upgrades for case A resulted in an increase in the energy efficiency of 50 points, while also increasing by 4 points in maintenance and fault prediction, 10 points in storage and 18 points in information to occupants. Given the estimation that 10 points increase in energy efficiency score would lead to 5% reduction in energy consumption, the resulting reduction in energy consumption for Case A would be around 25%. With the building's annual total energy consumption from the energy label report being approximately 440 MWh, this reduction corresponds to 110 MWh. Assuming an average electricity price of 1.60 DKK/kWh and a heating price of 550 DKK/MWh, it would be possible to achieve annual economic savings of approximately 10.45 k EUR.

5.3.2. Case B

The base case results of the BACS auditing of Case B resulted in an overall energy efficiency score of 73%, with the electricity and domestic hot water domains scoring the lowest with 29% and 42%, respectively. The scores for the other domains are relatively high, highlighting that these domains are already equipped with functionalities enhancing the energy efficiency quotient. Therefore, the improvement package for energy efficiency in this building majorly targets the electricity systems and domestic hot water functionalities and control patterns. The results in terms of points for each domain are depicted in Figure 12b, where the package has led to an increase of 10 points in energy efficiency and thereby an estimated reduction in energy consumption of 5%. These improvements also increased flexibility and storage by 3 points and comfort by 2 points. Assuming electricity and heating costs similar to Case A, implementation of the package would result in an annual economic savings of approximately 1.04 k EUR. Thus, implementing these improvements might not be worth the investment cost compared to the comparatively low energy reduction and savings attained.

5.3.3. Case C

Regarding Case C, the initial energy efficiency rating of the BACS as evaluated by IBACSA is 68%, with the dynamic envelope and domestic hot water domains being the least efficient with 38% and 42% respectively. But overall, the building scores relatively high, and therefore the resulting energy efficiency improvement package is also limited to measures targeting the domestic hot water and heating domains. The results of the energy efficiency improvements impact in terms of points for each domain can be seen in Figure 12c. It is highlighted that the energy efficiency improvement package would lead to an increase in the score by 17 points, with a corresponding energy reduction of around 8.5%. All other impact criteria points increased as follows: maintenance and fault prediction by 2 points, flexibility and storage by 5 points, comfort by 4 points and information to occupants by 2 points. Using the same assumption of heating and electricity cost prices as the other cases, the annual economic savings round up to around 3.95 k EUR.

	Energy Efficiency	Maintenance & Fault Prediction	Flexibility & Storage	Comfort	Information to Occupants	Total	Class
Total	91	10	15	40	17	-	-
Heating	20	2	2	9	5	38	B
Domestic Hot Water	9	0	5	2	0	16	C
Cooling	23	2	4	8	3	40	B
Ventilation	19	4	-	12	2	37	A
Lighting	6	-	-	3	-	9	A
Dynamic Envelope	0	0	-	0	0	0	E
Electricity	4	1	1	1	5	12	D
Monitoring & Control	10	1	3	5	2	21	C

(**a**)

	Energy Efficiency	Maintenance & Fault Prediction	Flexibility & Storage	Comfort	Information to Occupants	Total	Class
Total	97	20	9	41	27	-	-
Heating	22	4	1	9	6	42	A
Domestic Hot Water	7	2	2	1	3	15	C
Cooling	23	3	2	7	5	40	B
Ventilation	17	6	-	12	6	41	A
Lighting	6	-	-	3	-	9	A
Dynamic Envelope	7	0	-	2	0	9	C
Electricity	2	0	0	0	2	4	E
Monitoring & Control	13	5	4	7	5	34	A

(**b**)

	Energy Efficiency	Maintenance & Fault Prediction	Flexibility & Storage	Comfort	Information to Occupants	Total	Class
Total	99	16	17	44	28	-	-
Heating	17	2	1	7	5	32	B
Domestic Hot Water	7	1	2	1	3	14	C
Cooling	25	4	6	9	6	50	A
Ventilation	21	5	-	12	4	42	A
Lighting	6	-	-	3	-	9	A
Dynamic Envelope	3	0	-	2	0	5	D
Electricity	8	2	5	4	7	26	B
Monitoring & Control	12	2	3	6	3	26	B

(**c**)

Figure 12. Results of Energy Efficiency Improvements Package in (**a**) Case A, (**b**) Case B, and (**c**) Case C.

6. Discussion

Based on the results reported above for the three healthcare buildings, it can be noted that the construction year (or building age) tells a lot about the automation and control system installed and its functionalities and capabilities in Danish healthcare facilities. It is highlighted that newer buildings have, to a large extent, followed the recent guidelines and regulations in terms of systems design and automation and control units, while older existing buildings constructed years ago did not have the same technology and level of automation functionalities. In most cases, it can pay off to retrofit older buildings with newer technologies. Generally, the trend in Danish buildings retrofitting is to prioritize the envelope-targeting measures, as walls and roofs insulation and windows upgrade [38–40]. While such measures are important, dealing with the building systems and BACS design functionalities provide other options which in many cases have higher technical and economic feasibility. Such alternative measures could include the implementation of an EMS system, setting additional indoor comfort and air quality sensors, installing additional submeters for electricity, heating and/or other consumptions.

Figure 13 provides a holistic comparison of the class scores for the different domains in the three buildings in the four considered scenarios, the base case, with technical improvements, comfort improvements and with energy efficiency improvements. It can be seen from the scores reported for the three cases in their base case scenario that Case A is scoring the lowest in the majority of the technical domains, except for electricity, where Case B scores the lowest. As mentioned, the reason behind Case B scoring low in electricity is the lack of locally generated electricity, and the absence of the corresponding storage units, as well as the possibilities of charging EVs. The low score of Case C in the dynamic envelope is interesting, compared, for example to an older Case B, constructed 19 years before. However, the reason is that Case B has undergone a deep energy retrofit, where smart windows were implemented, and sensors for open/closed detection for the windows/skylights were fitted in.

	No improvements			Technical improvements			Comfort Improvements			Energy Efficiency Improvements		
	Case A	Case B	Case C	Case A	Case B	Case C	Case A	Case B	Case C	Case A	Case B	Case C
Heating	D	B	C	C	B	B	C	A	B	B	A	B
Domestic Hot Water	D	D	D	C	D	D	D	D	D	C	C	C
Cooling	D	B	B	D	B	B	C	A	A	B	B	A
Ventilation	C	A	A	B	A	A	B	A	A	A	A	A
Lighting	E	A	B	E	A	B	A	A	A	A	A	A
Dynamic Envelope	E	C	D	E	C	D	E	C	D	E	C	D
Electricity	D	E	B	D	C	B	D	E	B	D	E	B
Monitoring & Control	C	A	B	B	A	B	C	A	B	C	A	B

Figure 13. Comparison of the class scores for the different domains in the three buildings in the base case and the three improvements scenarios considered.

Figure 14 presents a comparison of the total points collected by each building in the different scenarios against all the five impact criteria considered. Overall, all three cases scored very low in flexibility and storage caused by, among other domains, the domestic hot water, which indicates that this is an area where hospitals and healthcare buildings in Denmark need to provide more concentration on. This score is also affected by the legislative constraint of water storage, due to legionella bacteria. It is very well noted that while the three packages allow higher points accumulation and relative high score in the three cases, Case A is the one exhibiting the largest increase in the number of points accumulated due to the lower initial level of building automation and control in this case compared to Case B and Case C. On the other hand, it is obvious that the comfort improvement measure has improved the comfort criteria in the three cases by 14, five and five points for cases A, B and C, respectively. In addition, implementing the energy efficiency improvement package has led to a drastic increase in the number of energy efficiency points in the three cases, with an increase of 50, 10 and 17 points in cases A, B and C respectively.

	No improvements			Technical improvements			Comfort improvements			Energy Efficiency improvements		
	Case A	Case B	Case C	Case A	Case B	Case C	Case A	Case B	Case C	Case A	Case B	Case C
Energy Efficiency	41	87	82	47	88	89	73	101	97	91	97	99
Maintenance & Fault Prediction	6	20	14	15	20	17	12	21	18	10	20	16
Flexibility & Storage	5	6	12	5	6	13	7	8	13	15	9	17
Comfort	22	39	40	27	40	41	36	44	45	40	41	44
Information to Occupants	13	27	26	30	31	28	15	28	29	17	27	28

Figure 14. Comparison of the total points collected by each building in the different scenarios against all the five impact criteria considered.

The current version of IBACSA tool used in this study aims at assessing the design and functionalities of the BACS along with evaluating the smartness of the building by focusing on 8 building domains from an energy and thermal comfort perspective. Moreover, five impact criteria are considered as a basis for the evaluation, including the two major criteria Energy Efficiency and Comfort. To provide a more holistic evaluation and inspired by the healthcare cases considered in this study, the suggestion for the tool post-development and improvement is to include some additional services to the technical domains as water usage, which tends to be a major domain in cases as hospitals, restaurants, and hotels. In addition, more impact criteria may be considered majorly dealing with security, wellbeing, and health.

With the recent outbreak in COVID-19, there is an increasing focus on establishing the optimal indoor air quality, thermal comfort, and air exchange in all buildings, specifically hospitals and healthcare buildings. This obviously highlights the importance of a well-designed, properly installed and controlled ventilation system. In this context, this means that installation of new controls and management units for ventilation systems will be more frequent, and thereby these areas of improvements are easier to justify despite the investment for installation costs and additional sensors and meters requirements. Though in these three cases, ventilation is one of the domains scoring the highest on various levels with respect to all impact criteria, supporting the idea that this is an indispensable domain in Danish healthcare buildings.

7. Conclusions

As a result of COVID-19 cases outbreak, the healthcare system and staff were put under enormous pressure, and the pandemic has caused increasing challenges for healthcare professionals globally aiming to cope with the new pandemic and limit its negative impacts. Denmark is not an exception, and the country has been hit hard by the coronavirus fast spread and negative impacts. This has created huge pressure on the Danish healthcare systems and calls for crucial and urgent measures and interventions. This work is the first study shedding light on the current status of building automation and control systems in Danish healthcare sector, and its capabilities to cope and provide proper indoor air quality and thermal comfort. To assess the BACS levels and functionalities, three healthcare buildings of different type and use are considered as case studies. The aim is to assess and evaluate the level of automation and control in the three buildings against various impact criteria. A first-of-its-kind tool (IBACSA) for BACS assessment and smartness evaluation is employed in the auditing process. IBACSA assesses 60 various building services under eight different domains in the building and reports the results against five impact criteria, including energy efficiency and comfort. Based on the base case BACS scenario assessment results, three improvement packages are suggested and investigated.

Overall, it was shown that Case A has a relatively lower BACS scoring compared to the other two healthcare case study buildings, in which one of them (Case B) has undergone a deep retrofitting process recently and the other case (Case C) was constructed and opened recently in 2019. In addition, one of the notes made based on the assessment is that the three buildings score relatively very low when it comes to the impact criteria of energy flexibility and storage. The reason is mainly either the absence of onsite energy generation units, the absence of integrated storage units, or the lack of connection to the grid. On the other hand, it is obvious that the ventilation system domain in the three buildings scores very high, highlighting the good condition of Danish healthcare buildings ventilation units and asserting the importance of such systems to establish good indoor air quality and thermal comfort. On the other hand, it is clear that the domestic hot water domain scores relatively low in the three healthcare buildings, highlighting that this domain needs to be considered more seriously in the Danish healthcare facilities in terms of the automation and control capabilities and functionalities. Nevertheless, this assessment considered only three case study healthcare buildings, but considering the variety in use and type of the selected buildings, the results could to some extent be generalized and scaled up to draw preliminary conclusions and notes on the overall status of the Danish healthcare sector facilities in terms of BACS design and automation and control levels. The results obtained in this study, and building upon the variety of case study healthcare facilities considered, can be used as a basis for future planning, standards, and legislative guidelines. The findings and the highlighted poor-performing technical domains and the poorly reported impacts should be considered more seriously in establishing regulations and standards for the design of future healthcare facilities as well as retrofitting of existing healthcare buildings. This will ensure that these buildings are equipped with effective and flexible BACS aiding with optimal decision-making and capable of delivering the energy and environmental goals and objectives in Denmark.

Energy, and thereby energy efficiency, might not be the main priority in healthcare buildings and hospitals, but generally, there is a very strong link between optimal BACS design and functionalities, higher energy-efficient performance, and better indoor comfort and air quality in such buildings. Moreover, we should not neglect and underestimate the impact of good indoor air quality and thermal comfort on the staff and practitioners' productivity as well as the patients' physical and mental health. In addition, with the strict environmental goals set, a continuous effort will most likely be put into such buildings, among other buildings, to lower their environmental impact and carbon footprint through energy-efficient measures for energy consumption reduction. The emerge of the COVID-19 pandemic and other similar diseases and infections that might hit humanity, calls for an elevated level of efforts towards establishing optimal control and management of the indoor air quality and thermal comfort in hospitals and healthcare facilities, which are already under ominous pressure.

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