Building Assessment Framework from Whole Building to Components: A Danish Case Study.

Kamilla Heimar Andersen [a,], Simon Pommerencke Melgaard [a], Rasmus Lund Jensen [a], Thomas Fehr [b], Anna Marszal-Pomianowska [a], Per Kvols Heiselberg [a]*

[a] Department of the Built Environment, Aalborg University, Aalborg, Denmark, * Kahean@build.aau.dk

[b] EK Energiekonzepte AG, Zürich, Switzerland

Abstract. Well-functioning buildings are crucial for the occupant's health and comfort and for reducing the CO_2 emissions from the building sector. A first step in assessing a well-functioning building is to know the current state of the building by, for example, relevant Key Performance Indicators (KPIs). Choosing suitable KPIs to provide a clear message can be challenging; however, beneficial to convey a message to the building actors. This study proposes a Building Assessment Framework to mitigate the latter, consisting of 1) a flexible and novel KPI tool and 2) a step-by-step KPI assessment methodology applicable to all buildings, systems, subsystems, and components. The KPI tool provides the user with a list of KPIs suited for all building systems, and with a separate backend and frontend, it is an easy tool to use. The KPI assessment methodology will guide the user through 5 steps and propose visualization of the chosen KPIs. The step-by-step KPI assessment methodology consists of 5 steps: 1) identification of the selected building resolution level 2) selection of the KPIs for the resolution level 3 + 4) recognition and cross-referencing of necessary sensors 5) choice of benchmarking for the data. The results from the KPI assessment using historical data from a university building located in Denmark demonstrate that the KPI tool is generic, making it applicable to all levels of a building and its systems. The Building Assessment Framework is flexible; it can be used over short and long periods (instantaneous to several years) and implemented in the building management system. However, it is necessary to be used with historical data, allowing for the real-time performance evaluation of the selected buildings or systems, thereby enabling the users to spot potential abnormal behavior that can lead to faults in the systems.

Keywords. Key Performance Indicators (KPIs), building systems, building assessment, energy use, rotary heat exchanger, air handling unit (AHU), open historical data
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1. Introduction

Recent developments in Danish national policies [1] and the European Commission highlight the importance of reducing energy use in buildings [2], thus decreasing CO_2 emissions. Since the newly built share accounts for only 1% annually, to reduce CO_2 emissions from the building sector, controlling and operating the existing building stock efficiently and transparently is essential. Key Performance Indicators (KPIs) have been shown to incentivize building actors such as building owners, managers, and occupants to reduce the energy use in buildings [3]. The development and use of KPIs and assessments have notably increased in the last decade [4] [5] [6]. The latter aims to calculate the performance of buildings, systems, and components and thus provide easily accessible and valuable information to the building actors.

Previous studies regarding the development of KPIs have mainly focused on comparisons with the designed value from a numerical calculation (e.g., simulation) [7]. It is known that this comparison can create a performance gap due to the difference between the assumptions in the numerical calculations and the real-life operational behavior of the building systems [8]. With the increased instrumentation monitoring and access to data from buildings [9] [10], a deeper assessment with real-life data of building systems is feasible. Another research gap identified was adapting KPIs to all building systems, from whole building to component level [7]. Also, there is still a lack of knowledge on selecting the appropriate KPIs, depending on the building monitoring level (data quality & frequency and measured variables) and analytic methods (KPI assessment type and data acquisition).

The Horizon2020 "SATO" (Self-Assessment Towards Optimization of Building Energy) project https://www.sato-project.eu/ aims to develop and implement a cloud-based platform that can perform self-assessment and optimization of energy-consuming devices in a building so-called the SATO platform. The SATO platform will use an artificial intelligence approach combined with 3D BIM-based visualization to provide an accurate vision of the real-life energy performance of buildings and appliances. In this project, definitions of key performance indicators got substantial attention as they play a prominent role in the self-assessment and self-optimization platform [11]. The first part of the SATO platform is the development of the SATO KPI Tool, providing a list of KPIs used to assess the whole building level to the component level.

This study presents a developed Building Assessment procedure using the SATO KPI Tool. Further, the step-by-step KPI assessment procedure is presented using real-life data from a campus building at Aalborg University. The future purpose of the proposed Building Assessment procedure is to be integrated into the SATO platform. Combined with the building management system (BMS), that will facilitate a more efficient real-time operation.

1.1 SATO KPI Tool

The SATO KPI Tool is currently an Excel (.xlsm) based tool to be integrated into the SATO platform, with a frontend and a backend. The full description of the SATO KPI tool, including a detailed list of KPIs, can be found in [12].

The backend of the SATO KPI Tool consists of two main tabs (Tab 1 and Tab 2) shown in Fig. 1 and is not intended to be changed by the general user but to support the selection of KPIs in the frontend. Tab 1 describes the energy system terminology and the SATO KPI Tool user-manual, which describes the content and scope. Tab 2 concerns the Key Performance Indicators, Input for KPIs, Necessary measured variables, Data acquisition methods, and Required time resolution.

The frontend consists of a "Parameter selection" tab (Tab 3) which supports the user in selecting desired KPIs for the chosen building system.

The green color indicates the introduction, the energy system terminology used throughout the KPI Tool, and the user manual. The blue color is the backend content, and the red color is the frontend, which is the only tab the user needs to change.

2. Step by step KPI assessment methodology

This chapter presents the step-by-step procedure of the KPI assessment and can be seen in Fig. 4.
A more detailed and explained step-by-step assessment procedure can be seen in chapter 4 applied to the case study. However, two more aspects must be foreseen before performing a KPI assessment. This consists of mapping the building resolution level and determining the data benchmark. The KPI assessment procedure uses the SATO KPI Tool and identifies specific information about the selected building of choice, the building resolution level, and the data benchmark. The use of the SATO KPI tool is not restricted to this framework, and it can also be used to select individual KPIs for stand-alone monitoring. However, knowledge of building systems is necessary to use this assessment procedure. This is because the KPI tool will assist in selecting KPIs, but the user determines the final choice.

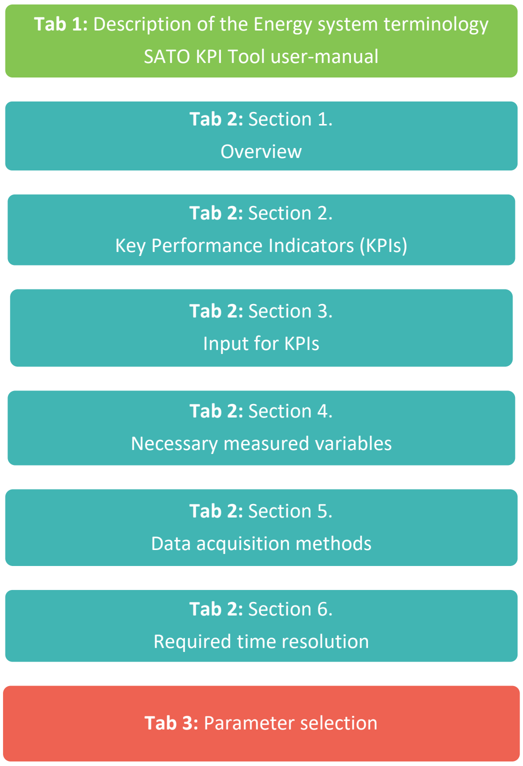


Fig. 1 – Overview of the SATO KPI Tool. It consists of an introduction (green), a frontend (blue), and a backend (red).

2.1 Step 1: Building resolution level

To determine which KPIs are applicable, it is essential to identify which inputs from the building systems are available. A proposed subdivision of a geometry-based and a system-based building resolution is proposed in Fig. 3 and Fig. 4. This type of subdivision can provide proper boundaries and insight into necessary and available inputs for the building and/or systems.

2.2 Step 2: Selection of KPIs

The KPI selection is conducted with the SATO KPI tool. It is expected that the SATO KPI Tool will be available online in April 2022 on this webpage: https://www.sato-project.eu/project-deliverables

2.3 Steps 3 and 4: Identify and cross-reference sensors

Steps 3 and 4 are performed partly with the SATO KPI Tool and manual sorting. Here the SATO KPI Tool will support to identify the physical sensors, resolution, and KPI method necessary for the selected KPI(s) for step number 3. Then, the manual cross-reference of needed sensors and already installed sensors in step number 4.

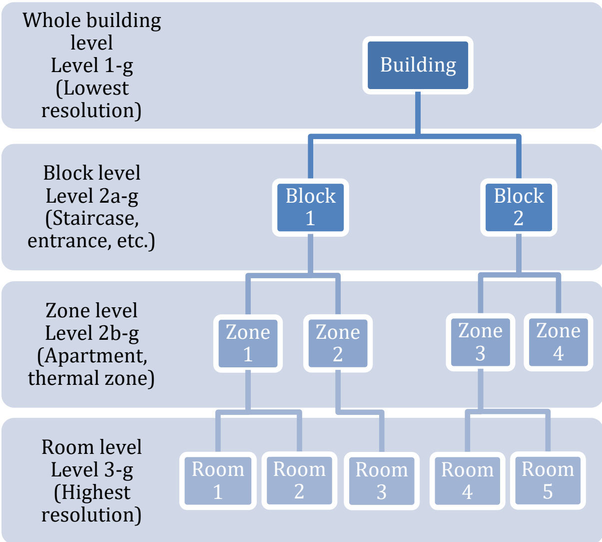


Fig. 2 – Building geometry-based resolution overview.

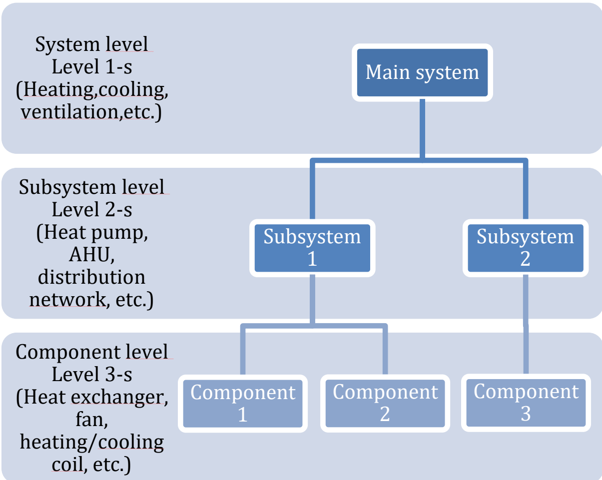


Fig. 3 – Building system-based resolution overview.

2.4 Step 5: Data benchmarking

The SATO project has developed three data benchmarks suggestions (Reference, Actual and Contextual), and one additional benchmark (Historical) is proposed below with examples and applicability.

Reference: Based on numerical simulation/model with standardized input values consisting of manufacturer data or standardized inputs according to standards/guidance compared with historical data from the same building, system, and area.
Example: The dimensioned SFP for an AHU compared to historical data, where the operating conditions are similar to the conditions for the dimensioned SFP.

Actual: Based on a numerical simulation/model with calibrated input values from the actual conditions compared with historical data from the same building, system, and area.

Example: A numerical simulation with calibrated values according to the historical data conditions, e.g., internal loads such as occupancy, lights, or weather for yearly heating use compared with historical data for yearly heating use.

Contextual: Based on historical data from the system and how well a specific service is achieved. Thereby indicating how efficient service is provided and if a higher target of the service causes possible higher/lower energy use.

Example: Heating energy use for a zone or room, compared to the level of thermal comfort provided.

Historical: Based on historical data from the current time period and compared to historical data from previous time periods for the same building, system, or area. If only the current time period is used, it gives an overview of the current performance, while if the previous time period(s) are used, an indicator for the change in performance is obtained. This benchmark is highly dependent on a high share of historical data as it is purely data-driven.

Example: Heating energy use for a year, compared to the heating energy use for the previous years. Coefficient of performance (COP) of a heat pump for a year, compared to the COP for the previous year.

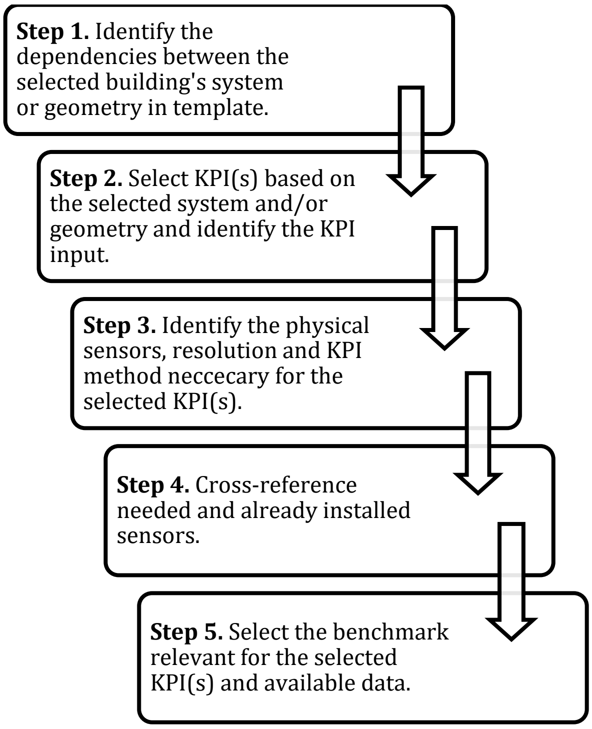


Fig. 4 – SATO KPI Tool step-by-step assessment procedure.

3. Case study

The case study is a university building located in Aalborg, Denmark, which houses the department of the Built Environment (BUILD) at Aalborg University, see Fig 6.

The building is ~9000 m² spread over four stories, with the area split into roughly 1/3 for laboratories and 2/3 for offices. The focus in this case study is only on the Air Handling Unit (AHU) supplying the western part of the offices, for example the 3rd floor can be seen on Fig. 5.

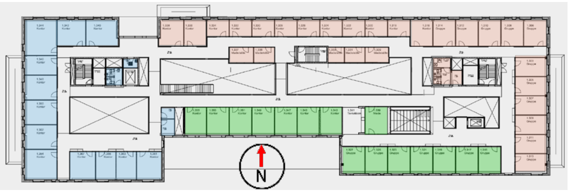


Fig. 5 - Thomas Manns Vej 23, 3rd floor coverage by AHUs, the blue area is covered by the AHU used in this paper.

The data for the case study is retrieved from the BMS system (Schneider Ecostruxure) and the energy management program (EMT Nordic EnergyKey) at Aalborg University. The data used are for the period from August 1st to December 23rd, 2021, with a 1-minute resolution.

Fig. 6 – Department of The Built Environment University building "Build department building" in Aalborg, Denmark.

4. Results and discussion

4.1 KPI Assessment

This subsection presents the result from the KPI assessment of the case study. The results are presented according to the step-by-step assessment procedure in section 2.

Step 1: Building resolution level
In this case study, the focus was on the AHU, so only the system-based building resolution level is shown in Fig. 7.

Step 2: Selection of KPIs
Based on the system from step 1, the SATO KPI tool is used to choose **three** KPIs, **one** for the **AHU** and **two** for the **rotary heat exchanger**. The selected KPIs are shown in Tab. 1.

Tab. 1 – Location, KPI, and the input needed for the KPI identified for the Build department building.

Location	KPI	Input needed for the KPI
Subsystem (AHU)	Specific AHU power (electricity use per m³ air)	Electricity use ; Air flow
Component (rotary heat exchanger)	Temperature efficiency ; Heat recovery	Efficiency ; outdoor air temperature

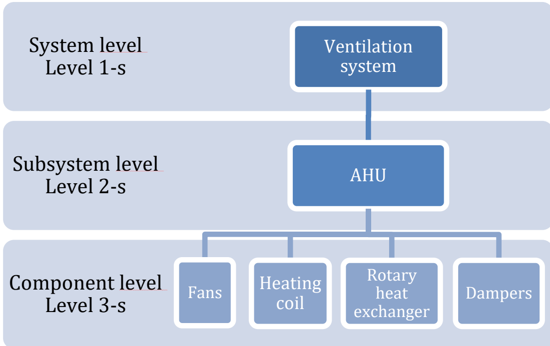


Fig. 7 – The Build department building system-based building resolution level for the ventilation system.

Step 3: Identify sensors and methods for calculating KPIs
From the previous step, the necessary input for each KPI is obtained; based on these, the KPI tool provides the sensor type, resolution, and if necessary, any sub inputs. These are all seen in Tab. 2 below.

Besides the input data, the methods for calculating the KPIs are also obtained. For the specific AHU power (per m³ air), the algorithm is shown in Equation 1.

$$AHU_{el} = \frac{E_{el}}{\sum_{i=1}^{60} Q_{air,i}} \quad (1)$$

AHU_{el} is the electricity use per m³ air $\left[\frac{kW}{\frac{m^3}{s}}\right]$
E_{el} is the electricity use per hour $[kW]$
$Q_{air,i}$ is the sum of the supply and extraction air flow per minute $\left[\frac{m^3}{s}\right]$

For the temperature efficiency and the heat recovery KPIs for the rotary heat exchanger, the algorithm for the temperature efficiency is shown in Equation 2.

$$HE_{eff} = \frac{T_{sup,out} - T_{sup,in}}{T_{ext,in} - T_{sup,in}} \quad (2)$$

$T_{sup,out}$ is the temperature on the supply-side after the heat exchanger [°C]
$T_{sup,in}$ is the temperature on the supply side before the heat exchanger (intake temperature) [°C]

$T_{ext,in}$ is the temperature on the exhaust side before the heat exchanger (extraction temperature) $[°C]$

Tab. 2 - Sensors and methods for calculating KPIs for the Build department building. S = sensor, CAL = calculation (Lower resolution than sensor), VS = virtual sensor (Same resolution as sensor), ES = external sensor (Sensor not located in the system/geometry), M = metadata (Static value from producer, design, etc.).

Parameter	Sensor type	Reso-lution	Input
Electricity use of AHU	S	1 hour	-
Air flow	CAL	1 hour	Supply air flow Extraction air flow
Supply air flow	S	1 min	-
Extraction air flow	S	1 min	-
Efficiency of HE	VS	1 min	Intake temperature Temperature after HE Extraction temperature
Outdoor air temperature	ES	1 min	-
HE rotation speed	S	1 min	-
Intake temperature	S	1 min	-
Temperature after HE	S	1 min	-
Extraction temperature	S	1 min	-

Step 4: Cross-reference needed and already installed sensors

Once the necessary input for the KPIs has been identified from the KPI tool, they must be checked against the sensors which are already installed; if all are available, there are no adjustments needed. If some are missing, these sensors must either be installed, or the SATO KPI tool can be used to check if another sensor can replace them. This case is shown in Tab. 3, where the air flows are not measured, so they must either be measured or replaced by a virtual sensor using the fan speeds and data sheets to calculate the air flow.

As this case did not have direct measurements for the air flow, it was chosen to make instead a virtual sensor based on the fans datasheet and take the fans control signal (recalculated to fan speed) and the dimensioned pressure increase over the fan as inputs. This adds uncertainty to the air flow, but, realistically, it will frequently occur in buildings, as many older systems do not measure flow directly.

The virtual sensor was created from the datasheet using points where fan speed, pressure increase, and air flow were known. The model was created according to the following Equation 3 in Python/Spyder 5.

$$Q_{fan,air} = \omega^a * b + p^c * d + (\omega * p)^e \qquad (3)$$

$Q_{fan,air}$ is the air flow across a fan $\left[\frac{m^3}{h}\right]$
ω is the rotational speed of the fan $[min^{-1}]$
p is the pressure across the fan $[Pa]$
a, b, c, d, e are coefficients for the model

The trained model had a Root Mean Square Error (RMSE) of 654 m3/h and a Coefficient of the Variation of the Root Mean Square Error (CV-RMSE) of 8,2% as calculated according to ASHRAE Guideline 14-2014 [13], indicating that it performs reasonably well. The most considerable uncertainty when using this kind of virtual sensor is the pressure loss of the distribution system. However, it is not a relatively large problem, as the system maintains a constant pressure in both the supply and extraction distribution network.

Tab. 3 - Already installed sensors and sensors needed to install in the Build department building.

Already installed sensors	Sensors needed to be installed	Can be replaced by
Electricity use of AHU	Supply air flow	Virtual sensor based on supply fan speed and the fan datasheet
Outdoor air temperature	Extraction air flow	Virtual sensor based on extraction fan speed and the fan datasheet
HE rotation speed	-	-
Intake temperature	-	-
Temperature after HE	-	-
Extraction temperature	-	-

Step 5: Data benchmark

Once it is confirmed that all necessary sensors are present, the benchmark is chosen. In this case study, the reference benchmark is selected for the temperature efficiency of the rotary heat exchanger and the historical benchmark for the heat recovery of the rotary heat exchanger, and the specific AHU power for the AHU.

*****The selected KPIs for visualization*****

The three KPIs are visualized with one or two of their most essential dependencies. The specific AHU power is plotted in Fig. 8 with the total air flow, which is the intake and exhaust air flow sum because this is the main parameter influencing the KPI as a reference benchmark. The heat exchanger's heat recovery is plotted in Fig. 9 with the outdoor air temperature and rotation speed because these parameters will have an essential influence on the efficiency of the heat exchanger. The heat exchanger temperature efficiency is plotted in Fig. 10, with the intake and extraction temperatures, to see which ranges are used to compare with the reference performance.

Fig. 8 illustrates one of the selected KPIs: the specific air handling unit power with respect to the total air flow. As one can observe in Fig. 8, the specific AHU power decreases as the flow increases, thereby becoming more efficient, indicating that for this case, the AHU performs the best when running at the higher air flows.

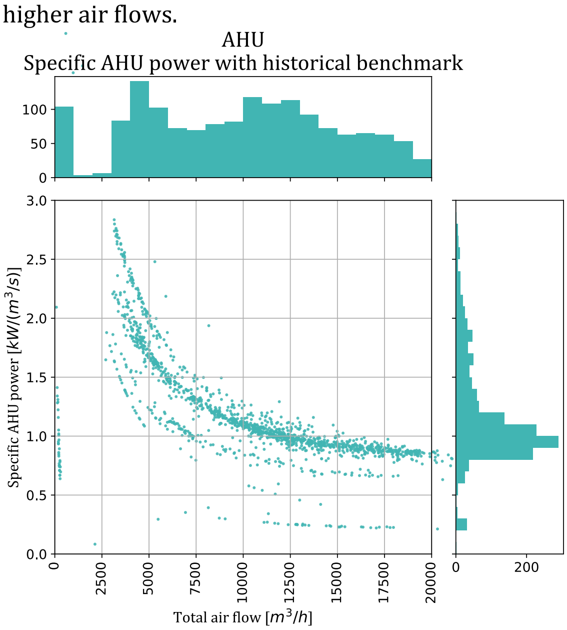


Fig. 8 - The KPI "Specific AHU power" is shown with the total air flow through the AHU (the sum of intake and exhaust air flow). The top and right plots are histograms for the total air flow and specific AHU power representing the number of data points within each range.

Fig. 9 shows that even though there is some variance in the HE efficiency, it follows the same trend. The efficiency increases as the outdoor air temperature decrease until it reaches approximately 5 °C. Naturally, this trend is observed to be due to the rotation speed of the heat exchanger; as it decreases with rising temperatures, so does the efficiency. This might not be a problem, as it could be due to the lowered need for heat recovery, but this cannot be concluded from this KPI alone.

Fig. 10 shows the temperature efficiency of the rotary heat exchanger under conditions as close to the manufacturer's calculation conditions as possible in the measured data. The conditions for performing this calculation are the rotation speed should be at max, and the flow should be balanced at a flow of 10000 m^3/h on both the supply and exhaust. The rotation speed is fulfilled, while for the flow, they are balanced, but not all are at the dimensioning flow of 10000 m^3/h. The lower flow will influence, but it is still possible to make a comparison near the manufacturer's conditions, to assess the performance of the components. For this component, it is necessary to accept a range for the different conditions, as for example, the intake temperature will very rarely be at the dimensioning conditions in Denmark, with the manufacturers intake temperature being -15 °C, which has only happened in one year within in the last 5 years.

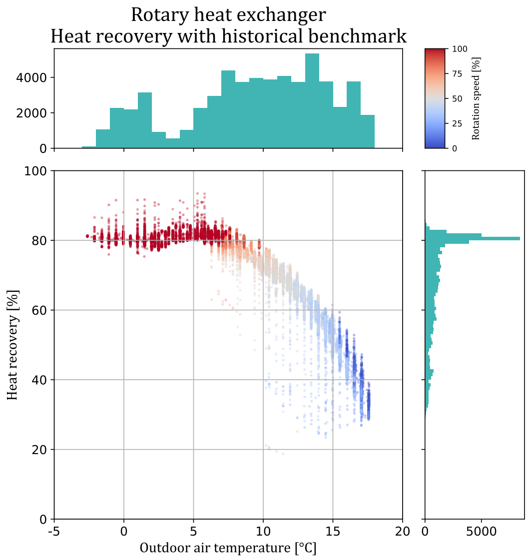
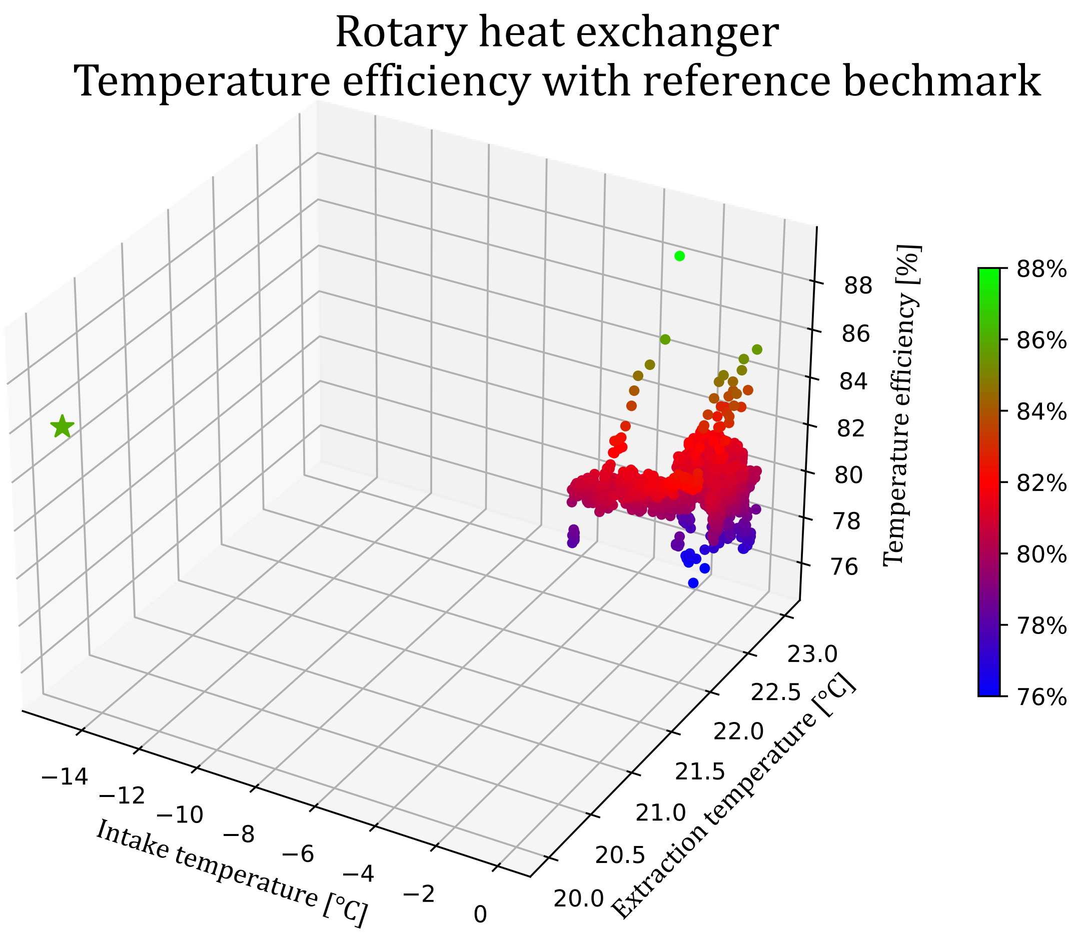


Fig. 9 - The KPI "Rotary heat exchanger (HE)", heat recovery with the historical data benchmark is shown with the outdoor air temperature and the rotation speed. The top and right plots are histograms for the outdoor air temperature and HE efficiency, representing the number of data points within each range.

4.2 Strengths and limitations

There are already existing studies developing and testing KPIs for building systems. However, to the best of our knowledge, no study was found to investigate KPIs for the full range of a building and system levels, with most studies investigating whole building or component level. The developed KPI assessment methodology can be applied to all building categories and suggests several benchmark options. The benchmarks encourage using historical data from the building or systems, providing realistic insights. This by comparing the historical data from the building or system with benchmarks based on real-life operating conditions. The KPI assessment methodology is developed to be an easy and understandable procedure for users.

Nevertheless, as all the benchmarks are partly data-driven, real-life operational data is needed. Also, as the developed KPI Tool is a selection tool, programming- and expert knowledge are still necessary. If the visualization is to be integrated into a BMS, expert knowledge on Information Technology (IT) is needed. However, adapting real-time building assessment and making clear guidelines is a significant task required to establish a valuable framework for building performance assessment and enable its practical use by the building industry.



The measured values are based on 2912 points	Manufacturer value	Measured average value	Measured standard deviation
Temperature efficiency	86%	80.4%	0.8%
Intake temperature	-15°C	-1.4°C	1.1°C
Extraction temperature	20°C	22.6°C	0.2°C

Fig. 10 - The KPI "Temperature efficiency" is shown in relation to the intake and extraction temperature. The star is the manufacturers data point with the accompanying efficiency, and the dots are the measured data points. The table underneath the 3D plot shows the summation of the results and inputs.

5. Conclusion and future opportunities

This study sheds light on a flexible and novel Building Assessment Framework consisting of 1) the SATO KPI tool designed explicitly for applicability of KPIs in all building systems and 2) a KPI assessment methodology that will guide the user through a KPI selection and visualization procedure. The KPI assessment can be used for any building category and interconnected systems.

A KPI assessment using the proposed methodology is presented in this study with three selected KPIs for visualization, 1) the specific AHU power for the AHU, 2) the heat recovery for the rotary heat exchanger, and 3) the temperature efficiency of the rotary heat exchanger.
From the three KPIs visualized, it can be seen that to provide useful insight on the building and systems, 1) a KPI should not necessarily be a single number but instead a function of the essential parameters, thereby indicating the performance over the entire working range of the system. 2) It is found that the dimensioning point from the manufacturer does not necessarily correspond to the operating points of the system or component, thereby making comparisons between the expected and achieved performance challenging.

Continuing to visualize desired KPIs will allow the actors to better understand and use their building to the best of its potential, consequently reducing energy and optimizing occupant's comfort and health.

The KPI assessment is designed for utilization over short and long time periods (instantaneous to several years), and in conjunction with the visualized KPI graphs, allows the actors to get a better idea of the building and systems performance in the different parts of the operating range, thereby allowing for detection and optimization of abnormal behavior. These capabilities are planned to be further explored and expanded in the author's future building systems.

The visualization code created in Python/Spyder 5 and the historical data from the university building is available on the author's GitHub repository: https://github.com/aauphd2024/CLIMA22_data_code

6. Acknowledgments

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