Rightsizing HVAC components using an ontology-driven Common Data Environment

Ali Kücükavci[a,b,*], Mikki Seidenschnur[a,b], Pieter Pauwels[c], Sara Juul Rhiger[a], Kristoffer Negendahl[a] and Christian Anker Hviid[a]

[a]Department of Civil Engineering, Technical University of Denmark, Denmark
[b]Rambøll, Copenhagen, Denmark
[c]Department of the Built Environment, Eindhoven University of Technology, Netherlands
[c]COWI, Kgs. Lyngby, Denmark

ARTICLE INFO

Keywords:
Indoor Climate & Energy
Hydraulics
Common Data Environment
Linked Data
Semantic Web

ABSTRACT

This study aims to improve data exchange between building information modelling (BIM) and building energy modelling (BEM) tools to aid HVAC engineers in applying rightsizing methods. An ontology-driven common data environment (CDE) is developed consisting of a centralized repository and four tools: a BIM model, a hydraulic calculation engine, a whole-building simulation engine and a data visualization tool. The study uses a primary school building in Denmark within a demonstration environment and evaluates the impact of rightsizing methods on indoor climate, material consumption, and energy consumption. The demonstration environment showcases the effectiveness of an ontology-driven common data environment in representing and managing heterogeneous building information throughout the HVAC design process. However, the study has limitations, such as only focusing on the ventilation system of an already-constructed building, not considering other HVAC systems, and using only one building. Further studies are needed to generalize the findings and consider factors such as user behaviour and energy sources.

1. Improving HVAC data management

The Architecture, Engineering and Construction (AEC) industry is under increasing pressure to deliver high-performing buildings. This pressure comes from clients, regulators, and the general public, who are increasingly aware of the importance of buildings being sustainable [1, 2]. AEC designers are adapting to meet the growing demand for high-performing buildings. Consequently, rightsizing Heating, Ventilation, and Cooling (HVAC) components has become a key strategy in designing high-performing buildings [2, 3]. An HVAC system and its components that are appropriately sized and designed to meet the specific requirements and needs of a building or space are said to be rightsized. This is an essential step in the building design phase, as correctly sized and installed HVAC components can provide an energy-efficient, comfortable, and healthy indoor environment [4].

Design of HVAC systems and their components are predominantly based on prescriptive sizing methods [5–7]. The prescriptive sizing methods are dictated by prescriptive factors, such as experience (rule of thumb), safety factors, building codes, regulations, and client requirements, to ensure that the HVAC components are never undersized [8]. Because of this approach, research literature [9–13] indicates that many buildings today have oversized HVAC systems and components. "Oversized" in this context means that the capacity of the HVAC system or component exceeds the actual HVAC load that the building requires. In the UK, Crozier [9] surveyed 50 different HVAC systems, discovering that 80% of the heating, 88% of the ventilation, and 100% of the cooling systems were oversized. Moreover, Knight and Dunn [10] surveyed 30 different HVAC systems in Wales, revealing that all HVAC systems were oversized. According to Felts and Bailey [11], 40% of ventilation systems installed were more than 25% oversized, while 10% were more than 50% oversized. Deng [12] recorded the highest operating cooling load of a cooling system to be 3,515 kW, while it was designed for a capacity of 8,000 kW. Similarly, Burdick [13] reported an oversizing of 161% for a cooling system.

1.1. Penalties of oversizing HVAC components

Although the literature covers how frequently HVAC components are oversized, it is also vital to understand their adverse effects. Oversizing HVAC components can result in several negative consequences, including higher initial, running, and replacement costs due to the increased capacity of the component [13]. In addition, an oversized HVAC component will often operate at low part loads for a significant portion of its operational time, which can lead to higher energy consumption and reduced efficiency [14]. Frequent cycling, which can occur when an HVAC component is oversized, can cause several problems, such as component failure, reduced lifespan, and reduced dehumidification in hot and humid climates, leading to mold and then health problems [4]. Furthermore, oversized components can result in higher humidity levels, which can lead to occupant

*Corresponding author
alikuc@byg.dtu.dk (A. Kücükavci)
ORCID(s): 0000-0001-9883-4633 (A. Kücükavci); 0000-0002-3881-9586 (M. Seidenschnur); 0000-0001-8020-4609 (P. Pauwels); 0000-0002-3535-3602 (S.J. Rhiger); 0000-0001-7895-5024 (K. Negendahl); 0000-0002-8340-7222 (C.A. Hviid)

discomfort and dissatisfaction. To avoid these negative consequences, it is essential to use rightsizing methods when designing HVAC systems and their components.

1.2. Rightsizing methods

The HVAC engineer must top-down estimate the design loads accurately for the spaces being served and, subsequently, size the HVAC components that service the spaces [15]. This involves whole-building simulation and hydraulic calculation.

A whole-building simulation is essential for designing high-performing buildings, as it allows for a more comprehensive and accurate assessment of a building's heating, cooling, and ventilation needs. By using Building Energy Performance Simulation (BEPS) tools to model the building envelope, occupants, equipment, and weather conditions, it is possible to determine the optimal size and configuration of the HVAC system. However, despite the usefulness of whole-building simulation, HVAC engineers often rely on simplified methods, such as single-room simulations or rules of thumb, which can lead to oversizing and inaccurate results [1, 16, 17]. To truly achieve high-performing buildings, it is necessary to implement whole-building simulation and use input parameters that reflect the real situation rather than relying on simplified methods that reduce time and complexity but may not accurately reflect real-life conditions [1, 17].

On the other hand, a hydraulic calculation involves estimating the pressure, mass flow and temperature inside ducts and pipes. This information determines the optimal size of HVAC components. Using this approach, the HVAC engineer can size HVAC components more accurately considering part-load efficiencies [18]. This can lead to reduced energy consumption, a longer component lifespan, and improved indoor comfort and health for building occupants [4]. The hydraulic calculation is often overlooked due to its complexity and time-consuming nature. Instead, HVAC engineers design HVAC components based on a static pressure loss calculation, which is simpler and easier to perform but can lead to the problems mentioned in Section **??**. However, calculating the pressure loss for part load conditions, rather than peak load, can provide a more accurate and efficient way to design an HVAC component [15, 18]. This is because most HVAC systems do not operate at peak load for extended periods of time. Instead, they typically only operate at peak load for short periods during extreme weather conditions. Considering the pressure loss under more typical partial loads allows HVAC engineers to predict its performance better and design the HVAC system and its components to meet the buildings' HVAC demand contributing to high-performing buildings [4].

1.3. A major barrier to rightsizing

One of the major challenges in using rightsizing methods to design high-performing buildings is the lack of seamless data exchange between Building Information Modeling (BIM) and Building Energy Model (BEM) tools [19, 20]. BIM, introduced in the early 2000s as a Common Data Environment (CDE) for the AEC industry, aims to improve coordination and communication between stakeholders and provides a structured method for representing and managing building data [21, 22]. BIM is already evolving towards level 3, enabling web-based seamless data exchange between different tools using standard and open formats [23]. However, the lack of interoperability between BIM and BEM applications, resulting in data loss and misinterpretation during information transfer, prevents rightsizing methods from being widely used in the AEC industry [19, 24]. To address these challenges, it is necessary to improve interoperability between BIM and BEM tools and to establish clear standards and solutions for the BIM-BEM data exchange process.

1.4. An ontology-driven CDE for rightsizing

Ontologies have emerged as an alternative solution to the lack of interoperability between BIM and BEM tools [19]. They are modular, polylithic, and have simple web-oriented data formats that can be interlinked and easily extended over time [23]. They provide a structured and standardized way of representing and organizing building information, allowing it to be easily shared and accessed by different domains and digital tools over the web and allowing vast quantities of data to be stored in accessible data servers [25]. In particular, the flexibility and modularity of ontologies can accommodate evolving industry needs, thus facilitating semantic interoperability across different domains and applications. This enables more efficient collaboration and decision-making across the AEC industry [25–27]. Using ontologies as a data format in CDEs can make it easier for stakeholders to exchange information, contributing to the design of high-performing buildings [28]. In this context, a recent study demonstrated how an ontology-driven CDE can be used to design the capacity and size of HVAC systems and components [28], emphasizing the potential of ontologies in providing flexibility and offering a modular means to link and rapidly extend heterogeneous data models. Most of the necessary information was represented using the ontologies Building Topology Ontology (BOT) [29], Flow Systems Ontology (FSO) [30], and Flow Properties Ontology (FPO) [28]. However, BOT, FSO, and FPO are insufficient to represent dynamic properties related to whole-building simulation and hydraulic calculations. A key research question is whether such properties can be described by interlinking existing ontologies or creating a new ontology.

A recent study demonstrated how an ontology-driven CDE can be used to design the capacity and size of HVAC components [28], emphasizing the potential of ontologies in providing flexibility and offering a modular means to link and rapidly extend heterogeneous data models.

1.5. Aim

The aim of this research is to develop an ontology-driven CDE that aids HVAC engineers in applying rightsizing methods in building design. The goal is to enhance building performance, reduce the information gap between BIM and BEM applications, and reduce the negative consequences of oversizing, such as increased costs and energy consumption.

To achieve this goal, the following research tasks will be carried out:

- Combine modular ontologies to represent HVAC-related information, enabling more effective data management in the building design phase.
- Implement an ontology-driven a CDE for demonstration purpose.
- Demonstrate the advantage of an ontology-driven CDE in terms of sizing HVAC components in a practical design setting

1.6. Outline

Section 2 provides an overview of the current HVAC design process and previous work on CDE related to rightsizing methods. We also highlight the gap in the existing literature that our research aims to fill. The presented work is limited to CDEs based on OWL, Industry Foundation Classes (IFC), and green building Extensible Markup Language (gbXML). The specific information that needs to be represented for whole building simulation and hydraulic calculations using existing ontologies is described in Section 3. In Section 4 we describe the ontology-based CDE and its process to evaluate three different Key Performance Indicator (KPI)s of rightsized HVAC systems. In Section 5, we present the results of applying simplified and rightsizing methods within our ontology-driven CDE to a real-world building model. We also quantify each method's impact on indoor climate, material usage, and energy performance. In Section 6, we discuss the implications of our findings and the potential for further advancements in the field. We also address our study's limitations and suggest future research directions. Finally, in Section 7, we summarize our contributions and conclude whether we have achieved the goals outlined in the introduction and filled the gap identified in the background section.

2. Background

The HVAC engineer is responsible for designing a building's HVAC system. The purpose of an HVAC system is to provide building occupants with acceptable thermal comfort and indoor air quality. The HVAC design process involves several steps:

1. Defining a system concept
2. Defining the distribution concept at zone level
3. Defining the control concept
4. Calculating HVAC demand at zone level
5. Determining the capacity and size of HVAC components
6. Selecting products from manufacturers

As HVAC engineers spend most of their time on steps 4 and 5 in the HVAC design process, we have limited the scope of our study to these steps. In Section 2.1, we provide an overview of the current state of our research, including what has been achieved and what is needed to successfully implement the rightsizing methods in steps 4 and 5 using an ontology-driven CDE.

2.1. Overview of CDEs in the AEC industry

Several CDEs have been developed to support the management and coordination of building information, processes, and stakeholders. Commercial platforms such as Autodesk's BIM 360 [31], Trimble Connect [32], Asite [33], Aconex [34] and ProCore [35] offer a range of features and functionalities to support BIM workflows and enable collaboration among various project stakeholders. There are also several open-source CDEs available for the AEC industry, such as BIMserver [36], ProjectWise [37] and OpenProject [38], which are all free and can be used to share and manage BIM data.

BIM 360 is the most commonly used commercial CDE in the AEC industry. It was officially introduced in 2010 as a project management platform [39]. It offers a range of features and software tools to help stakeholders share, review, and track project data. One of the key features of BIM 360 is the ability to create and share Revit models in the cloud and collaborate with other stakeholders. However, HVAC engineers may encounter data loss when exchanging information between Revit and other applications, including BEM applications such as EnergyPlus/OpenStudio, IES-VE, IDA ICE, and TRNSYS. One reason for this data loss may be the difficulties encountered when using the two most comprehensive open file formats IFC and gbXML, for interoperability between BIM and BEM tools [19]. IFC can be complex and have a narrow expression range, making it difficult to extend and potentially causing problems with data transfer between different applications [40].

2.2. The research gap

Several studies have been conducted to address the problem of data loss during the transfer of information between BIM and BEM tools. G.B. Porsani et al. [20] conducted a study evaluating the compatibility between the BIM authoring tool Revit with the BEM authoring tools Open Studio, DesignBuilder, and CYPETHERM HE. The evaluation was conducted on a residential building and a warehouse. The results showed that data loss occurred when transferring information from BIM to BEM using either IFC or gbXML. In particular, Porsani et al. [20] found that building envelope parameters were missing in the BEM authoring tools.

Other studies concluded the same problems when transferring data between BIM and BEM tools. Karen and Douglas [41] encountered data loss when they generated an Input Data File (IDF) file based on an IFC file exported from Revit and used it to perform BEPS and visualize the results. Dimitriou et al. [42] encountered data loss when they used a gbXML file exported from Revit to generate an IDF for EnergyPlus, which was then used to perform

BEPS. Similarly, Krygiel and Nies [43] experienced data loss when they used a gbXML file to transfer data between Revit and GBS to evaluate the energy performance of two facade systems.

To improve BIM-BEM interoperability, the authors of these studies suggest the need for alternative data formats or strategies to address these limitations. Kücükavci et al. [28] proposed an approach to improve BIM-BEM interoperability by using an ontology-driven CDE to exchange building information across multiple domains and tools over the web. They demonstrated how lightweight ontologies like BOT, FSO, and FPO can be interconnected to represent a building and its services in a modular way.

However, the proposed ontologies FSO and FPO are limited in their ability to represent the dynamic properties required for simulating the performance of HVAC systems under different conditions and loads. Dynamic properties refer to how a system responds to changes in external factors such as weather conditions, occupancy patterns, and internal loads. These properties are especially important for part-load hydraulic calculations, which rely on understanding how components like pumps, valves, and other components respond to changes in flow rates and loads. Without such properties, simulation results may not accurately reflect the system's performance under real-world conditions, potentially leading to suboptimal design decisions based on inaccurate predictions.

To address this gap, we propose interlinking existing lightweight ontologies to describe the dynamic properties and perform part-load calculations for a real-world building model. This ontology-driven CDE approach can enable better collaboration, efficient data exchange, and streamlined data management among stakeholders and design tools involved in designing HVAC systems, leading to more sustainable and cost-effective building designs. The demonstration of this approach in Section 5 will showcase its potential benefits for BIM-BEM integration.m

3. Interlinking multiple domains for rightsizing

In this section, we will explore the specific information required for whole building simulation and hydraulic calculations using existing ontologies. Table 1 shows the namespaces and prefixes used in this article.

Table 1
Used prefixes and namespaces.

Prefix	Namespaces
fpo	https://w3id.org/fpo#
fso	https://w3id.org/fso#
bot	https://w3id.org/bot#
ex	https://example.com/ex#
caso	http://www.w3id.org/def/caso#
brick	https://brickschema.org/schema/Brick#
xsd	http://www.w3.org/2001/XMLSchema#
dco	http://info.deepcarbon.net/schema#
inst	https://example.com/inst#
weat	https://bimerr.iot.linkeddata.es/def/weather#

3.1. Whole building simulation

Several input parameters are required to perform a whole building simulation, including building geometry, internal loads, weather conditions, HVAC systems, operating strategies, schedules, and simulation-specific parameters. These parameters are used to model the building, its systems, and the environmental conditions. Once all the input parameters are provided, a simulation engine can use them as input to predict the energy performance or the indoor climate of the building. The simulation engine outputs results such as energy performance, heating and cooling loads, and indoor comfort. Using ontologies, we can effectively capture their relationships by representing the input and output parameters. However, it should be noted that this paper does not cover building geometry or simulation-specific parameters.

3.2. Internal gains

Internal gains refer to the heat, moisture, or CO2 generated within a building by people, lights, and equipment, which can affect the heating and cooling loads of the building. To effectively represent internal gains using ontologies, we need to understand the components that make up internal gains and how they relate to the building.

An internal gain can consist of an occupant or equipment, a schedule, and a day load. Occupants can generate heat, moisture, and CO2, while equipment can only generate heat. The schedule represents when the building is occupied and used, while the day load defines the occupancy percentage for each hour over 24 hours for a given space.

Internal gains are usually defined at the room level as the number and type of occupants, and their schedules can vary between spaces. For example, a dining area or office space within the same building may have different amounts of occupants, and they may occupy the space on different schedules.

To represent this information, we can use existing ontologies such as BOT [29], Brick [44], Occupancy Profile Ontology (OP) [45] and Time ontology [46], as shown in the internal gain area in Figure 1.

BOT ontology is used to specify the building, its storeys, and specific rooms. Since a `bot:Space` or a group of `bot:Space` can have similar heating and cooling needs, we define a thermal zone in which the `bot:Space` can be a part of using `brick:Zone`. Input and output parameters related to whole-building simulation will be assigned to the thermal zone.

As shown in the Internal gain area in Figure 1, we can define an occupant with `op:Occupant` and relate it to a thermal zone with `op:hasOccupant`. The capacity of an occupant, including heat, moisture, and CO2 generation, can be represented with classes such as `oum:Number`, `oum:HeatCapacity`, `ex:CO2Capacity`, and `ex:MoistureCapacity`. The occupancy schedule, including specific dates and times, can be represented with `time:Instant` and `ex:DailyLoadProfil`. The instance `inst:Schedule1` is assigned particular dates to capture the variations in internal gains throughout the year, month, and day.

The `ex:DailyLoadProfil` captures the daily variations in internal gains and consists of a collection of `ex:HourlyLoadProfile`. Each instance of type `ex:HourlyLoadProfile` represent a load's start and end time, and the load's value and unit are expressed with `fpo:hasValue` and `fpo:hasUnit`.

3.3. Building systems

A building system, such as HVAC, lighting, and shading systems, can be represented similarly to internal gains.

Figure 1 illustrates how building systems, their components and building spaces can be represented and interlinked using BOT, Brick, FSO, FPO, DogOnt, and Time ontology. A heating system is represented with the class `fso:System` and is directly assigned to the thermal zone. The system's capacity-related properties are represented using the FPO ontology and are directly assigned to the heating system. The schedule, similar to internal gains, is represented using the Time ontology and captures the specific year, month and day in which the system is in use. The control system of the heating system is represented using the class `dogont:Control`. For example, a control parameter of type `brick:HeatingTemperatureSetPoint` is assigned to the class `dogont:Control` to define a setpoint. The value and unit of the setpoint is expressed with `fpo:hasValue` and `fpo:hasUnit`.

3.4. Weather data

In a whole-building simulation, weather data is primarily accessed through weather files. A weather file containing various weather-related data, such as temperature, humidity, solar radiation, wind speed and direction, and precipitation. These data are typically recorded at specific intervals, such as hourly or daily, and are usually specific to a certain location.

Figure 1 illustrates how the weather file or weather-related data can be related to a building and its site using BOT, BIMERR Weather Ontology (WEAT), Context Aware System Observation Ontology (CASO), FPO and Time ontology. An instance of type `bot:Site` can be related to a location and a weather data property such as wind speed using the object property `weat:locatedIn` and `ex:hasWindSpeed`. We can express a link to the location of the weather file using `weat:EPWFile` and represent the relation between the weather file and the weather data using the object property `weat:isDefinedBy`. To represent the wind speed at different states (times), we can relate an instance of type `weat:WindSpeed` to an instance of type `caso:State` and assign a value, unit and timestamp to the state. In this example, we have just shown that the instance of type `weat:WindSpeed` has only one state, but in reality, it will consist of multiple states. For example if we want to describe the wind speed for each hour for an whole year, we would have 8760 instances of type `caso:State` and assign a value, unit and timestamp to the state. In this way, we can represent HVAC properties dynamically.

3.5. Simulation outputs

When all the inputs required for a whole-building simulation engine are available, it is possible to predict energy performance, heating and cooling loads, and indoor comfort.

Figure 1 demonstrates how indoor comfort-related data can be represented. Since the output data from the whole building simulation engine is simulated for each hour for a given period, the data structure will be similar to the data structure of the weather information. In the example shown in Figure 1, we express the CO2-concentration using `dco:CO2Concentration` from domOS Common Ontology (DCO) and relate it to the thermal zone. Since the thermal zone can have a CO2 concentration for different timestamps, we assign it to a `caso:State` and apply a value, unit and timestamp to the instance of type `caso:State`. In this way, we can represent the CO2 concentration for each simulated timestamp.

3.6. HVAC component performance

When performing hydraulic calculations, it is necessary to represent HVAC components' capacity-related properties dynamically. In Figure 1, we demonstrate how the pressure drop can be represented at any given point in time for a given HVAC component. This can be used to determine the HVAC component's efficiency and any problems that may be present. A state can be assigned to the pressure drop using the object property `caso:hasState`, similar to how weather and indoor climate output data are represented. The pressure drop can be related to an HVAC component through its port. In this example, an instance of `fso:SpaceHeater` is related to an instance of `fso:Port` using the object property `fso:hasPort`, and the instance of `fso:Port` is related to a capacity-related instance of type `fpo:PressureDrop` with the object property `fpo:hasPressureDrop`.

Besides representing the performance of an HVAC component with `caso:State`, static values can also be assigned directly to instances of type `fso:PressureDrop`. The static value represents the HVAC components' maximum capacity. As a result, we are able to define the HVAC component's maximum capacity (static property) and performance (dynamic property) over time within the same representation.

4. Comparative Analysis of Two Methods for Three KPIs in a Demonstration Environment

To aid HVAC engineers in applying rightsizing methods in building design, we have developed an ontology-driven CDE, as shown in Figure 2. The CDE consists of a centralized repository and five tools: a BIM model, a hydraulic calculation engine, a whole-building simulation engine, a data visualization tool, and a manufacturer tool. In this study, their functions and purposes are as follows:

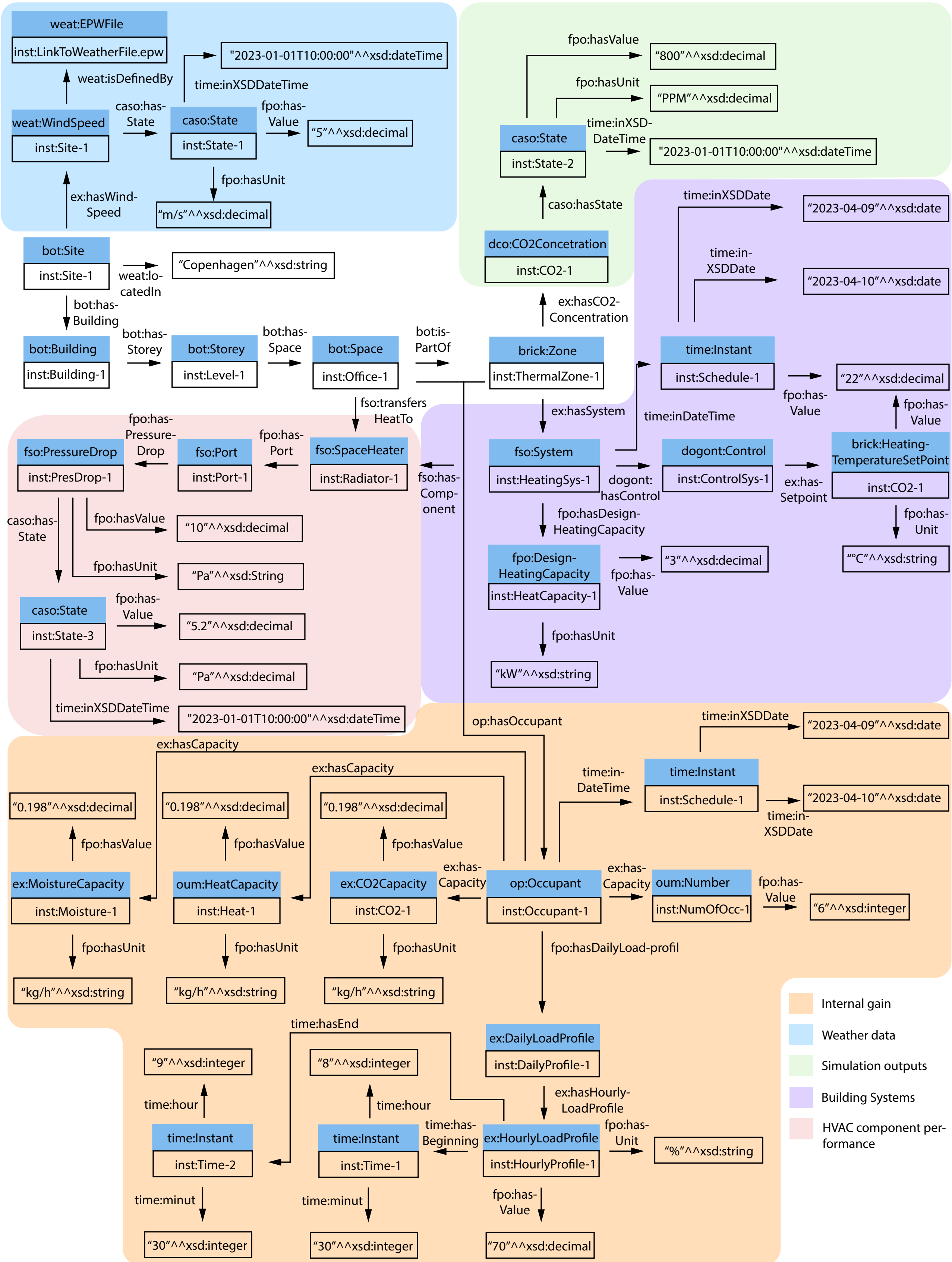


Figure 1: The figure illustrates the representation of building zones, HVAC systems, components, occupants, weather data, and indoor climate using ontologies. The blue section displays weather data related to a site, while the orange section shows the capacity and schedules of building occupants. The purple area represents the capacity of the HVAC system, and the red area illustrates the performance of HVAC components. Lastly, the green section represents simulation outputs related to indoor climate.

1. Centralized repository: The CDE's centralized repository is ontology-driven and will be used to store, manage, and share data among the different tools using web-based communication protocols.

2. BIM model: The BIM model will contain information about the building, including its geometry, materials, and systems.

3. Hydraulic calculation engine: The hydraulic calculation engine will be used to analyze the pressure drop of a building's HVAC system. It is used to design and optimize the distribution components of the HVAC

4. Whole-building simulation engine: This engine is used to predict the ventilation demand for each zone in a building.

5. Data visualization tool: The data visualization tool will be used to present data in a visual format, allowing stakeholders to understand and interpret the analysis results easily. This study will use the tool to visualize each room's indoor climate, the distribution system's material usage, and the air handling unit's (AHU) energy performance.

6. Manufacturer tool: The manufacturer tool will be used to access and retrieve product data, such as performance characteristics. This information will be used to determine AHU's yearly energy performance.

In our study, we will compare simplified sizing methods with rightsizing methods and assess their impact on indoor climate, material usage, and energy performance. We do not intend to introduce a new rightsizing method but rather improve the interoperability between BIM and BEM by using an ontology-driven CDE to aid HVAC engineers in applying rightsizing methods during the design process. The simplified sizing approach uses prescriptive-based input parameters, while the rightsizing approach uses input parameters that reflect the actual situation. By comparing the results of both methods, we aim to quantify the benefits of using rightsizing methods for real-world building projects. However, it is important to note that these methods are limited to the ventilation system of an already-constructed building project. For the rest of the article, we will refer to simplified rightsizing methods as the simplified HVAC design approach and rightsizing methods as the rightsized HVAC design approach.

Before diving into the detailed description of the methods used to measure three key performance indicators in the following subsections, we provide an overview of the two approaches: the simplified HVAC design approach and the rightsized HVAC design approach. In the simplified approach, we base our ventilation demand and distribution component sizes on the already-constructed building project, which we refer to as the existing HVAC system. We also select an air handling unit based on the peak-load condition for the existing HVAC system. On the other hand, the rightsized approach involves simulating the ventilation demand individually and resizing the distribution component, which we refer to as the new HVAC system. We select an air handling unit based on peak-load and part-load conditions for the new HVAC system, allowing for a direct comparison between the two conditions.

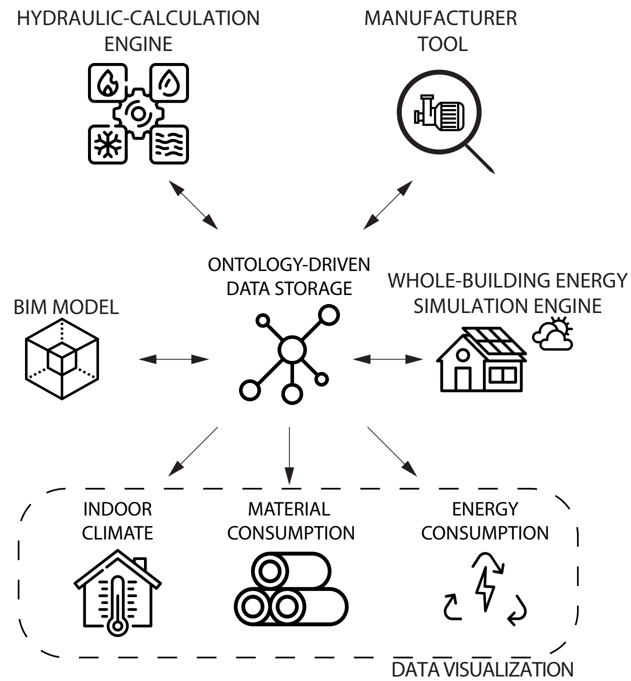


Figure 2: The proposed ontology-driven CDE, consisting of a central repository and five tools.

4.1. KPI 1: Indoor Climate

In KPI 1, we aim to determine and visualize the indoor climate, specifically, whether the CO2 concentration and operative temperature for each room in the building model comply with the standards. This requires utilizing the BIM model, the ontology-driven data repository, the whole-building simulation engine, and the visualization tool.

4.1.1. Indoor Climate: Simplified approach

To determine and visualize the CO2 concentration and operative temperature with the simplified HVAC design approach, we will follow these steps:

1. Transfer input parameters from the BIM model to the ontology-driven data repository

2. Transfer input parameters from the ontology-driven data repository to the whole-building energy simulation engine

3. Transfer output parameters from the whole-building simulation engine to the ontology-driven data repository

4. Use a query to retrieve CO2 concentration and operative temperature which complies with the standards

5. Create a chart using the retrieved data in the visualization engine.

Since the real-world building model is already constructed, we don't need to estimate the ventilation demand for each room as the information is already available. However, the ventilation demand at this stage is based on prescriptive methods; hence this approach is called the simplified HVAC design approach.

4.1.2. Indoor Climate: Rightsized approach

We follow the steps mentioned in Section 4.1.1 to determine the indoor climate with the rightsized HVAC design approach. However, instead of using a prescriptive-based approach to determine the ventilation demand, we use an algorithm to calculate the demand for each room individually. This allows us to design the distribution components more accurately.

4.2. KPI 2: Material Usage

In KPI 2, we aim to determine and visualize the total volume of the distribution system. This requires utilising the BIM model, the ontology-driven data repository, the whole-building simulation engine, the hydraulic calculation engine, and the visualization tool.

4.2.1. Material Usage: Simplified approach

To determine and visualize the total volume of the distribution system using the simplified HVAC design approach, we perform the following steps:

1. Transfer the existing distribution components from the BIM model to the ontology-driven data storage.
2. Use a query to retrieve the total volume of the distribution components
3. Transfer the total volume retrieved by the query from the ontology-driven data repository to the data visualization tool to visualize the total volume of the distribution components

4.2.2. Material Usage: Rightsized approach

To compare the total volume of the distribution components for both the simplified and rightsized HVAC design approaches, we need to maintain the same total pressure drop in the distribution system as a reference point. To calculate the current pressure drop in the distribution system, we will use the ventilation demand outlined in Section 4.1.1. This process includes:

1. Calculate the existing total pressure drop of the distribution system using the existing ventilation demand given in Section 4.1.1. This includes (1) moving the distribution components from the BIM model to the data repository using ontologies. (2) Using a query to transfer the information needed for hydraulic calculations to the calculation engine. (3) Saving the pressure drop of each component in the ontology-driven data repository. (4) Running another query to find the total pressure drop of the distribution system.
2. Resize the distribution components based on the new ventilation demand and recalculate the total pressure drop of the distribution system.
3. If the new total pressure drop is not identical to the existing total pressure drop, repeat the previous step until the new total pressure drop matches the existing total pressure drop. Once the new total pressure drop is identical, write a query to retrieve the total volume of the distribution system and transfer it to the data visualization engine.

4.3. KPI 3: Energy Performance

In KPI 3, we aim to determine the most energy-efficient AHUs by comparing their yearly energy performance under different conditions, namely peak-load and part-load. To select an AHU for peak-load conditions, we will use the maximum capacity of the AHU for the existing ventilation demand given in Section 4.1.1 and the individually simulated ventilation demand given in Section 4.1.2. For part-load conditions, we will select an AHU based on the individually simulated ventilation demand given in Section 4.1.2. This process will enable us to compare the yearly energy performance between peak-load and part-load conditions for the new system. The process involves using the ontology-driven data repository, the hydraulic calculation engine, the manufacturer's tool, and the visualization tool.

4.3.1. Energy Performance: Simplified approach

We need to know the distribution system's total flow rate and pressure drop to select an air-handling unit based on the peak-load condition. The total pressure drop for the peak-load condition, also known as the total static pressure drop, is determined in Section 4.2.2. The total flow rate is also available in the data repository since the flow rate in each flow port is represented by the ontologies FPO and FSO. Therefore, we will write a query to retrieve the AHU's total pressure drop and flow rate. Next, based on the total flow rate and pressure drop, we will choose a product from the manufacturer.

However, we won't be able to calculate the yearly energy performance based on the total flow rate and pressure drop during the peak-load condition. We must determine the total flow, pressure drop and fan efficiency for each hour throughout the year. These three parameters determine the hourly energy performance, and by summing the hourly energy performance for each timestamp, we can determine the yearly Energy performance. We will therefore calculate and store these three parameters in the ontology-driven data repository and use a query to calculate the yearly energy performance of an AHU.

We will perform this step twice, first, by using the existing ventilation demand given in Section 4.1.1. Then, using the individually simulated ventilation demand from Section 4.1.2.

4.3.2. Energy Performance: Rightszied approach

To select an AHU from a manufacturer based on the part-load condition, we will perform the last step of Section 4.3.1 to determine the yearly energy performance of an AHU. We will perform this step using the individually simulated ventilation demand from Section 4.1.2.

5. Results

5.1. BIM model

For the demonstration environment, we used a BIM model of a real-world building located in Sorø, Denmark. The building is a primary school constructed in 2017 and named Frederiksberg Skole. Frederiksberg Skole has a gross floor area of 6,970 m2 and is divided into the Northern and Southern buildings. Each building has three floors, as shown in Figure 3. The original BIM model has been modified by Seeberg and Tangeraas [47] to include only the northern building and its heating and ventilation system. It has 84 thermal zones, each heated with radiators and ventilated with supply and extract air terminals. Both systems are located in the basement of the northern building [28]. Seeberg and Tangeraas have parsed the Revit model to an IDF file using the FSO [30]. In this study, we use the IDF file in Energy Plus to perform a whole building simulation. For both HVAC design approaches, we used similar input settings to create a comparable basis. The input settings for the simulation can be found in Table 2 and Figure 4. The inputs are kept constant throughout all simulations.

5.2. KPI 1: Indoor climate

This section determines and visualizes the indoor climate using the simplified and rightsized HVAC design approach. The evaluation of both methods is based on the following indoor climate criteria:

1. Operative temperature, which must be within the range of 20-26°C, but may exceed 26°C for a total of 100 hours during occupancy hours

2. CO_2 concentration, which must not exceed a maximum of 1000 PPM.

The currently installed system at Frederiksberg Skole is designed based on the simplified HVAC design approach. The ventilation demand is calculated using the rule of thumb, standards, and the mass balance equation [49]. The ventilation demand in each space in the building is designed to have a maximum CO_2 concentration of 1000 PPM. The original engineer calculated the ventilation demand for the rooms in Frederiksberg Skole and provided it as part of the documentation. As a result, there was no need to determine the ventilation demand for the simplified HVAC design approach.

With the rightsized HVAC design approach, we determine each zone's ventilation demand individually. To determine the ventilation demand individually for each zone and process dynamic data, we use the Algorithm 1. This algorithm determines a percentage cutoff and sets an upper bound for the ventilation demand. The ventilation demand for the zone is the maximum value remaining that meets the

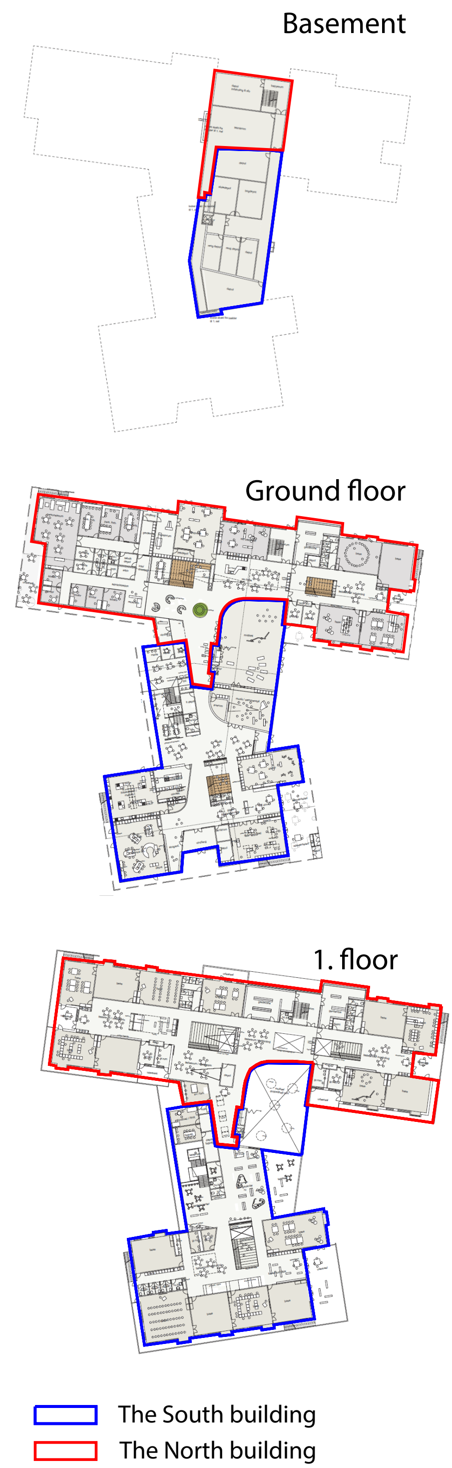
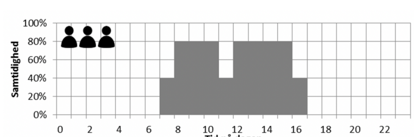


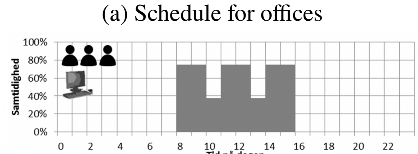
Figure 3: The illustration shows the floor plans of Frederiksberg Skole in Sorø, Denmark. The south building is marked with blue, while the south building is marked with red [47]

Weather data file	DryCph2013.epw
HVAC system:	
System type	Ideal load HVAC system
Heating schedule	Not available from 15/5 to 15/9
Cooling schedule	Never available
Inlet temperature	18 °C
Heat recovery	0.8
Night ventilation	Available from 15/5 to 15/9
Set points:	
Heating	22 °C
Night ventilation	21 °C
Internal gains:	
Activity level	70 W/person (Weighting between activity level for adults and children [47])
People classrooms	30 persons
People offices	8 m^2/person
People group rooms	3 m^2/person
People SFO	8 m^2/person
Equipment	Classrooms 8 W/m^2 Offices 12 W/m^2
Lighting	5 W/m^2
Infiltration:	
In occupancy hours	0,13 l/s·m^2
Remaining hours	0,09 l/s·m^2
Schedules:	
Offices/Common areas	Figure 4a
Meeting rooms	Figure 4b
Classrooms	Figure 4c

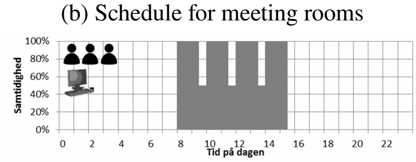
Table 2
Input parameters used in the whole building simulation engine for both the simplified and rightsized HVAC design approach



(a) Schedule for offices



(b) Schedule for meeting rooms



(c) Schedule for classrooms

Figure 4: Schedules used in the whole building simulation engine for both the simplified and rightsized HVAC design approach [48]

indoor climate criteria. The algorithm and related documents are available at Github [1].

[1] https://github.com/SaraRhiger/Prescriptive-vs-performance-based

Algorithm 1 Determining percentage cutoff

```
Require: Hourly airflow demand for all zones
Ensure: The percentage cutoff for each zone

  %=100 ;                                   ▷ % = The %-cutoff

  List with hourly airflow demanded;
  while % >= 0 do
      sort list with flows by size;
      i=len(list)/%·100;                    ▷ Find index
      flow = list[i];                       ▷ Value of index
      Update IDF-file with the found airflow;
      Run simulation;

      if Overheating < 100 hours then
          % = %-1;
      else
          % = %+1;
          Break;
      end if
  end while
  Executed for all thermal zones in the same simulation
```

Method	Ventilation demand [m^3/h]
Simplified	23,625
Rightsized	13,832

Table 3
The ventilation demand when using the simplified HVAC design approach

The input settings shown in Table 2 are kept constant for both the simplified and rightsized HVAC design approach. Moreover, the ventilation demand for the toilets is also kept constant in both methods.

5.2.1. KPI 1 results

The total ventilation demand for both methods is shown in Table 3. The ventilation demand in the rightsized HVAC design approach is 42% lower than in the simplified HVAC design approach. This reduction is due to the consideration of the actual users of the building. In the simplified HVAC design approach, the occupancy load is based on a standard value, which is having a heat moisture and CO2 generation of an adult. In the rightsized HVAC design approach, we use the heat, moisture and CO2 generation for the actual users, which in this case is a combination of children aged 5-12 years and some teachers. The children have a lower heat, moisture and CO_2 production. Using occupancy load based on the actual user leads to a more precise calculation of ventilation demand, reducing the total ventilation demand in the rightsized HVAC design approach.

Figure 5 illustrates the results of the maximum CO_2 concentration among all zones over the entire year for both methods. These results were obtained using the SPARQL query found in Listing 1. Both design methods comply with the atmospheric indoor climate criteria requirement: a maximum concentration of 1000 PPM.

Listing 1 A SPARQL select query to retrieve the maximum CO2 concentration for all rooms from the ontology-driven data repository

```
SELECT (MAX(?value) AS ?maxCO2Value)
WHERE {
  #RETRIEVING CO2-CONCENTRATION VALUES FOR ALL ROOMS
  ?space brick:isPartOf ?thermalZone .
  ?thermalZone ex:hasCO2Concetration ?CO2Concentration .
  ?CO2Concentration caso:hasState ?state .
  ?state time:inXSDDateTimeStamp ?timeStamp .
  ?state fpo:hasValue ?value .
}
```

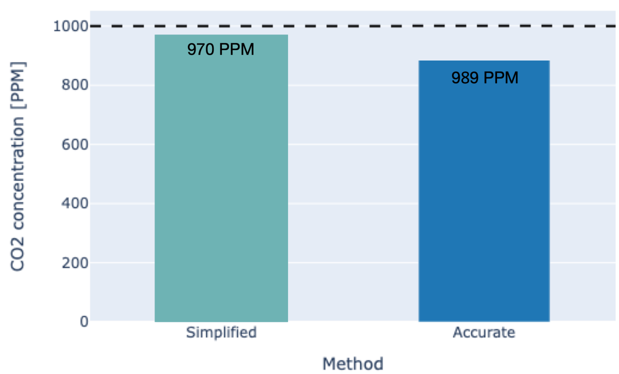


Figure 5: The maximum CO2 concentration among all zones over the year. The dashed line at 1000 PPM is the criteria for the maximum CO2 concentration.

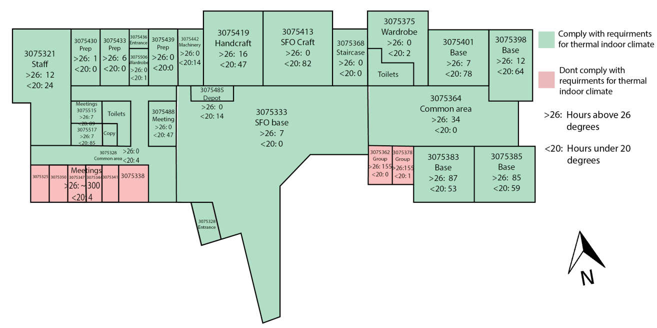
Figure 6 illustrates which rooms meet the thermal indoor comfort criteria using the simplified HVAC design approach. 10 of the 84 zones fail to meet the requirements for the thermal indoor climate. The zones that fail are marked as "Don't comply with requirements for thermal indoor climate", while the zone that complies is marked as "Comply requirements for thermal indoor climate". The visualization engine illustrates Figure 6, with the data provided by the following SPARQL query, Listing 2. The query retrieves the spaces which exceed the indoor comfort criteria.

For the failing zones, the requirements for thermal indoor comfort are exceeded by up to 300 per cent, which means the ventilation demand is undersized in these zones. Using actual occupancy loads rather than standard occupancy loads allows us to reduce the ventilation demand up to 90% for certain zones while complying with the thermal requirements. The failing zones require a higher ventilation demand, specifically an increase of up to 350%. This is because the simplified HVAC design approach does not consider external factors such as solar gain and outdoor air temperature, while the rightsized HVAC design approach does. This means that the ventilation demand for these zones needs to be adjusted accordingly to account for these external loads in the rightsized HVAC design approach.

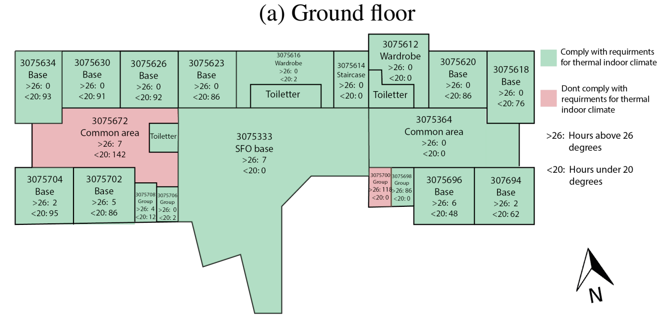
Listing 2 A SPARQL select query to retrieve the amount of hours above 26 °C from the ontology-driven data repository

```
SELECT ?space (COUNT(?value) AS ?tempValue)
WHERE {
  #RETRIEVING THE TEMPERATURE VALUES FOR ALL ROOMS
  ?space brick:isPartOf ?thermalZone .
  ?thermalZone ex:hasTemperature ?Temperature .
  ?Temperature caso:hasState ?state .
  ?state time:inXSDDateTimeStamp ?timeStamp .
  ?state fpo:hasValue ?value .

  #RETRIEVING ONLY TEMPERATURES ABOVE 26 °C
  FILTER (?value > 26)
} GROUP BY ?space
```



(a) Ground floor



(b) 1. floor

Figure 6: Overheating hours for each zone using the simplified HVAC design approach. Green zones comply with the thermal indoor climate requirement and red does not comply with the requirement.

5.3. KPI 2: Material usage

In this section, we will determine and visualize the total volume of the distribution components for both the simplified and rightsized HVAC design approach.

For the simplified HVAC design approach, we determine the total volume of the distribution components by using the existing BIM model of Frederiksberg Skole. We transfer the information from the BIM model to the ontology-driven data repository using the parser from the Semantic HVAC Tool. Once the information is in the repository, we use the SPARQL query, described in Listing 3, to calculate the total volume of the distribution components.

For the rightsized HVAC design approach, we determine the total volume of the distribution components using the

Listing 3 A SPARQL select query to calculate and retrieve the total volume of `fso:Duct` based on its shape from the ontology-driven data repository.

```
SELECT (sum(?ductVolume) as ?totalVolume)
WHERE {
   {
  #SELECTING ROUND DUCTS
  ?roundDuct a fso:Duct .
  ?roundDuct fso:hasPort ?port .

  #SELECTING ONLY OUTLET PORTS
  ?port fpo:hasFlowDirection ?flowDirection .
  ?flowDirection fpo:hasValue "Out" .

  #SELECTING THE DIAMETER
  ?port fpo:hasOuterDiameter ?diameter .
  ?diameter fpo:hasValue ?diameterValue .

  #SELECTING THE LENGTH
  ?roundDuct fpo:hasLength ?length .
  ?length fpo:hasValue ?lengthValue .

  #CALCULATING THE VOLUME OF THE COMPONENT
    BIND(((?diameterValue/2)*(?diameterValue/2))*3.14159265359 *
    ↪  ?lengthValue AS ?ductVolume)
 }
  UNION
  {
  #SELECTING SQUARE DUCTS
  ?squareDuct a fso:Duct .
  ?squareDuct fso:hasPort ?port .

  #SELECTING ONLY OUTLET PORTS
  ?port fpo:hasFlowDirection ?flowDirection .
  ?flowDirection fpo:hasValue "Out" .

  #SELECTING THE WIDTH AND HEIGHT
  ?port fpo:hasWidth ?width ;
        fpo:hasHeight ?heigth .
  ?width fpo:hasValue ?widthValue .
  ?heigth fpo:hasValue ?heigthValue .

  #SELECTING THE LENGTH
  ?squareDuct fpo:hasLength ?length .
  ?length fpo:hasValue ?lengthValue .

  #CALCULATING THE VOLUME OF THE COMPONENT
  BIND(?widthValue * ?heigthValue * ?lengthValue AS ?ductVolume)
   }
 }
```

same query, Listing 3, for new duct sizes. We tried to maintain the same pressure drop for both the simplified and rightsized HVAC design approach. The total pressure drop on the supply side and return side of both methods are shown in Table 4. It can be seen that the pressure drop on the supply side for both methods deviates by approximately 3%. The same applies to the return side for both methods.

Figure 7 illustrates the material usage of round and rectangular components when designing with the simplified and rightsized HVAC design approach. The material usage can be reduced by 11% when using the rightsized HVAC design approach.

Method	Supply-side [Pa]	Return-side [Pa]
Simplified	496	471
Rightsized	484	477

Table 4
The pressure drop from supply and return fan when using the simplified and rightsized HVAC design approach.

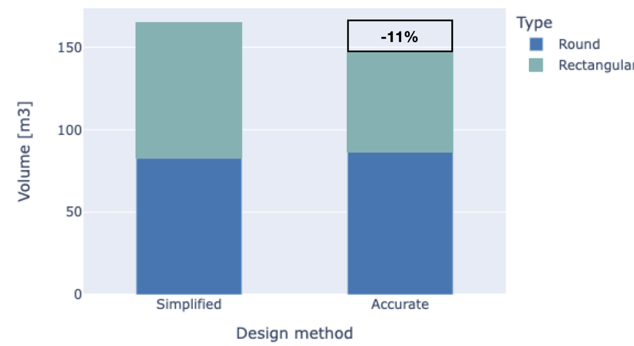


Figure 7: The total volume of round and rectangular ducts used when designing with the simplified and rightsized HVAC design approach.

5.4. KPI 3: Energy Performance

We evaluate the energy performance of the AHU using simplified and rightsized HVAC design approaches.

We first determine the energy performance in the simplified HVAC design approach by considering two cases: (1) the existing ventilation system with existing ventilation demand and distribution component sizes and (2) the new system with individually simulated ventilation demand and resized distribution components. The pressure drop and flow rate for these cases are illustrated from Table 3 and Table 4 and retrieved from the data repository. We input the values into a manufacturer's [50] tool to suggest appropriate air handling units for each case, as shown in Table 5. Based on the peak-load condition, the tool recommends the AHU of type Geniox29 for the existing system and Geniox22 for the new system.

Next, using the rightsized HVAC design approach, we evaluate the yearly energy performance for each AHU of type Geniox based on the part load condition. We select the one that can deliver the necessary airflow for the new system with the lowest yearly energy performance. Fan efficiencies from the manufacturer's tool are used along with an algorithm to calculate efficiency throughout the year, which we then save in the data repository. Using a SPARQL query, listed in 4, we determine the yearly energy performance of the AHU. In this case, the Geniox18 AHU has the lowest energy consumption for the new system.

To compare the impact of these two selection processes, we also calculated the yearly energy performance the AHUs that we selected based on peak-load conditions. The results in Table 4 show that the simplified HVAC design approach with the existing system has the highest energy performance, while the rightsized HVAC design approach

Listing 4 A SPARQL select query to calculate and retrieve the yearly energy performance of a ventilation system from the ontology-driven data repository

```
SELECT DISTINCT (SUM(?hourlyEnergyConsumption) AS
  ?yearlyEnergyConsumption)
WHERE {
  #RETRIEVE THE FLOW MOVING DEVICES FOR AN AHU
  ?system a fso:System .
  ?system fso:hasSubSystem ?subSystem .
  ?subSystem fso:hasComponent ?fan .
  ?fan a fso:Fan .

  #RETRIEVE THE FAN EFFICIENCY FOR EACH TIMESTAMP
  ?fan fpo:hasEfficiency ?fanEfficiency .
  ?fanEfficiency caso:hasState ?efficiencyState .
  ?efficiencyState fpo:hasValue ?efficiencyValue .
  ?efficiencyState time:inXSDDateTimeStamp ?timeStamp .

  #RETRIEVE OUTLET PORT
  ?fan fso:hasPort ?port .
  ?port fpo:hasFlowDirection ?flowDirection .
  ?flowDirection fpo:hasValue "Out" .

  #RETRIEVE THE FLOW RATE FOR EACH TIMESTAMP
  ?port fpo:hasFlowRate ?flowRate .
  ?flowRate caso:hasState ?flowRateState .
  ?flowRateState fpo:hasValue ?flowRateValue .
  ?flowRateState time:inXSDDateTimeStamp ?timeStamp .

  #RETRIEVE THE PRESSUREDROP FOR EACH TIMESTAMP
  ?port fpo:hasPressureDrop ?pressureDrop .
  ?pressureDrop caso:hasState ?pressureDropState .
  ?pressureDropState fpo:hasValue ?pressureDropValue .
  ?pressureDropState time:inXSDDateTimeStamp ?timeStamp .

  #CALCULATE THE PRESSURE DROP FOR EACH TIME STAMP
  BIND(((?flowRateValue/1000) * ?pressureDropValue)/?efficiencyValue
    AS ?hourlyEnergyConsumption)

} GROUP BY ?system
```

Condition	AHU Type	Energy Cons. [kW]
Peak-load cond. with existing system	Geniox27	128,245
Peak-load cond. with new system	Geniox22	96,400
Part-load cond. with new system	Geniox18	89,369

Table 5
The selected AHU types and their energy consumptions based on peak-load and part-load conditions for the existing and new system using the manufacturer's tool.

with the new system has the lowest energy performance. The simplified HVAC design approach with the new system has a lower yearly energy performance of 25% compared to the simplified HVAC design approach with the existing system. The rightsized HVAC design approach with the new system has a lower energy performance of 31% compared to the simplified HVAC design approach with the existing system. Lastly, the rightsized HVAC design approach has a lower energy performance of 7% compared to the simplified HVAC design approach with the new system.

The data repository and Revit models for the simplified and rightsized HVAC design approaches used in this section are available at Zenodo [2].

6. Discussion

6.1. Achievements

The objective of this research was to develop an ontology-driven CDE to aid HVAC engineers in applying rightsizing methods in the building design process. Our findings provide new insights into improving data exchange between BIM and BEM applications and reducing negative consequences of oversizing and expand upon previous research in several important ways. The CDE consists of a centralized repository and five tools, including a BIM model, a hydraulic calculation engine, a whole-building simulation engine, a data visualization tool, and a manufacturer tool.

First, we showed how ontologies can provide flexibility and modularity for linking and extending heterogeneous data models, thus enabling semantic interoperability across different domains and applications.

Second, we produced a demonstration environment that shows how our ontology-driven CDE can be applied to a real-world building project. This contribution provides a practical demonstration of how our proposed solution can be used to improve the efficiency of the HVAC design process.

Third, our research showcased the effectiveness of our ontology-driven CDE in representing and managing heterogeneous information in the built environment. In particular, we displayed how our solution can effectively represent and manage the indoor climate, material usage, and energy performance of an HVAC system. Furthermore, this approach aligns with the semantic web's vision of transitioning from a document-centric to a data-centric paradigm, providing an innovative path for the Architecture, Engineering, Construction, and Operation (AECO) industry. It promotes a shift towards a data-centric method, centralizing all relevant data in a single, accessible, and interoperable format. This shift not only substantially improves data accessibility, quality, and consistency, but it also establishes a trustworthy source that all stakeholders can rely upon, lowering the barrier to applying rightsizing methods, and setting up the stage for more sustainable and high-performing building designs.

Furthermore, our study provides a foundation for future research in this area, highlighting the importance of utilizing ontologies and a CDE in the building design process.

6.2. Limitations

Several limitations should be acknowledged. One limitation of this study is that it only focused on the ventilation system of an already-constructed building project and did not consider other HVAC systems, such as heating and cooling systems. In addition, the study focused on a single building, and a broader study would be needed to generalize the findings. This could be achieved by incorporating a wider range of building projects and HVAC systems.

[2] https://zenodo.org/record/7704836#.ZAcyhXbMI7E

This study has revealed that oversizing can occur with simplified HVAC design methods, which can have negative consequences such as increased costs and environmental impact. However, oversizing also provides a buffer for unexpected changes and deviations from typical building usage. It is still unanswered whether it provides a valuable buffer for future building occupancy patterns and extreme weather conditions. Future studies focusing on user behaviour and incorporating more precise occupancy schedules may improve the rightsizing method. Furthermore, future KPI may assist buildings in adapting to specific scenarios not directly addressed in the design brief. These KPIs may consider energy loads further up the system, such as peak loads and time effects on district heating systems and peak demand linked to electricity distribution systems. This study focuses on energy consumption and the hydraulic performance of the ventilation system, but it does not consider energy sources and their impact. It is recognized that buildings must adapt to changes in behaviour and climate and the resulting energy demands in the system, both upstream and downstream. To achieve this, a multivariate analysis of future scenarios may be necessary to better understand the interactions between various factors affecting energy demand. This analysis could help identify ways for buildings to adapt to changing demands and minimize costs and environmental impact.

The indoor climate is evaluated based on two KPIs: an absolute limit for CO2 concentration and the maximum number of hours outside a specific range. While these KPIs provide valuable information, they do not fully capture all aspects of indoor climate comfort. In future work, it may be beneficial to include additional KPIs, such as Permitted Mean Vote (PMV) and Percentage of Dissatisfied (PDD), to provide a more comprehensive assessment of indoor climate. Additionally, this study does not compare the proposed ontology-driven approach to commercially available alternatives, such as Autodesk [31], Trimble [32], Aconex [34], or Procore [35], or other open data formats, such as IFC [51] or gbXML [52]. Therefore, further evaluation is needed to assess the performance of the proposed approach in terms of usability, flexibility, stability, and other process and business-driven KPIs.

6.3. A roadmap for future work

This study aimed to close the gap between BIM and BEM tools using an ontology-driven CDE. We exchanged data between the BIM and BEM tools to perform steps 4 and 5 of the HVAC design process, described in Section 2, which involves calculating the HVAC demand at room level and the AHU capacity. However, we encountered several challenges in step 6 of the HVAC design process when selecting products from manufacturers. Integrating the product data directly into BIM or BEM tools was difficult due to API limitations in the manufacturer's tools. Additionally, the manufacturer's tools only provided limited information about their products, so we had to access the rest from their webpage in pdf format. The reliance on pdf documents has several consequences, including difficulty updating and maintaining product information. The ontology-driven CDE developed in this study handled data exchange for a single project. It does not, however, have the ability to access information across multiple building projects simultaneously.

To address these challenges, we extended the ontology-driven CDE to the design shown in Figure 8. This ontology-driven CDE allows manufacturers to store product data in an ontology-based data repository and access it individually or simultaneously through APIs and an aggregator API. Using a GUI, a manufacturer can access multiple building projects simultaneously and create a list of suitable products for sale to their clients (designers). On the other hand, using a GUI, designers will be able to access product information and use it within their BIM and BEM tools for analysis purposes. Moreover, the designers will be able to store product information within their ontology-driven data repository, making it easy to access throughout the building life cycle. By eliminating the reliance on pdf documents and enabling the exchange of data between manufacturer and designer tools, this CDE can improve the accuracy and efficiency of both the design and manufacturing processes.

To validate the effectiveness of the extended CDE, future work includes the development of the extended CDE and conducting a demonstration case to test its use from both the designer's and manufacturer's perspectives. From the designer's perspective, the demonstration case involves the following steps:

1. Based on the AHU capacity, the designer searches for products among multiple manufacturers using the manufacturer's aggregator API.
2. The designer uses the product data within its BEM tool to analyse its energy performance
3. The designer saves the product information in the project's ontology-driven data repository so that it may be accessed easily during the operation and maintenance phase

From the manufacturer's perspective, the demonstration case involves the following steps:

1. The manufacturer accesses HVAC components across multiple building projects using the designer's aggregator.
2. The manufacturer matches its products with the accessed HVAC components
3. The manufacturer creates a list of suitable products for sale for the different projects

7. Conclusion

In this study, we presented an ontology-driven CDE to improve data exchange between BIM and BEM tools to aid HVAC engineers in applying rightsizing methods in the building design process. We showed how our solution can effectively represent and manage the heterogenous

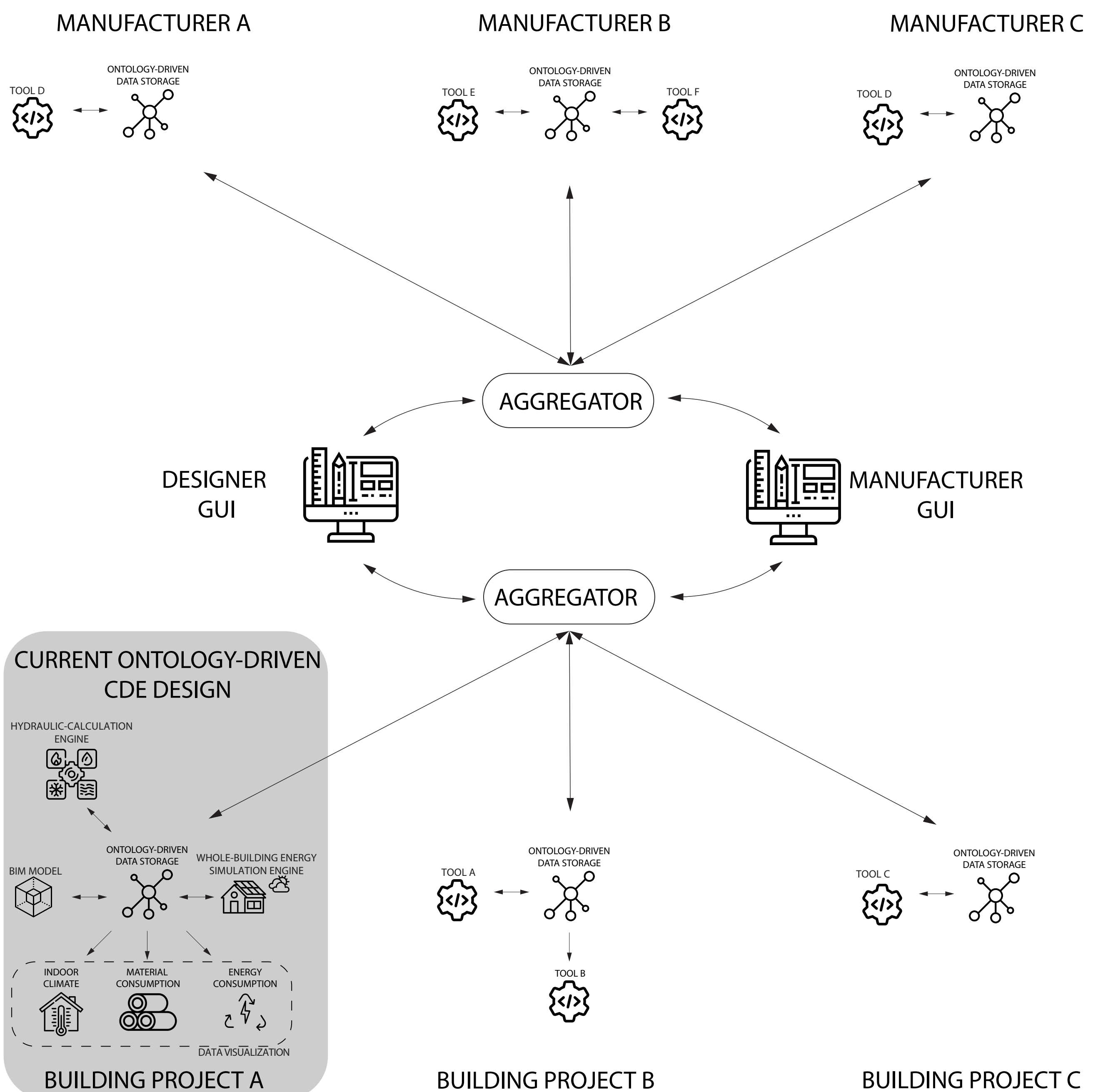


Figure 8: The figure illustrates how the ontology-driven CDE can be extended to support the data exchange between manufacturers and the designers The extended ontology-driven CDE allows manufacturers to store product data in an ontology-based data repository and access it individually or simultaneously through APIs and an aggregator API.

building information, particularly for the HVAC domain. We found that applying rightsizing methods to a specific building project resulted in improved indoor climate and reduced material usage and energy consumption compared to a simplified HVAC design approach. However, the study has several limitations, and further evaluations are needed to assess the performance of the proposed approach. Despite these limitations, the proposed CDE has the potential to be a valuable tool for efficient evaluations of HVAC design and can be extended to include more complex measures of comfort and adapt to future scenarios.

8. Acknowledgements

This work was supported by EU-Interreg ÖKS "Data-driven Energy Management in Public Buildings"; the Innovation Fund Denmark (grant 9065-00266A); the Ramboll Foundation; and COWI A/S. We thank Sorø municipality for providing the BIM model for Frederiksberg Skole. Additionally, we would like to express gratitude to the LBD Hackers group from the 2022 AEC Hackathon in Copenhagen, for enlightening us on how to bridge the gap between building designers and manufacturers through the use of ontologies.

References

[1] M. W. Ellis, E. H. Mathews, Needs and trends in building and hvac system design tools, Building and Environment 37 (2002).
[2] T. Häkkinen, K. Belloni, Barriers and drivers for sustainable building, Building Research and Information 39 (2011).
[3] E. Djunaedy, K. van den Wymelenberg, B. Acker, H. Thimmanna, Rightsizing: Using simulation tools to solve the problem of oversizing, 2011.
[4] J. L. Gorter, Hvac equipment right-sizing: Occupant comfort and energy savings potential, Energy Engineering: Journal of the Association of Energy Engineering 109 (2012).
[5] P. Huang, G. Augenbroe, G. Huang, Y. Sun, Investigation of maximum cooling loss in a piping network using bayesian markov chain monte carlo method, Journal of Building Performance Simulation 12 (2019).
[6] W. Obrien, A. Abdelalim, H. B. Gunay, Development of an office tenant electricity use model and its application for right-sizing HVAC equipment, Journal of Building Performance Simulation 12 (2019).
[7] V. Monetti, E. Davin, E. Fabrizio, P. André, M. Filippi, Calibration of building energy simulation models based on optimization: A case study, Energy Procedia 78 (2015).
[8] E. Djunaedy, K. V. D. Wymelenberg, B. Acker, H. Thimmana, Oversizing of hvac system: Signatures and penalties, Energy and Buildings 43 (2011).
[9] B. Crozier, Enhancing the performance of oversized plant (AG 1/2000), Technical Report, BSRIA, 2000. URL: https://www.bsria.com/uk/product/Rrbw4n/enhancing_the_performance_of_oversized_plant_ag_12000_a15d25e1/.
[10] G. Knight, I. and Dunn, Size Does Matter, Building Services Journal (2006).
[11] D. R. Felts, P. Bailey, The state of affairs - packaged cooling equipment in california, volume 3, 2000.
[12] D. Shiming, Sizing replacement chiller plants, ASHRAE Journal 44 (2002).
[13] A. Burdick, Strategy guideline: Accurate heating and cooling load calculations, Guidelines for Improved Duct Design and HVAC Systems in the Home (2012) 103–138.
[14] M. Sherman, I. Walker, Right-sizing hvac: It can be just plain wrong, ASHRAE Journal 53 (2011).
[15] D. H. Nall, Rightsizing HVAC equipment, ASHRAE Journal 57 (2015) 48–51.
[16] M. Shin, J. S. Haberl, Thermal zoning for building HVAC design and energy simulation: A literature review, Energy and Buildings 203 (2019).
[17] E. M. Ryan, T. F. Sanquist, Validation of building energy modeling tools under idealized and realistic conditions, Energy and Buildings 47 (2012) 375–382.
[18] E. Bettanini, A. Gastaldello, L. Schibuola, Simplified models to simulate part load performances of air conditioning equipments, Eighth International IBPSA Conference Eindhoven, Netherlands August 11-14, 2003 (2003) 107–114.
[19] E. Kamel, A. M. Memari, Review of bim's application in energy simulation: Tools, issues, and solutions, 2019. doi:10.1016/j.autcon.2018.11.008.
[20] G. B. Porsani, K. D. V. de Lersundi, A. S. O. Gutiérrez, C. F. Bandera, Interoperability between building information modelling (Bim) and building energy model (bem), Applied Sciences (Switzerland) 11 (2021) 1–20.
[21] R. Sacks, C. Eastman, G. Lee, P. Teicholz, BIM Handbook: A Guide to Building Information Modeling for Owners, Designers, Engineers, Contractors, and Facility Managers, 2018.
[22] I. Esnaola-Gonzalez, F. J. Diez, Integrating Building and IoT data in Demand Response solutions, 2019. URL: http://project-respond.eu.
[23] J. Werbrouck, P. Pauwels, J. Beetz, L. van Berlo, Towards a decentralised common data environment using linked building data and the solid ecosystem, Advances in ICT in Design, Construction and Management in Architecture, Engineering, Construction and Operations (AECO) : Proceedings of the 36th CIB W78 2019 Conference (2019) 113–123.
[24] J. M. Werbrouck, M. Senthilvel, J. Beetz, Querying Heterogeneous Linked Building Data with Context-expanded GraphQL Queries, 2019. URL: https://www.w3.org/TR/sparql11-query/.
[25] P. Pauwels, D. V. Deursen, R. Verstraeten, J. D. Roo, R. D. Meyer, R. V. D. Walle, J. V. Campenhout, A semantic rule checking environment for building performance checking, Automation in Construction 20 (2011).
[26] J. Lee, Y. Jeong, User-centric knowledge representations based on ontology for AEC design collaboration, Computer-Aided Design 44 (2012) 735–748.
[27] M. H. Rasmussen, M. Lefrançois, P. Pauwels, C. A. Hviid, J. Karlshøj, Managing interrelated project information in AEC Knowledge Graphs, Automation in Construction (2019).
[28] A. Kücükavci, M. Seidenschnur, P. Pauwels, M. H. Rasmussen, C. A. Hviid, Efficient management and compliance check of HVAC information in the building design phase using semantic web technologies (2023). [Manuscript submitted for publication].
[29] M. H. Rasmussen, M. Lefrançois, G. F. Schneider, P. Pauwels, Bot: The building topology ontology of the w3c linked building data group, Semantic Web 12 (2020) 143–161.
[30] V. Kukkonen, A. Kücükavci, M. Seidenschnur, M. H. Rasmussen, K. M. Smith, C. A. Hviid, An ontology to support flow system descriptions from design to operation of buildings, Automation in Construction 134 (2021) 104067.
[31] Autodesk BIM 360: Construction Management Software, 2022. URL: https://www.autodesk.com/bim-360.
[32] Trimble Connect: Collaboration made easy, 2022. URL: https://connect.trimble.com.
[33] Asite: Common Data Environment, 2022. URL: https://www.asite.com/project-portfolio-management-ppm/common-data-environment-cde.
[34] Aconex: Construction Management from Oracle, 2022. URL: https://www.oracle.com/industries/construction-engineering/aconex.
[35] Procore: Construction Management Software, 2022. URL: https://www.procore.com/en-gb.
[36] BIMServer: BIM-Environment, 2022. URL: https://github.com/opensourceBIM/BIMserver.
[37] Projectwise: Infrastructure Project Delivery Software, 2022. URL: https://www.bentley.com/software/projectwise.
[38] Openproject: The future of Construction Project Management, 2022. URL: https://www.openproject.org/bim-project-management.
[39] Autodesk BIM 360 – the heart of construction, 2022. URL: https://aecmag.com/news/autodesk-bim-360-2/.
[40] A.-H. Hamdan, M. Bonduel, R. J. Scherer, An ontological model for the representation of damage to constructions, 2019. URL: http://www.w3.org/1999/02/22-rdf-syntax-ns#.
[41] K. M. Kensek, D. E. Noble, Building Information Modeling: BIM in Current and Future Practice, volume 53, 2014.

[42] V. Dimitriou, S. K. Firth, T. M. Hassan, F. Fouchal, Bim enabled building energy modelling: development and verification of a gbxml to idf conversion method, Ibpsa (2016).

[43] B. Schwegler, Green bim: Successful sustainable design with building information modeling by eddy krygiel and bradley nies, Journal of Industrial Ecology 14 (2010).

[44] B. Balaji, A. Bhattacharya, G. Fierro, J. Gao, J. Gluck, D. Hong, A. Johansen, J. Koh, J. Ploennigs, Y. Agarwal, M. Bergés, D. Culler, R. K. Gupta, M. B. Kjærgaard, M. Srivastava, K. Whitehouse, Brick: Metadata schema for portable smart building applications, Applied Energy 226 (2018) 1273–1292.

[45] S. Chávez-Feria, G. Giannakis, R. García-Castro, M. Poveda-Villalón, From obxml to the op ontology: developing a semantic model for occupancy profile, in: LDAC, 2020.

[46] S. Cox, C. Little, J. R. Hobbs, F. Pan, Time Ontology in OWL. W3C Recommendation, Technical Report October, 2017. URL: https://www.w3.org/TR/2017/REC-owl-time-20171019/.

[47] F. Seeberg, J. Tangeraas, Integration of Thermal Building Simulation Tools and Cloud-Based Building Information Models, 2022.

[48] M. H. Vorre, M. H. Wagner, S. E. Maagaard, P. Noyé, N. L. Lyng, L. Mortensen, Branchevejledning for indeklima, 2017.

[49] D. standard, Ventilation i bygninger – Mekaniske , naturlige og hybrid e ventilationssystemer, Ds 447 (2013) 1–3.

[50] Systemairs selection software for Geniox air handling units, 2022. URL: https://www.systemair.com/support/product-selection-tools/systemaircad.

[51] IFC Specifications Database, 2022. URL: https://technical.buildingsmart.org/standards/ifc/ifc-schema-specifications/.

[52] GBXMLS: An industry supported standard for storing and sharing building properties, 2022. URL: https://github.com/greenbuildingxml.