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Automated model generation for integrated building and HVAC performance simulation

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Kurzfassung

Steigende Anforderungen und neue Technologien stellen Architekten und Gebäudeplaner vor immer größere Herausforderungen. Gebäudesimulation kann das thermische und energetische Verhalten von Gebäuden abbilden, bevor sie gebaut oder verändert werden, und damit energieeffiziente Planung unterstützen. Heizungs-, Lüftungs- und Klimaanlagen (HLK) spielen bei Energieeffizienzfragen eine wichtige Rolle, und sollten in der Simulation berücksichtigt werden.

Ausführliche Gebäude- und HLK-Simulationen werden aber durch den Aufwand der Modellvorbereitung gehindert, vor allem in der Entwurfsplanung, wo sie den höchsten Beitrag leisten könnten. Während Gebäudegeometrie für Simulationszwecke mittels Building Information Modeling (BIM) extrahiert werden kann, sind im Falle von HLK-Anlagen ähnliche Modellumwandlungen schwieriger. Außerdem stehen detaillierte Modelle der zu untersuchenden Systemen oft nicht zu dem Zeitpunkt zur Verfügung, zu dem eine Simulation bei Design-Entscheidungen nützlich wäre.

Um dieses Problem zu lösen, wird in dieser Arbeit eine Methode entwickelt, die es ermöglicht ausgehend von verfügbaren Gebäudemodellen Modelle von möglichen HLK-Anlagen zu generieren. Der Anwendungsbereich der Methode wird anhand von drei Anwendungsfällen festgelegt, in denen bei der Planung von Gebäuden und Warmwasserheizungsanlagen mehrere Varianten verglichen werden sollen. Unter Berücksichtigung dieser Anwendungsfällen werden Anforderungen für eine Methode und deren Softwareumsetzung spezifiziert. Aus Gebäudemodellen sollen entsprechende auf Komponenten basierende HLK-Modelle abgeleitet werden, und zur integrierten Simulation von Gebäuden und HLK-Anlagen eingesetzt werden. Die erstellten Modelle, wenn auch nicht so detailliert wie gleichungsbasierte Modelle, stellen gegenüber idealisierten und auf allgemeinen Systemen basierenden Modellen eine Verbesserung dar. Den Kern der vorgeschlagenen Methode bilden also Verfahren, die Modelle von an einem Gebäude angepassten HLK-Anlagen automatisch erstellen. Am Anfang dieser Verfahren steht die Ermittlung von Auslegungslasten. Anschließend folgt der Aufbau von Systemmodellen der Gliederung in Teilanlagen für Nutzerübergabe, Verteilung und Wärmebereitstellung. Ein Schwerpunkt liegt dabei auf die Verteilung, die eine Schwachstelle in bisherigen Ansätzen zur automatischen Modellerstellung darstellt. Zur Bestimmung möglicher Verteilungsstrukturen wird eine auf Graphen basierende Methode entwickelt. Ausgehend von der Gebäudegeometrie und von der Anordnung der Übergabekomponenten, werden gewichtete Graphen gebildet, die mögliche Verteilungskomponenten darstellen. In diesen Graphen entsprechen Vor- und Rücklaufleitun-

gen zyklenfreien Teilgraphen.

Die Methode wird als Softwaresystem implementiert. Dabei wird die Erstellung von komponentenbasierten HLK-Modellen von derer Übersetzung in Eingänge für Simulationstools getrennt. Zwei Möglichkeiten der Simulation werden eingesetzt: integrierte Simulation mit EnergyPlus, und Co-Simulation zwischen EnergyPlus für die Gebäudesimulation und TRNSYS für die Anlagensimulation. Es wird dargestellt, wie das Softwaresystem auf die vorher definierten Anwendungsfälle angewendet werden kann.

Für die Verifizierung und Validierung des Systems werden mehrere Ansätze herangezogen. Vom System gelieferte Ergebnisse werden mit vergleichenden Tests geprüft, indem Eigenschaften von erstellten Modellen mit denen von realen Anlagen und mit Standardwerten verglichen werden. Verschiedene Vereinfachungen werden in ihrer Wirkung untersucht. Ein systematisches Zonierungsverfahren wird benutzt, um Zonen nach gewissen Merkmalen zusammenzulegen. Der Einfluss der resultierenden Zonierungen auf Simulationsergebnisse wird anhand von 5 Beispielgebäuden untersucht. Auch Verfahren zur Vereinfachung von HLK-Modellen werden entwickelt und evaluiert. Weiters werden Methoden zum Parameterscreening und zur Modellkalibrierung auf das entwickelte System angewendet. Mit der Elementareffekt-Methode können unwichtige Eingangsparameter identifiziert werden. Weiters wird die Möglichkeit von Modellkalibrierung dargelegt. Dafür können automatisch Parameter variiert und die Differenzen zwischen Simulations- und Messwerten minimiert werden. Diese Möglichkeit wird anhand von künstlichen und anhand von realen Daten untersucht.

Indem die vorgelegte Methode dazu beiträgt, integrierte Gebäude- und Anlagensimulation erschwinglicher zu machen, kann sie die Lücke zwischen Simulation und Entscheidungsunterstützung in der Entwurfsplanung verkleinern.

Abstract

With growing requirements and changing technologies, making the right decisions in building design is more challenging than ever. Building performance simulation (BPS) has the potential to support the planning of more energy-efficient buildings by modeling their thermal behavior in its complexity before their actual construction or modification. This involves taking into account heating, ventilation and air-conditioning (HVAC) systems and their interaction with the building and its occupants.

Still, obtaining a detailed evaluation of the performance of building and HVAC systems in early planning stages is made difficult by cumbersome model preparation. While building geometry from building information models (BIM) can be translated for use in building performance simulation, such model transformations are more problematic when it comes to HVAC data. Moreover, detailed descriptions of HVAC systems whose performance is to be assessed are generally not available during those early stages in which simulation could be most useful.

The approach developed in this thesis aims at avoiding this difficulty by creating models of potential HVAC systems corresponding to available building models. The scope is defined by three use cases in conceptual design of building and hydronic HVAC systems, for new constructions as well as for refurbishment. Requirements for a method supporting these use cases and for a software system realizing this method are specified. The software system is to derive component-based models of possible HVAC systems from building models, and use these models for integrated building and HVAC simulation with existing simulation engines. While coarser than equation-based models which may represent HVAC systems most realistically, the targeted component-based models can be assumed to represent an improvement on conceptual and system-based HVAC modeling.

Procedures for the automated creation of component-based HVAC models are at the heart of the proposed method. These procedures start with the determination of design loads, and follow a traditional decomposition of hydronic systems in delivery, distribution and generation subsystems. For each subsystem, the procedures are developed by adapting processes described in the corresponding engineering literature to our requirements, and formalizing or simplifying such processes where necessary. In this context, some emphasis is put on distribution subsystems, which represent a weak link in current approaches to automated HVAC model creation. Distribution layouts are determined with a graph-based method, based on networks of potential distribution components which match building geometry and delivery components. Supply and return distributions are

derived from acyclic subgraphs in these networks.

A software system prototype realizing the method is developed. The design of this software system separates the creation of component-based HVAC models, as described above, from their transformation into simulation inputs. The system prototype is implemented for integrated simulation with EnergyPlus, and for co-simulation between EnergyPlus (building domain) and TRNSYS (HVAC domain). The application of the system to the three targeted building and HVAC design use cases is illustrated.

Different efforts aiming at the verification and validation of the proposed system are presented. Results are subjected to comparative testing. Characteristics of generated system models are compared with those of existing HVAC systems and with standard values. Simulation results obtained with different simulations are compared. The effects of various model simplifications are investigated. Using a systematic zoning procedure, the impact of several zoning schemes on simulation results is observed for five floors plans, distinguishing between simulation zoning and HVAC zoning. Procedures simplifying the structure of HVAC models and reducing the number of components are defined and evaluated. The use of parameter screening and calibration with the proposed system is also investigated, which contributes to its validation but also opens up possibilities for applications beyond the three initial use cases. Parameter screening with the method of elementary effects is applied to various sets of building and HVAC-related parameters. For automated simulation calibration with the proposed system, a method based on the minimization of differences between simulated and measured values is suggested, and tested with synthetic as well as with real data.

By making detailed assessments of the integrated performance of building and HVAC concepts more affordable, the method for automated model generation proposed in this work may fill a gap in the use of simulation for decision support in the conceptual design phase.

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Contents

Chapter 1

Introduction

Ways to predict the thermal and energetic behavior of building concepts before their realization are seen as relevant to meet challenges related to building energy efficiency. Only with the help of computational tools can the variety of relevant processes and interactions be taken into account [1, 2]. Building performance simulation tools developed to this end have continuously evolved since the 1970's, and have acquired confidence among the research community [3, 4]. Nonetheless, they still face important challenges, notably when it comes to supporting the design and operation of buildings on a wide basis.

Until now, the production of a building model for performance simulation is considered to be a time consuming and error prone process. In order to accurately model the performance of heating, ventilation and air-conditioning (HVAC) systems, their dynamic behavior and their interaction with the rest of the building should be taken into account. Integrated simulation of buildings and HVAC systems makes this possible, but it represents an additional challenge for model creation. As a result, current practice usually foregoes such integrated simulation by using only highly simplified models of the HVAC systems. Streamlining the model creation process for integrated building and HVAC simulation thus appears as a major step in making dynamic simulation more widely applicable.

This thesis aims at automating the creation of integrated models for the simulation of both building and HVAC systems. This may help bridge the gap between sophisticated simulation tools and planning support for energy efficient buildings.

1.1 Background

This section presents background information on energy efficiency in buildings and HVAC systems, followed by an introduction to building energy performance simulation and its data requirements.

1.1.1 Energy efficiency of buildings

Buildings account for a large share of the global energy use. This is particularly true in the European Union, with almost 40% of final energy use [5, 6]. The environmental impact of this energy use is significant, including but not limited to global warming and various kinds of local and global pollution [7]. Such amounts of energy also play an important role in major economic and political issues, including those related to the security of energy supply [8]. Fortunately, the better design of new buildings and the refurbishment of existing ones can lead to an important reduction of energy consumption. The European Directive on Energy Performance of Buildings [6], seeing a "great potential for energy savings", makes the application of requirements to the energy performance of buildings mandatory for all member states. Building energy efficiency is thus pursued as a highly desirable goal. However, it is not straight-forward to define it in a quantitative and robust way [9].

Efficiency in general may be defined as "the ability to do something or produce something without wasting materials, time, or energy" [10]. It is often expressed as the ratio of a useful quantity to a quantity used to obtain it. In the case of energy efficiency, the denominator would be a quantity of consumed energy, considered at a given system boundary. The varying costs of different sources of energy introduce some complexity. In particular, the costs and availability of renewable energy sources, which are seen as a key answer to the energy challenges mentioned above, are subject to wide variations.

As for the numerator in this energy efficiency ratio, it may take on various aspects corresponding to the various purposes for which energy may be consumed in buildings. End energy uses correspond to services including space conditioning (heating, cooling and ventilation), preparation of hot water, cooking, lighting, refrigeration and use of other appliances. When aggregating all these uses, the total energy consumption is often specified for one year and simply measured against space area or volume. Commonly used in this case is an energy use intensity (kWh/(m^2a)), which represents the inverse of an efficiency ratio. Such an indicator is only meaningful when combined with some information about the level and quality of the provided services. This is described below in more detail for heating, ventilation and air conditioning.

Heating, ventilation and air conditioning systems represent a significant to major share of building energy consumption, depending on building types and on the consideration of end uses more or less related to buildings [5]. For instance, HVAC systems account for about half of the energy consumption in offices in the USA and UK, as indicated in Table 1.1. Moreover, HVAC energy use is most dependent on building design, as opposed to the use of office, cooking, washing or entertainment appliances. The present work focuses on energy performance with regards to the energy used by HVAC systems.

Table 1.1: Proportions of energy consumption in office buildings by end use, according to [5].

End energy use	**USA** %	**UK** %
HVAC	48	55
Lighting	22	17
Appliances	13	5
Hot water	4	10
Food preparation	1	5
Refrigeration	3	5
Others	10	4

1.1.2 Heating, ventilation and air-conditioning

Systems ensuring thermal comfort and air quality inside of buildings are grouped under the acronym HVAC (heating, ventilating, and air-conditioning). Heating and air-conditioning consist in supplying spaces in the building with thermal energy, and in extracting thermal energy from them, in order to keep temperature and humidity at a level comfortable for the occupants or favorable for certain processes. Ventilation aims at maintaining good air quality by the circulation of air to and from occupied places. This circulation of air at different physical conditions naturally interacts with heating, cooling, humidification and dehumidification.

Different typologies and classifications of HVAC systems and components can be established. To start with, one can distinguish systems according to "service levels" [11], depending on their ability to heat, cool, provide natural or mechanical ventilation, humidify and/or dehumidify air.

According to their arrangement in buildings, a distinction can be made between centralized and decentralized HVAC systems [12]. In the latter, the heating, ventilation or cooling equipment is located in the respective spaces they serve. In centralized systems the equipment is located in one central facility, and linked to conditioned spaces by a distribution network. According to the circulated fluid, one can distinguish between air systems, hydronic (water) systems and steam systems [13]. Hot water and steam systems can be further differentiated according to temperature and pressure. Different mediums can also be used in separate loops, for instance in so-called air-water HVAC systems.

Inside of a whole HVAC system, a distinction is usually drawn between primary and secondary components. Primary HVAC components ensure the conversion of primary energy sources to carriers of thermal energy. They are for instance chillers, for cooling, boilers and heaters, for heating, and heat pumps, which can be used for both purposes, as well as thermal storage equipment [14]. Secondary HVAC components represent the connection between primary components and the building. They include fluid distribution components and air-handling equipment.

Both primary and secondary components can be either distribution components or heat and mass transfer components.

Heating systems can also be decomposed into subsystems corresponding to generation, storage, distribution and delivery [15]:

- *Delivery* (or emission) components are responsible for delivering energy to the conditioned spaces.
- *Distribution* components are responsible for transmitting energy until the emission components.
- *Generation* actually refers to the transformation of fuel or electric energy into thermal energy, or in the case of district heating the mere supply of thermal energy at the desired temperature. Energy is not generated but converted from one form into another.
- A possible *storage* subsystem, aiming at smoothing out differences between emission and generation, may be included in the generation subsystem or considered separately [15].

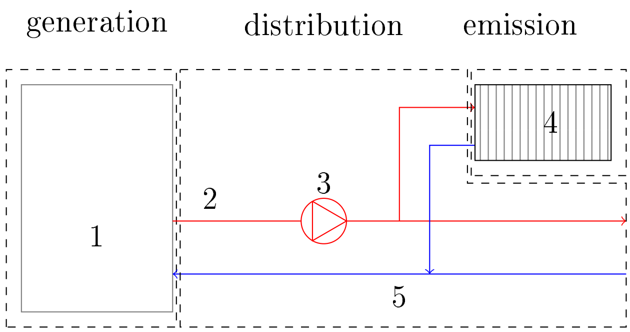


Figure 1.1: HVAC subsystems at the example of a simple hydronic heating system, adapted from DIN EN 15316-1 [15]. 1: boiler. 2: supply pipe. 3: pump. 4: radiator. 5: return pipe. No storage subsystem is present in this system.

A consistent system overview can be based on these subdivisions [16], beginning with delivery. In the case of decentralized systems, it is the only domain. The tracking of different types of losses can also be based on this kind of subdivision. Alternatively, efficiency factors may be determined for each domain, the product of which gives the overall system efficiency. Graphically, one may follow the flow of energy along the system with the help of a so-called Sankey diagram [17], as illustrated in Figure 1.2. Energy amounts being proportional to the breadths of arrows, efficiency factors may be read as the ratio of outcoming on incoming dimensions.

Auxiliary energy used by different components (particularly pumps and fans), which is electric energy, features separately from thermal energy. One could follow

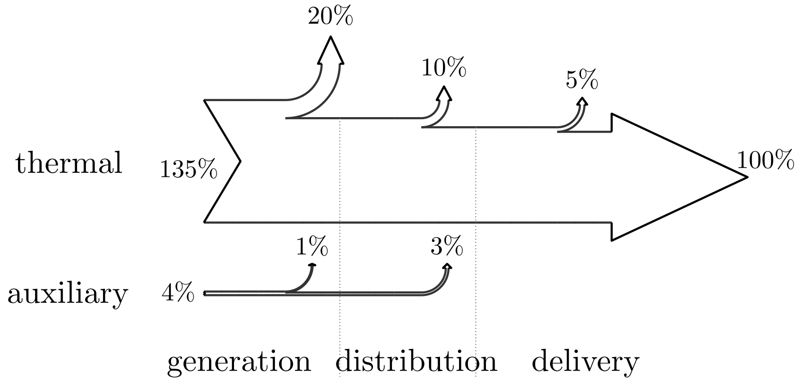


Figure 1.2: Example of Sankey diagram for hydraulic space heating.

energy flows further, outside of the building and towards the source, which may reveal the respective costs of fuel and electrical energy.

Control represents an important aspect, present in and across all these subsystems. Control inefficiencies may impact different levels of the system and thus be difficult to attribute to a specific domain.

Getting back to the problem of energy efficiency, a number of reasons make the definition of the efficiency of HVAC systems a non-trivial task.

A prerequisite to the definition of the efficiency of HVAC systems and their subsystems is the determination of their respective limits. Different types of energy can only be compared based on their relative costs and environmental impacts. A simple approach is to weigh amounts of final energy with primary energy factors. The cost of energy may also vary in time.

The services against which energy use is to be measured primarily consist in the provision of thermal comfort and acceptable air quality. Thermal comfort and indoor air quality are challenging to quantify, linked to each other and to other aspects of the built environment. Thermal comfort is a dynamic phenomenon depending on multiple variables (summarized in Figure 1.3) and subject to individual variations. Several mechanisms of thermal adaptation have been shown to be more or less significant, depending on the opportunity for occupants to adapt [18]. Beyond dissatisfaction with the environment, thermal discomfort may impact human performance on a variety of tasks [19].

Indoor air quality may be affected by a multiplicity of contaminants, e.g. under the form of particles, bioaerosols or gases [20, ch.9]. The impacts of these various types of contaminants on human health, well-being and productivity can be significant, but they are still incompletely understood [21]. Frequently used indicators of indoor air quality are carbon dioxide concentration, ventilation rates per person and air change rates. CO_2 concentration is frequently used to evaluate air quality, not only because of the effects of this gas on human health and performance, but also owing to its practical role as a tracer gas emitted by occupants. Complex relationships between contaminant sources, air concentrations and exposures also explain the lack of general agreement on acceptable ventilation rates to avoid ad-

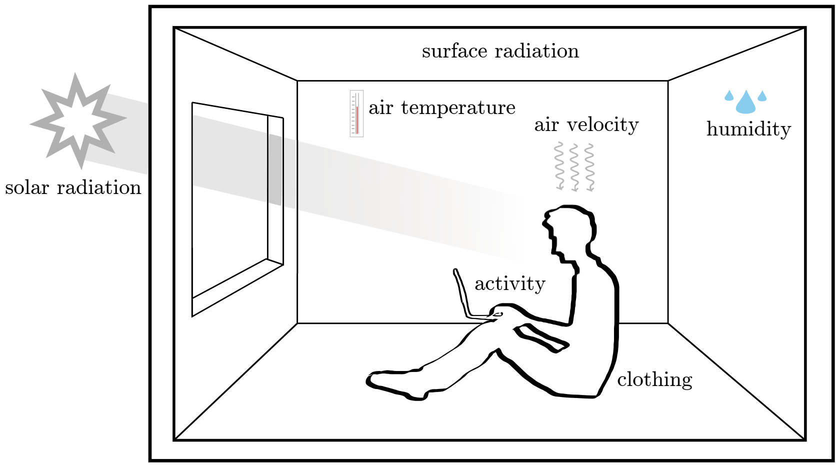


Figure 1.3: Variables determining thermal comfort.

verse effects [21]. This is problematic for the definition of building performance, not least because of the energy consumption required by higher ventilation rates.

To make things simple, energy consumption is often measured against a conditioned area or volume, for which acceptable thermal conditions and air quality are assumed. The previous discussion shows that this is a drastic simplification, which is necessarily based on multiple non-indisputable assumptions. Measuring energy use against the number of persons to which a comfortable thermal environment is provided can already lead to a significantly different appreciation of building energy efficiency [22].

The performance of HVAC systems is influenced by a wide range of factors, including building characteristics, climate, occupancy and operation. Time-varying and context-dependent factors complicate the quantification of HVAC energy efficiency.

The design of an appropriate HVAC system demands that these factors influencing its performance should be specifically considered. For building performance simulation to contribute to the design of more efficient buildings and HVAC systems, it should also take into account these factors and their dynamic interplay.

1.1.3 Building performance simulation

Many tools have been developed for the assessment of building performance, differing in their targeted use, scope, complexity and method. Several generations of such tools can be distinguished, ranging from handbook-oriented steady-state tools based on simplified physics to programs with an increasingly good match with reality [1]. The latter, aiming at emulating reality and its complex physical interactions, are called building performance simulation (BPS) tools. While many definitions can be found, simulation in general consists in some experimentation on models [23]. This may cover, for instance, the investigation of lighting conditions on the scale model of a building. In the following, we will use a more restrictive definition of simulation, also common in other engineering domains, where the experiment is carried out with computational means, and involves the execution of a model over time. Building performance simulation tools vary in their integration of multiple more or less tightly coupled domains, including for instance heat flow in the building envelope and in HVAC systems, air flow, moisture flow, daylight, artificial lighting and acoustics. Focusing on the aspects of thermal and energy performance, as in the following, one often speaks of dynamic thermal simulation [24], building energy modeling [25] or building energy simulation [26].

As opposed to other procedures for the estimation of building energy performance, dynamic simulation tools are characterized by a high temporal resolution, with hourly or shorter time steps. As for spatial discretization, thermal simulation uses a division of buildings into *zones*, whereas simpler heat balance calculations often lump all building rooms together, and airflow simulation usually operates on significantly smaller cells.

Concerning the design of mathematical models, a general distinction is that between law-driven models, which describe the behavior of a system based on established laws, and data-driven models, which can be derived from observed relations between inputs and outputs [27]. The latter are also referred to as black box models, as the inner workings of the system remain unknown, as opposed to white box or glass box models, which imply a knowledge of the system structure. Grey box models combine equations based on first principles with data-driven parameter identification [28]. In this general distinction of data-driven and law-driven models, the simulation tools discussed here are law-driven in their general structure, as they are based on physical principles like energy and mass conservation. However, components of the model (e.g. boiler model or convection at a wall boundary) may result from a data-driven approach. The calibration of building simulation models also yields hybrid models, neither black box nor glass box.

As law-driven models, the models upon which building performance simulation operates must encapsulate a wide variety of information relevant for building performance. From Figure 1.4, which illustrates the main components of simulation input, it appears that building geometry, as well as the description of internal loads and HVAC systems, are all linked to simulation zones. One may question this breakdown of simulation models, remarking that the domains are interlinked and partially overlap. For instance, occupant behavior may be assigned partially to internal loads, but it also plays a role in the HVAC domain with system operation, and even in the construction domain if one considers the operation of window coverings. The corresponding data requirements, which are explained in the following paragraphs, may represent a challenge for users. In particular, it will become apparent that building models for BPS differ significantly from typical architectural models.

A three-dimensional description of the building geometry is a prerequisite for dynamic thermal simulation. A building is generally divided in zones exchanging thermal energy between each other and with the exterior through surfaces referred to as space boundaries.

Simulation zones. Although the concept of zone is central to dynamic thermal simulation, definitions and recommendations as to the ways of determining the

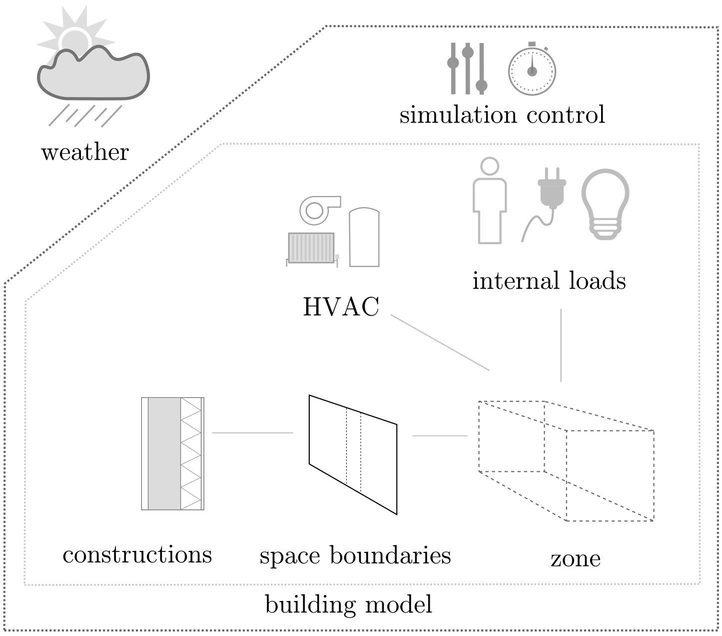


Figure 1.4: Main input domains for building performance simulation. Simulation inputs generally consist of a main simulation file and separate weather data. The former includes a description of the modeled system (building model), but also simulation control information.

zones to use in simulation seem to differ. The Merriam-Webster dictionary defines a zone as "an area that is different from other areas in a particular way". In the case of building energy performance simulation, the difference will consist in thermal and energetic aspects. While the Austrian standard EN 12831 for the calculation of design heat loads [29] concisely defines a zone as a "group of rooms with similar thermal properties", it is not obvious how to quantify these properties, which may be influenced by many factors. In simulation tools such as EnergyPlus or ESP-r, a zone corresponds to an air space with uniform properties, bounded by heat transfer surfaces, based on which an energy balance is calculated.

It is generally assumed that thermal zones can be formed on the basis of rooms, by combining some of them according to certain criteria [30, 31], or in certain cases subdividing them.

Geometrically, thermal zones considered for purposes of simulation should be fully bounded by surfaces. Usually, they should also be connected, which implies that only adjacent rooms can be joined in one zone.

Space boundaries. The surfaces bounding thermal zones are defined in a specific way, which differs from usual architectural drawing. Several types of space boundaries have been defined, as will be explained in the next chapter.

They separate a building zone from outside, or from another building zone, in which case they come in pairs, with a one-to-one relationship between the two surfaces. A space boundary usually represents the boundary between a building element and an (exterior or interior) air space. Virtual surfaces can be used to separate zones in the absence of physical boundary.

Cases where a space boundary of level one, corresponding to one architectural element, needs to be divided in several space boundaries of second level, are: (i) if a construction element is adjacent to three zones or more, since only one zone can be situated on each side of a pair of second level space boundaries; (ii) if the space boundary corresponds to different adjacent constructions, for instance in the case of a wall thicker on one side. On the contrary, one should use only one pair of second level space boundaries for layered building elements made out of different materials in the depth direction [32].

If radiation is modeled in detail, spaces need to be fully enclosed, which may require the inclusion into the model of space boundaries without thermal flow.

In state-of-the-art thermal simulation tools, space boundaries have a planar polygonal geometry. The determination of heat transfer direction, as well as radiation calculations, imply that the orientation of surfaces should be correctly defined [32]. The convention applied in common simulation tools is to have normal vectors pointing out of each zone.

Building fabric. Dynamic thermal simulation requires the specification of material properties for the building envelope, as well as for building elements separating zones, and those contributing to thermal inertia. This is generally done in terms of *constructions* attributed to the space boundary elements. These constructions can be composed of several layers corresponding to different materials.

Each material should be characterized by its conductivity ($W/(m^2\,K)$), density (kg/m^3) and specific heat ($J/(kg\,K)$). These properties are usually assumed to be homogeneous (and, for conductivity, isotropic) in each layer, as well as constant over time. Emissivity and absorptivity of external layers should also be specified, for the simulation of long-wave radiation. The description of transparent surfaces requires more data. Typically, each transparent layer is characterized by transmittance and reflectance coefficients, as unique averaged values or as spectral values.

Another aspect of building fabric is air-tightness, which is often subject to uncertainties and can be modeled in various ways. Infiltration can be specified as a constant (or scheduled) infiltration rate, or as coefficients depending on external conditions, notably wind velocity and air temperature.

Weather data. Dynamic thermal simulation implies the use of weather data, specified at a high resolution, typically hourly, for the whole simulated period. Important variables are: (i) outside (dry-bulb) temperature (°C); (ii) direct solar radiation (W/m^2) and diffuse solar radiation (W/m^2); (iii) wind speed (m/s) and direction (degrees); (iv) relative humidity (%).

The selection of appropriate weather data for thermal simulation can be challenging. In particular, the representation of typical weather patterns for the evaluation of average values and that of extreme periods for sizing and the assessment of building performance under extreme conditions would call for the use of different data [33]. Climate change may have a significant impact on building performance, and represents an additional source of uncertainty [34].

Internal loads and occupancy. As well as outside conditions, the way a building is used and the corresponding internal conditions are of paramount importance for its energy performance and should be included in simulation models.

Occupants affect the thermal behavior of buildings in several ways, "passively", for instance through the release of sensible and latent heat, as well as "actively", for instance by manipulating windows, shading devices and other devices [35].

Internal heat gains are generally modeled with the help of different schedules, differentiated according to the source (people, light, equipment) and the mode of heat transfer (convective, radiative, latent).

The temporal resolution of schedules, like that of weather data, is at least hourly, but schedules are often only specified per day type (e.g. weekdays, saturday, sunday). Schedule values may be given directly per zone, or indirectly per floor area or per occupant.

Active effects of occupants may also be represented with the help of schedules, but adaptive behavior may be modeled with functions of environment variables, such as internal or external temperature. The devices with which these active effects are achieved may also need to be more or less explicitly modeled. This is the case of HVAC systems, which should respond, for instance, to thermostat setting.

HVAC simulation models. Heating, ventilation and air conditioning (HVAC) systems may be represented at different levels of abstraction [14]:

- In the *conceptual* system modeling approach, HVAC systems are completely idealized. They are assumed to deliver exactly the right amount of energy to maintain set point conditions in the zones. It is thus assumed that the systems are perfectly controlled, and that they can deliver power without capacity limits and without time lags. The outputs of simulation are called *ideal loads*.

- In the *system-based* modeling approach, systems with fixed configurations and control strategies are used, with the possibility of specifying some parameters such as efficiency factors or flow rates.

- In the *component-based* modeling approach, a system is defined on the basis of interconnected components with their own models.

- In *equation-based* modeling, components are further decomposed in equations representing each considered physical process. This makes even finer granularity and greater flexibility possible [36].

Conceptual system models fundamentally only require the specification of set points for zone temperatures (and possibly air humidity), according to which energy is provided to the building in an ideal way. With increasing flexibility, system-based and component-based modeling also come with additional data requirements, to characterize the different components, their connections and the control strategies applied to them.

1.2 Problem statement

Following the background section, and anticipating the literature review of the next chapter, the present thesis is motivated by the promising role of integrated building and HVAC simulation for the support of energy efficiency in planning, and the difficulty of creating the models required by such simulation.

In the current situation, creating component-based simulation models of HVAC systems fitting a building is knowledge-intensive and time-consuming if done manually, and cannot be subject to automation by translation from available data.

Assembling models of HVAC systems requires knowledge of both the systems to be modeled and simulation tools. Determining and verifying connections of HVAC components between themselves and with the building geometry can be tedious work.

As established in the next chapter, the translation of HVAC systems into a form usable by energy simulation still faces considerable challenges. Indeed, the semantics of current building information modeling (BIM) data formats are not rich enough to carry all the information needed for HVAC simulation. What is more, one may not expect detailed HVAC models to be available at the concept design stage, let alone models of multiple HVAC alternatives. The intention of using BPS to simulate multiple alternatives makes HVAC model translation less likely, and it exacerbates the drawbacks of manual model preparation. In response to these issues, we propose the notion of automated model generation for integrated building and HVAC performance simulation.

As argued above, a scenario in which a simulation expert derives information from an architect and an HVAC engineer and combines it to create a performance simulation model could only incompletely and laboriously be subjected to automation. In comparison, it is expected that a two-role workflow in which models of HVAC systems are created from the beginning - based on building data - could be automated to a much higher degree. The present works thus follows this path for automated model generation for integrated building and HVAC performance simulation.

Based on these considerations, the proposed research question is as follows:

> On the basis of schematic architectural design, can integrated building models and component-based HVAC system models encompassing all subsystems be created automatically in such a way that their use in simulation provides better support for energy-efficient planning than building simulation with conceptual models?

Compared to this general question formulation, the present research is further narrowed down by several considerations. The use of existing simulation tools is a key decision. Demands and techniques for heating, ventilation and air-conditioning vary with time and place. This work is shaped by the current state of HVAC technology in Europe, where central systems, and in particular hydronic systems, prevail. Thus, the presentation of the method and its validation are focused on hydronic heating. Still, the applicability of the method to a broader range of HVAC systems is envisaged and discussed. The ambition to create models encompassing all subsystems leads us to put emphasis on distribution subsystems, which appear as a weak link as far as automated HVAC model preparation in current approaches is concerned. As automation may affect the trade-off between model complexity and practicability, the level of detail of simulation models and its impact on results is also a focus of the present work.

The research question is decomposed into the following subquestions, which correspond to the next chapters of this thesis:

1. What are the gaps in automated model creation for integrated building and HVAC performance simulation?
2. What are the software system requirements implied by a method of automatically creating building and HVAC models for BPS?
3. How can component-based HVAC system models be derived from building data?
4. How can a software system be structured that automatically derives building and HVAC simulation models from schematic building design? On which data model can this system operate?
5. To what extent can the proposed system support conceptual design of buildings and HVAC systems?
6. How can the accuracy of simulation results produced by the system be ascertained for varying boundary conditions?
7. Given the need to minimize required input and computational time and maximize simulation transparency and accuracy, to what extent are model simplifications acceptable?
8. How can simulation results be compared with measured data, and how can the created models be calibrated?

1.3 Objectives

- Develop a method for fully-automated creation of integrated building performance simulation models in early design stages, including detailed HVAC configurations derived from available building data for given system types.

- Implement this method in a prototype software system.
- Validate the system by means of sensitivity analysis, comparison of results with standard values and real buildings.
- Determine the acceptability of simplifications and the appropriate level of detail for planning support.

1.4 Methodology

The methodology adopted for this work had to address the research question and the objectives stated above. This involves the design of a software system realizing the proposed method.

The methodology can be outlined in terms of successive phases of analysis and synthesis. The research starts with an analysis of multiple requirements linked to the issue of automated BPS model creation and of gaps in current approaches. This is followed by the synthesis of algorithms for the creation of HVAC system models, and of a software design in which these algorithms can be used for the creation of simulation inputs. The resulting system is then subject to analysis. It is examined how the original design use cases can be accommodated by the developed system. Comparative testing is carried out, comparing results of the proposed system with each other, with existing system characteristics and with standard values. Investigations of the impact of model and parameter simplifications complete this analysis of the proposed system, but also introduce a further synthesis. In particular, it is shown how simulation models produced by the system can be calibrated automatically, which may lead to new applications.

The main synthesis remains the design of a method for creating simulation models. In fact, the present work has to do with design in more than one way. Firstly, it is concerned with the planning of buildings and HVAC systems. Secondly, it addresses the design of a software system with the aim of supporting decision-making in building and HVAC design. The energy performance of building and HVAC concepts ought to be considered in the design process, and the corresponding performance analysis process ought to be made efficient. This concern about how systems "ought to be" is characteristic of engineering and design, which are driven by the goals to be achieved as much as by the physical laws involved [37, p.5]. The methodology reflects these different domains of engineering, in terms of building systems and in terms of software.

The software system implementing the proposed method plays a central role in this work and, to a large extent, the methodology follows a typical software development process. This starts from the identification of a need, which is formalized by writing use cases, based on which functional and non-functional requirements are specified. Following this, algorithms are developed, a software design is proposed, and an implementation thereof is made, which is then tested. Several reasons lead to iterations in this process. Testing reveals the need of changes in design, which in turn lead to implementation changes and renewed testing. What is more, increments in analysis breadth (considered building and HVAC configurations) and depth (level of simulation detail) potentially have repercussions on the whole process.

Still, software development is not the only engineering field that determines the methodology. In particular, the methodology reflects the contexts of building and HVAC design and of building performance simulation. In the first part of the work, the relevance of the problem is ascertained by a literature review, and with the definition of use cases based on which the system requirements are defined. It is attempted to develop a method allowing integrated building and HVAC simulation to support these use cases.

A major assumption here is that, after input parameters are set, simulation inputs should be created without requiring any human intervention. A possible alternative would have been to develop more flexible workflows with only partial automation, which would have posed the difficult question of user interfaces. Also, total automation seems particularly valuable for the defined use cases. Indeed, these have in common the comparison of several alternatives, for each of which a model should be created and used in simulation. This makes the reduction of effort and the consistency offered by total automation all the more desirable.

The use of component-based HVAC modeling also defines the method. This modeling level is assumed to be the most appropriate. Compared to conceptual and system-based modeling, it makes it possible to create more realistic and accurate models. Still, these models remain coarser than those which can be obtained with equation-based modeling.

Key decisions are the decision to use existing simulation engines and the choice of these engines. The extent of development and validation efforts to develop existing tools motivates the first decision. The choice of EnergyPlus and TRNSYS as simulation engines can be related to the choice of component-based HVAC modeling, and is partly justified by their dominant position in research and practice. These tools represent determining factors for the present research. Their data requirements and the concepts underlying them are reflected in the proposed system.

Turning back to the modeled systems, the methodology is also characterized by the focus on hydronic heating systems. As the whole variety of HVAC technology could not be embraced in this work, it was decided to focus on the systems most widely used in Europe. The applicability of the method to other types of systems was envisaged, but validation attempts concentrated on hydronic heating.

Even within this limited scope, validating the proposed software system represents a significant challenge, for which inspiration could be drawn both from software testing and from BPS tool validation. The proposed system could potentially be applied to infinitely many configurations of buildings and HVAC systems. Ground truth for validation would correspond to well-planned, correctly installed and operated HVAC systems, for which adequate documentation and measurements would be available. Such complete instances of ground truth were not available for the present work. Still, validation was attempted through comparisons of: (i) characteristics of generated HVAC models with the characteristics of real systems; (ii) characteristics of generated HVAC models with standard values; (iii) simulation results obtained with different simulation options; and (iv) simulation results with measurement data. This use of several complementary techniques for validation can be compared to approaches used for the validation of building simulation tools.

Comparing simulation results with measurement data leads to the problem of calibration. As calibrating simulation models manually is considered to be a time-consuming process, it had to be determined if automated procedures could also be applied to calibration with the proposed system. Accordingly, a method based on the mathematical minimization of the discrepancy between simulation results and measured data is proposed.

The computational cost of the many simulation runs required by calibration, but also the fact that created models can be large and complex, and the general drive to make simulation more manageable, all contribute to making the question of model simplifications a relevant one for this thesis. This is addressed with the development of systematic model simplification procedures which can be embedded in the proposed system and investigated in studies on several buildings and/or parameters. Finally, the high number of input parameters also calls for parameter simplifications. The application of parameter screening to the proposed system is demonstrated, and it is argued that the sensitivity analysis technique used for parameter screening can also contribute to system testing.

1.5 Thesis overview

Following the present introduction chapter, a literature review presents the state of the art in user interfaces and automated approaches for BPS, as well as the integration of HVAC systems in simulation. Use cases and requirements for the proposed software system are presented in Chapter 3. A method to determine and size HVAC system models is described in Chapter 4. Chapter 5 describes the design of the proposed software system, showing how the previous models can be transformed and used for simulation. Chapter 6 illustrates how the proposed system can be used to support planning. Chapter 7 presents some testing of the proposed system by comparing results obtained with various parameters with each other, with the characteristics of real HVAC systems and with standard values. Chapter 8 explores the impact of different model and parameter simplifications. Finally, Chapter 9 describes how the proposed system can be used for calibration with monitoring data.

An overview of the thesis structure is presented in Figure 1.5, where some significant links between non-consecutive chapters are also illustrated: the software system design introduced in Chapter 5 follows the requirements determined in Chapter 3, and the use cases preceding the requirements in Chapter 3 are demonstrated in Chapter 6. Model simplification procedures introduced in Chapter 4 are investigated in Chapter 8. The comparison of results with measured values, presented in Chapter 9, continues the validation effort introduced in Chapter 7.

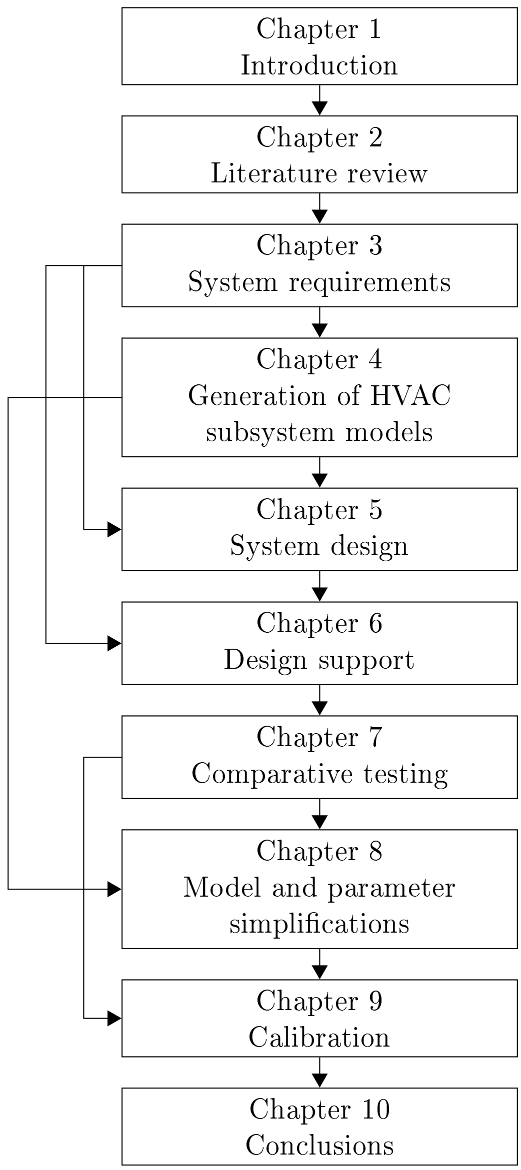


Figure 1.5: Thesis structure with respect to the developed software system.

Chapter 2

Literature review

This chapter describes existing work related to the present research. The first section maps out briefly the use of building performance simulation in practice and describes what interfaces current users have at their disposal. The second section focuses on possibilities of automated data translation for simulation. How to complete missing data (which cannot be translated) is the subject of the third section. The last section elaborates on resulting gaps in the state of the art, with a focus on HVAC models.

2.1 State of the art in building performance simulation

This section deals with the current state of the art in building performance simulation, focusing on the way it is used in practice and on the interfaces available for users.

2.1.1 Use of BPS in practice

Information on the actual use of BPS in practice is rather scarce. Individual surveys only give samples of the situation in given countries at a point in time, while tools and their use in practice evolve.

Interviews of architects and consultants in the Netherlands [38] revealed that computational tools were generally used at a later stage than the one at which design decisions with an impact on energy-efficiency were taken. A survey [39] confirmed that the selection of energy-saving components mostly took place without support from computational tools, which tended to be used for parameter optimization and verification of already taken decisions. Also in 2000, a survey in Singapore [40] found 46% of engineering firms to use computational tools, but mostly in the form of tools provided by HVAC manufacturers for sizing and selection, rather than generic performance simulation tools. Energy simulation was practically not used by architects. In 2003, less than 20% of the participants in a survey on the use of BPS tools by architects in Austria were found to use these tools [41].

According to a recent report of institutions involved in their development, the last versions of EnergyPlus and OpenStudio were downloaded more than 35,000 times [42].

The American Institute of Architects (AIA) provides yearly reports which document the use of energy models in projects involved in its 2030 Commitment initiative [43]. The fact that a majority of the reported projects (59% of around 6,000 projects in 2015) made use of energy modeling cannot, however, be extrapolated to general practice.

Despite the variability of situations, the previous surveys seem to agree on a low level of BPS use in practice, and on some of the obstacles explaining it. Major barriers to the use of BPS in practice were found to be lack of interest, perceived need or requirement from clients, time and cost pressure, difficulty in using tools and lack of trained staff [40, 41].

This also leads to the question of who carries out simulation. According to data reported to the AIA summarized in Figure 2.1, architecture teams are only responsible for energy simulation in a minority of cases. In a majority of projects, they would leave this concern to design engineers, that is to engineers who also carry out design activities, such as HVAC planning. For about 30% of projects, consultants specialized in modeling and simulation would be in charge of it.

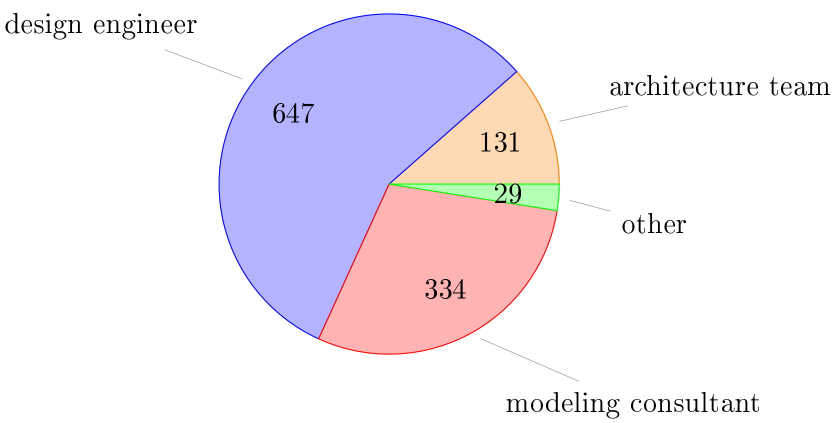


Figure 2.1: Responsible parties for energy modeling by number of projects, data from AIA 2030 Commitment 2015 progress report [43, p.12].

Some of the highlighted barriers to simulation use are embedded in the building planning and construction processes. Others have to do with available tools, their ease of use and interoperation capabilities.

2.1.2 User interfaces for BPS

Data requirements for building performance simulation, introduced in Section 1.1.3 and exemplified later in Section 3.3 for the chosen simulation tools, represent a challenge for users. In many cases, the complexity of input and output data make an interface between simulation engine and potential users necessary. This section presents a selection of BPS tools, focusing on front end software.

A general overview of building energy simulation programs [44] presents a choice among twenty such major tools. At the time of writing, the web directory of building energy software tools managed by IBPSA-USA [45] lists 165 programs, among which 60 for whole-building energy simulation, of which EnergyPlus and a dozen other tools making use of the EnergyPlus engine. The present section focuses on some of the latter, which represent a mere fraction of all available BPS tools. Other popular BPS tools would include open-source software, such as ESP-r [4], and commercial software, such as IDA Indoor Climate and Energy (IDA ICE) [46], TRNSYS [47], Carrier's Hourly Analysis Program (HAP)[1], IES Virtual Environment (IESVE)[2] and EDSL Tas[3].

EnergyPlus is a state-of-the-art building performance simulation engine widely used both in research and engineering practice. In its strategy for building energy modeling, the U.S. Department of Energy focuses on the development of EnergyPlus (and OpenStudio) as a general platform, with numerous use-case specific applications [42]. This role of EnergyPlus as an open-source simulation engine based on which a variety of third-party tools can be developed, and its leading position in BPS research, as illustrated in Section 3.3.1, motivate our restriction of the following discussion to software leveraging this particular simulation engine.

The text-based IDF Editor, which is the default tool for the creation and modification of EnergyPlus input files, allows one to browse through the different elements making up such a file, and to identify and modify these elements. However, the use of EnergyPlus calls for the use of more appropriate user interfaces. A number of them have indeed been developed, with different levels of complexity. Figure 2.2 locates some of these interfaces in terms of the geometrical complexity they accommodate.

Simple interfaces. Some interfaces deliberately limit the scope and complexity of the model. This simplifies data input, and thus makes the model creation faster or more accessible for novice users.

The *EnergyPlus Example File Generator* [48] is a free service developed by the American National Renewable Energy Laboratory (NREL) and Department of Energy (DOE). It generates input files for EnergyPlus, thus making an application of the program to simple and easy cases possible.
Model information can be entered either in simple or in detailed form. Even in the latter case, the building geometry is defined by simple configurations (such as rectangle or L-Shape) with geometric parameters. For the zone layout, the user can choose between two options, either partitioning the floor geometry in a small

[1] www.carrier.com/commercial/en/us/software/hvac-system-design/hourly-analysis-program/

[2] www.iesve.com

[3] www.edsl.net

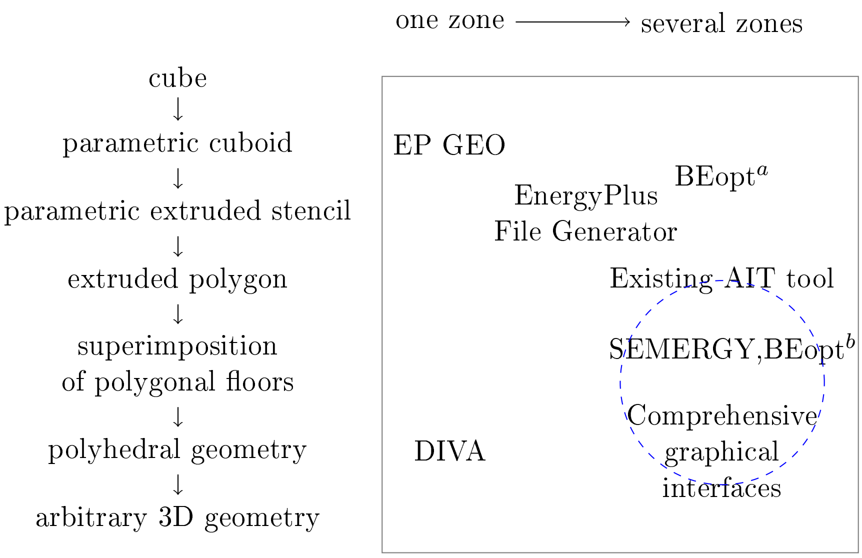


Figure 2.2: Levels of building geometry complexity for various simulation tools and interfaces. The circle represents the positioning of the current research effort. Some tools, like BEopt, offer the possibility of dealing with geometry at several levels of complexity.

number of rectangles or differentiating core and perimeter zones.
The choice of a targeted ASHRAE standard and that of a building type determine many of the parameters of the simulation model. Some of these parameters can either be specified by the user or given a default value. HVAC systems can be selected based on standard types defined in ASHRAE 90.1-2004 (Appendix G) [49].

EP GEO[4] is a simple spreadsheet-based interface for the creation of input data files. Rectangular zone geometry is defined with height, width and length. Window geometry, constructions, internal gains and other parameters can also be entered in the spreadsheet, and converted to the IDF format.

Comprehensive graphical interfaces. Several programs, commercial or not, provide graphical interfaces allowing different types of users to access a majority of the capabilities offered by the EnergyPlus engine. More than interfaces, these programs can be seen as analysis tools of their own, which leverage simulation capabilities of EnergyPlus.

DesignBuilder is a modular software application using EnergyPlus as its simulation engine [50]. Considered to be a state-of-the-art interface [51], it is available in different packages, aimed at energy assessors, architects and engineers. Its 3D Building Modeller module represents an advanced user interface, where three-dimensional building models can be drawn by means of *block* elements, with the

[4]www.natural-works.com/energyplus/interface.php

possibility of using two dimensional plans displayed as background layers for support. The import of BIM models in the form of gbXML files is also possible.

OpenStudio is an "open source analysis platform and toolkit" [52]. It started by offering the possibility of defining geometry and other required data for EnergyPlus in a SketchUp plugin. The data was then stored in the OpenStudio data format (.osm), with translation possibilities to and from IDF. The OpenStudio platform now includes several applications in which simulation models can be prepared and used. OpenStudio provides a software development kit (SDK) allowing different audience-specific applications to be rapidly developed, including the simple web-based "OpenStudio Live" [53]. OpenStudio *measures* give users the possibility of running scripts on OpenStudio models.

Sefaira is a software product "for building designers" using both the EnergyPlus engine and its own energy analysis engine [54]. Geometry is imported from Sketchup or Revit. HVAC systems can be "quickly" defined and sized, thanks to built-in templates.

Simergy is the result of a development effort involving several partners, including the U.S. Department of Energy (DOE), Lawrence Berkeley National Laboratory, Trane and Digital Alchemy. Major assets of this front-end are the flexible HVAC diagramming possibilities and the numerous validation rules for geometry as well as HVAC.

DIVA is a plugin for the Rhinoceros 3D Non-Uniform Rational B-Spline (NURBS) modeling program. It integrates thermal simulations using EnergyPlus and daylight simulations with DAYSIM [55]. These daylight simulations, which are more accurate than those possible in EnergyPlus, are carried on the architectural model, with the potentially complex geometry allowed by the NURBS modeling program. Still, for thermal analysis, the user has to redraw a simple perimeter one-zone volume.

Ladybug and Honeybee are plugins for Grasshopper3D, itself a parametric design plugin for Rhinoceros. Ladybug allows the user to visualize weather data and, through its extension Honeybee, to access the simulation capabilities of EnergyPlus, RADIANCE and DAYSIM [56].

Summary. A wide range of interfaces are available, only a small selection of which are presented in this section. Interfaces differ in terms of targeted users, targeted design phases, complexity, ease of use and level of automation. These are not independent dimensions. Rather, there seems to be a trade-off between them. The more comprehensive an interface is, the less accessible it is for most users, and the longer model creation tends to be.

2.2 Data translation for BPS

Building energy performance simulation as outlined in the previous section is only possible because it relies on computers rather than humans for calculations. This means it is, from the start, "automated" to some extent. However, in the following, automation refers more specifically to the use of procedures reducing the amount of human intervention for the creation of simulation models. Table 2.1 illustrates the level of automation of different tools. Ahn et al. [57] contrast "full automated building energy simulation", in which a shared building model is converted into a simulation file "based on the use of pre-defined defaults without requiring human intervention" and "semi-automated" simulation, requiring "human data entry for uncertain simulation inputs". This implies the availability of a building model representing a starting point from which a simulation model can be created. Automated building performance simulation will depend on the information contained in this model, and how it is structured, for the creation of a building energy model (BEM).

Table 2.1: Levels of automation in different tools and frameworks. Black circles: model creation steps to be carried out manually, size correlating with the estimated expense. White circles: automated model creation step. Grey cell: creation step does not apply to the framework.

Tool	determine thermal zoning	draw surfaces	write coordinates	match surfaces	import geometry	check geometry	assign constructions	assign loads to zones	chose simulation options	document model
EnergyPlus IDF Editor	•	⬤	⬤	⬤			●	●	•	•
OpenStudio (drawing)	•	⬤	○	•		•	•	•	•	•
OpenStudio (from gbXML)	•	○	○	•	•	•	•	•	•	•
IFC to IDF ([58])		○	○	○	•	•				

Even in the most favorable case, where data required for thermal simulation is already available, the problem of multiple views [59] makes some data transformation necessary. Each of the multiple disciplines involved in architecture, engineering and construction (AEC) is concerned with specific functions of given objects, and accordingly takes a specific view shaped by specific concepts. A simulation model reflecting thermal properties and used for certain types of heat balance calculations will differ from an available model, typically based on an architectural view of buildings, for which for instance spatial organization and aesthetics are more relevant.

2.2.1 Building information modeling

A building information model (BIM) is a "shared digital representation of physical and functional characteristics of any built object" [60]. The use of such models is seen as a key to data interoperability in the architecture, engineering and construction industry.

Ideally, this common model can allow building information to be shared, enriched and re-used during the entire building life cycle. By avoiding the recreation of data, this leads to time gains while achieving better consistency. The industry foundation classes (IFC) [61, 62] and the green building XML schema (gbXML)[63] are two of the most frequently used data formats for BIM. BIM as a data source for thermal simulation can make data input more efficient [64].

In the following, we assume some kind of BIM data is available for translation. Should this not be the case, the additional difficulty of transforming less structured data (from traditional computer-aided design (CAD) or even paper plans) into more structured BIM data should be considered. For instance, CAD drawings without semantic information require additional steps for the identification and matching of spaces and surfaces [65].

2.2.2 Translation of geometry data

Building performance simulation uses 3D models of buildings. However, these 3D models are generally not equivalent to the ones used in BIM.

BIM standards like IFC use flexible geometry models with various representations. For instance, the same solid could be represented with the help of boundary surfaces (B-rep, e.g. *IfcFacetedBrep*), of a swept area (extrusion or revolution, e.g. *SweptSolid*) or of boolean operations on other solids and half spaces (e.g. *IfcCsgSolid*).

Such flexible geometry modeling is not to be found in BPS tools. Rather, the geometry of BPS models is much more narrowly defined, as it corresponds to a specific view of buildings, which is related to computation methods. Characteristic for this view is the division of buildings into zones, separated from one another by space boundaries. Typical geometry elements are illustrated in Figure 2.3.

Space boundaries. The definition of different "levels" of space boundaries represented a first step in dealing with building geometry translation for BPS [66]. Five levels of space boundaries were defined, which are illustrated in Figure 2.4:

1. First level space boundaries model surfaces in their "full length per instance", possibly separating different pairs of zones, without consideration of the flow through the surface. Architectural drawings usually make use of such first level space boundaries models.

2. Second level space boundaries are defined under the condition of a "unique and consistent rate of transmission or flow" through their surfaces. When located between two zones, they come in pairs of parallel congruent surfaces.

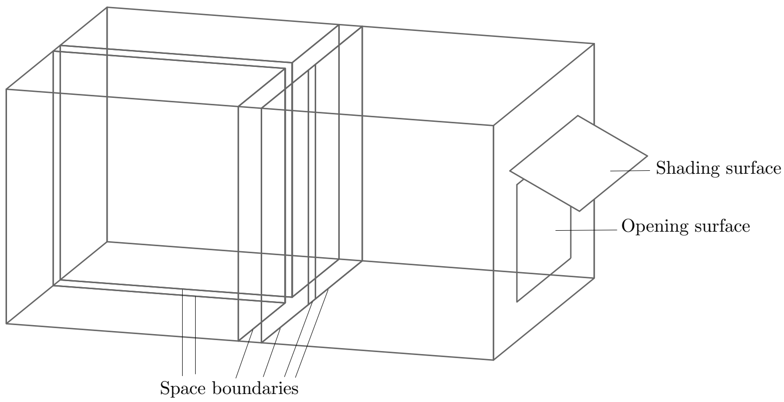


Figure 2.3: Geometry elements for a simple three-zone building model: space boundaries (3 pairs between zones, 7 adjacent to exterior, 1 of level 2b), shading surface, opening surface.

3. When the extremity of a building component touches a perpendicular building component, the surface segment of the latter component opposite to the extremity of the first component corresponds to a third level space boundary.

4. In the case of three building components, each being perpendicular to each other, a surface segment opposite to the intersection of the other two components corresponds to a fourth level space boundary.

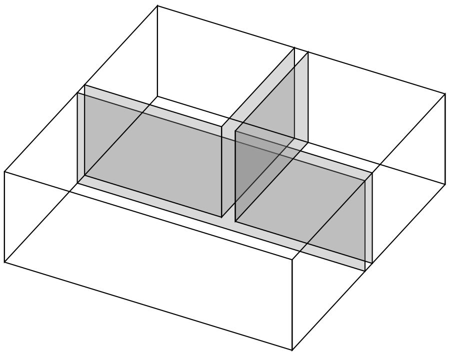
5. Fifth level space boundaries correspond to the surfaces that remains unaccounted for when building components intersect at an angle different from 90 degrees.

Third, fourth and fifth level space boundaries all model surface segments through which transmission or flow does not occur because there is no space perpendicular to them. They are however necessary to ensure that spaces are fully enclosed.

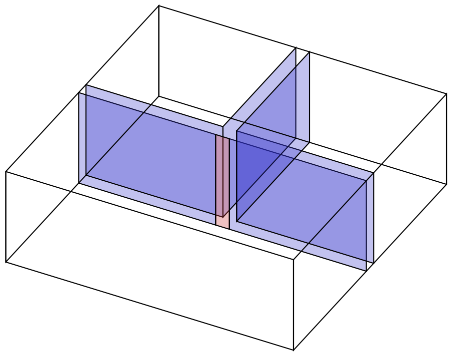
The IFC data model makes use of a similar classification, whereby second level space boundaries are classified as 2a, while space boundaries of third, fourth and fifth level, which have the same behavior, are grouped as 2b.

Based on this breakdown into different levels of space boundaries, a "Space Boundary generation Tool" and a "Geometry Simplification Tool" have been developed, the successive application of which allows geometry to be converted from IFC to IDF format. The "Geometry Simplification Tool" is based on data transformation rules [58], such as "skipping of internal wall objects when walls are entirely contained within the same thermal zone", "redefinition of embedded columns as separate wall objects", or "recognition of exterior building shade types".

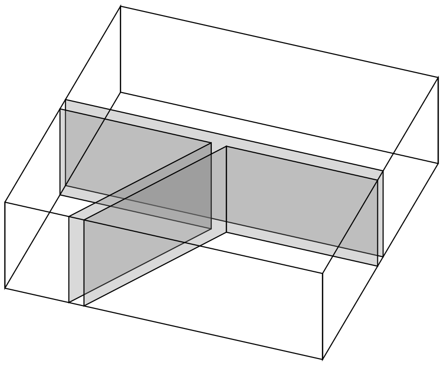
Limitations of geometry translation. The acquisition of geometry from BIM remains challenging, especially for larger buildings. A comparison [67] was made



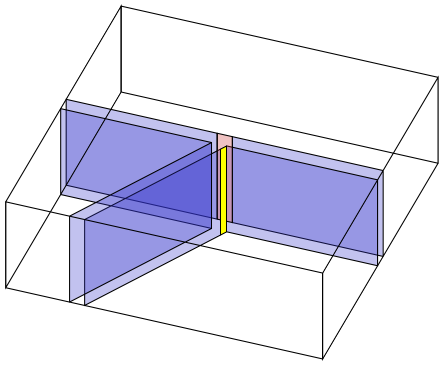
(a) Space boundaries of level one



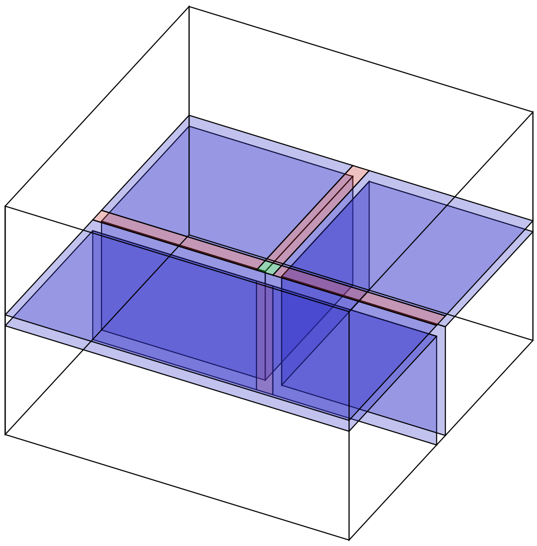
(b) Space boundaries of level two (2a) and three (2b)



(c) Space boundaries of level one



(d) Space boundaries of level two (2a) and five (2b)



(e) Space boundaries of level two (2a), three (2b) and four (2b)

Figure 2.4: Space boundaries of different levels according to detailed differentiation [66] and IFC (in parentheses). Level one in gray, level two in blue, level three in red, level four in green, level five in yellow.

between semi-automated building energy simulation processes using gbXML and IFC files generated from two major commercial BIM authoring tools for a range of simple building models. It demonstrated a number of failures, including subsurfaces and inclined roof slabs not recognized as space bounding elements, inability to deal with colums or virtual boundaries, and volume miscalculations. These failures varied with the authoring tool and the file format used, and were often linked to elusive differences between models generated with the two authoring tools. In practice, greater building complexity and various inaccuracies in the original models add to these challenges.

Model checking can be carried out with tools such as Solibri Model Checker. It includes the use of visual checks and lists of space boundary numbers differentiated according to space boundary levels [66]. Based on several case studies, Maile et al. [32] suggest that duplicate objects at the same location are "possibly the most common problem in IFC geometry files". Other typical errors mentioned by the cited guidelines include incorrect space volumes, incorrect normal vector directions and inconsistencies between the geometry of spaces and that of building elements. Bazjanac et al. [68] acknowledge the general imperfection of submitted building models and the resulting need for "variable tolerances" in model checking.

2.2.3 Material and construction data

Heat transfer elements and heat storage elements are characterized not only by their geometry, but also by thermal and physical properties required for energy performance simulation. Various properties of space boundaries can be derived from an IFC model [69, p.79]. The boundary type (internal, external, ground) is indicated by the *InternalOrExternalBoundary* attribute of an *IfcRelSpaceBoundary*. However, information about the thermal properties of construction materials, which could be referred to through the *RelatedBuildingElement* attribute, are not exported by current IFC export tools [69, p.83]. BIM authoring tools feature materials that can be retrieved from databases and assigned to building elements [70, p.1542]. Yet presently they are mainly used to define the appearance of constructions rather than physical or thermal properties. Databases such as the "Building Component Library" [71] may allow material and construction data to be exchanged.

Modeling of air-tightness presents additional difficulties. Infiltration rates required for simulation differ from potentially available infiltration rates, which are only measured or defined for a given pressure. Thus, direct translation from building data is implausible. Still, a methodology proposed for the modeling of infiltration [72], which implies the calculation and integration of wind-driven pressures on exterior surfaces for the determination of a wind-dependent infiltration coefficient, could potentially be automated.

2.2.4 Time series

In addition to static data, building performance simulation inputs also include time-dependent values for occupancy, air change rates, or internal gains due to persons, lights and other appliances. These may be defined at different time resolutions, ranging from constant values to high-frequency values for the whole simulation period, quite frequently as hourly schedules defined for a few day types. In most cases, these values are not directly available, and one may have to resort to default values, as for construction properties. However, several cases may be evoked where time series are available for translation.

In the case of prescriptive simulation, standard values are to be used for some variables. For instance, the European standard EN 13790 for calculation of space heating and cooling energy use states that "hourly and weekly schedules of heat flow rate for metabolic heat from occupants and dissipated heat from appliances shall be determined on national basis, as a function of building use, (optionally) occupancy class and purpose of the calculation" [73, p.45]. For this kind of application, the issue is to determine a building's use together with the occupancy classes of spaces defined by the architect in order to retrieve associated schedules. Attention should be paid to the reference quantities used, e.g. net or gross floor areas, which may vary and require conversion.

In existing buildings, real measured values may be used as inputs. A co-simulation methodology was proposed for the use of dynamic data in BPS [69], allowing automatically generated thermal models to be used for model-based control. Since some quantities (e.g. occupant heat output) cannot be directly measured, correlations between sensed quantities and simulation inputs may be required. For instance, building occupancy may be derived from passive infrared motion detectors, carbon dioxide sensors [74], doorway counting sensors, or even classroom scheduling data [75]. Occupant heat output would then be obtained by multiplying the estimated number of occupants by an assumed metabolic rate.

Regarding their inclusion in BIM, *IfcTimeSeries* can be used for all kinds of time series, regular as well as irregular.

2.2.5 HVAC data

Data on existing or planned HVAC systems serving a building may be available and translated for use in energy performance simulation. While all previously considered data may be be obtained from the architect, HVAC data would typically stem from a different source. Thus, automated generation of models for integrated building and HVAC energy performance simulation would require multiple exchanges. Several views are also to be distinguished here:

- HVAC system engineers tend to base system design on static calculations, mostly for the full load case [76]. Moreover, pressure distribution plays an important role in their view of HVAC systems.

- For energy performance simulation, the dynamic behavior of systems, and thus part load conditions, are of primary importance. On the other hand, some processes are assumed to be perfect. For instance, the adjustment of pressure resistances to achieve the flow rates required for energy transfer is mostly not explicitly considered [76].

- Architects and other disciplines are more concerned with the spatial aspects of HVAC systems, including openings and collision avoidance. The corresponding constraints on dimensions and changes in direction influence resistances in distribution systems and noise effects.

Similar to building data, a common format should be able to support these different views. For energy simulation, the modeling of HVAC systems requires diverse data, including construction properties (e.g. of pipe elements) and time series (e.g. set points and operation schedules). The complexity and diversity of HVAC systems and components contribute to making the integration of information relative to HVAC in BIM a challenging issue.

Despite successive extensions of the “HVAC part” of the IFC data model [77, 78], IFC data do not yet satisfy the requirements for building energy performance simulation [79, 80]. Liu et al. [81] identified information requirements for HVAC performance analysis, mapped them to IFC, gbXML and EnergyPlus formats, and showed that, while IFC had the highest coverage, none of these formats could cover all requirements. Some sort of extension is thus necessary if HVAC simulation models are to be derived from BIM. Several approaches to extend BIM for energy simulation can be distinguished [82]: (i) extending the BIM schema itself, which requires a wide consensus; (ii) extending BIM data using existing interfaces and proxy objects, or (iii) using a domain-specific link model. As of now, this last possibility seems to be the most promising. With the development of the SimModel data model [79], for instance, more data relevant for BPS can be stored than using current versions of IFC. Wimmer et al. [80] resorted to the SimModel data model [79] in order to support BIM-based HVAC definitions in Modelica.

2.2.6 Co-simulation

Co-simulation represents another way of sharing model data without actually translating it.

In case HVAC designer and building performance simulation user are different persons, they will probably use different tools. It has been argued [83] that the connection of different simulation programs with data exchange at run-time makes it possible to use the best suited tool for each particular aspect. It may also allow each domain expert to use their favorite tool. In the more restricted meaning which we will use in the following, co-simulation refers to this interaction of two executable simulators. In a broader sense, co-simulation corresponds to simulation scenarios where two or more solvers interact [84]. Co-simulation implementations can differ in many respects, including interfaces, data transfer mechanisms and the roles of the different simulators. Time synchronization is an important issue in co-simulation [84, 85]. One ought to distinguish between physical time in the modeled system, the simulator’s representation of time, and “wallclock time” [85]. One usually distinguishes between several coupling strategies [84], also illustrated in Figure 2.5:

- In *strong coupling*, also refered to as “fully-dynamic coupling” or “onion coupling” [86], the two simulators iterate within one time step until the satisfaction of a convergence criterion.

- In *loose coupling*, also refered to as or "quasi-dynamic coupling" or "ping-pong coupling" [86], coupling data is predicted based on data from previous steps.

Loose coupling can follow a sequential or a parallel execution. In the first case, input data to one of the simulators is predicted based on the data in the previous time steps, on the basis of which updated data is calculated and subsequently used by the other simulator. In the second case, both simulators are executed in parallel and use predicted data based on previous time steps.

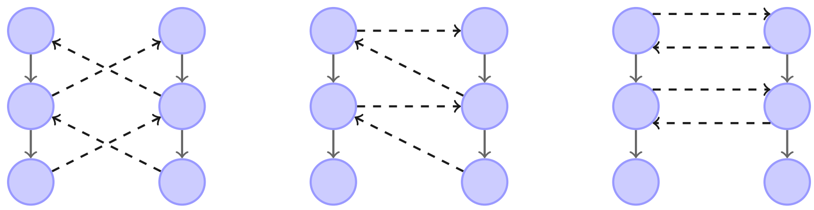


Figure 2.5: Coupling data exchanges time-step schemes (adapted from Trčka [84]). The dashed arrows indicate which coupling data (time-step wise) are available to each subsystem before the time step calculation is performed. Left: strong coupling. Middle: sequential loose coupling. Right: parallel loose coupling.

Generally, strong coupling allows the same accuracy to be obtained with longer time steps. However, this does not necessarily translate into simulation time gains, because of iterations within one time step. What is more, these iterations may represent important implementation difficulties with traditional simulation tools.

Co-simulation implementations for building performance simulation have been proposed with the coupling of heat and air flow calculations [86] or with the coupling of energy and lighting simulation [87]. Coupling of building energy performance simulation with simulation of mechanical systems has also been implemented in different settings. Beausoleil-Morrison [83] described the design of a co-simulator with strong coupling between ESP-r, treating the building domain, and TRNSYS, treating part or all of the energy systems. The approach of a co-simulation involving EnergyPlus and TRNSYS in the context of innovative integrated HVAC systems in buildings has already been justified and validated [88].

The variables to be exchanged between the two simulators are an important characteristic of the co-simulation setup. It is of benefit to use physical variables. In a co-simulation scenario typical for the present work, the heat delivery components present in each zone (e.g. radiators) represent the link between *building simulator* and *HVAC simulator* :

- Zone temperatures (in °C) are outputs of the building simulator and inputs of the HVAC simulator.

- Equipment delivered energy rates (in W) are outputs of the HVAC simulator and inputs of the building simulator.

The Building Controls Virtual Test Bed (BCVTB) [89] is an open-source middleware that has been created for co-simulation involving EnergyPlus and other software such as Modelica and MATLAB, as well as real-time simulation. This middleware represented a new approach to co-simulation, as opposed to the direct coupling with master-slave architecture of most earlier instances [83], where one simulation tool controls data exchange.

The functional mock-up interface (FMI), a standardized interface for the digital assembly (model exchange and co-simulation) of different models [90], going further in the integration of multiple domains and tools, aims at eliminating the need to develop one-to-one coupling interfaces between an increasing number of supported tools. The function required from each tool could be encapsulated in a functional mock-up unit (FMU).

Co-simulation represents an alternative way of using separate models for different domains without having to translate them into a common model. Rather, two models can be evaluated concurrently by two distinct simulators exchanging data at run time. Still, cases remain where data required for BPS is not available at all. Approaches to automatically complete missing data in these cases are presented in the next section.

2.3 Automated completion of missing data

2.3.1 Use of default values

When required data are not available, some assumptions are necessary to complete the building model. Use of default values for unknown variables is common in approaches for automated BPS [57, 91, 92]. For instance, standard constructions may be chosen in function of the building age, and internal loads based on room functions. Default values may be taken from a variety of sources, such as standards, guidelines, or handbooks, with different levels of credibility.

Default values often originate from the aggregation of large amounts of data. In urban building energy modeling, they may be derived from the abstraction of a building stock into a limited number of archetypes [93]. The TABULA project [94] identified building typologies for a dozen of European countries, and established reference values for energy-related features in each building type.

Mandatory upper limits for U-values or infiltration in recent building codes represent a case of relatively trustworthy default values, as they represent legal requirements. Air pressure tests are systematically carried out to evaluate the air-tightness of passive houses.

It has been argued that a template format encapsulating non-geometrical properties of building zones could allow default values to be well documented and correctly exchanged, contributing to a fast and consistent setup of BPS models [95]. The "Building Component Library" follows a similar goal of facilitating the sharing of well-defined pieces of input [71].

Difficulties in the use of default values may arise from variations in the considered references. For instance, the floor area relatively to which internal loads are often specified may be the net floor area (DIN V 18599-10), or a different reference area (ÖNORM B 8110). This calls for a good documentation of these values, including the definition of references, boundary conditions and underlying assumptions.

Because of uncertainties in data, it would be reasonable to consider value intervals. Uncertainty and sensitivity analysis have indeed been used in conjunction with BPS, for instance to predict building performance under future conditions [34]. One study used uncertainty analysis in order to identify the most significant inputs, and determine which inputs require human intervention in the context of semi-automated simulation [57]. However, gathering data on the possible range and distribution of input variables represents a significant effort.

2.3.2 Completion of HVAC system models

State-of-the-art simulation engines make the simultaneous simulation of building structure and HVAC systems possible. However, detailed HVAC simulation requires a high modeling effort. Moreover, its integration in automated procedures for building performance simulation is not well developed, which can be explained by the translation difficulties described in Section 2.2.5. State-of-the-art interfaces such as the Simergy GUI for EnergyPlus [96] or DesignBuilder [50] use automatic data translation from a graphical view familiar to engineers to a simulation model. The HVAC system is manually assembled from different components linked to each other. Pre-defined templates, autosizing features and the possibility to group zones served by the same type of equipment may speed up this process. It is also automatically checked if the restrictions induced by the EnergyPlus simulation engine are respected. For instance, no more than one set of parallel branches should be present on each side of a water loop. A paper [57] distinguishing fully automated and semi-automated building energy simulation highlighted the limits of autosizing and default values for HVAC system variables such as chiller performance coefficients or condenser loop set points.

Limits of autosizing for current simulation tools and interfaces are apparent for the sizing of pump and fan components. Maximum flow rates can indeed by autosized, but not the pressure difference to be overcome (pump head). An appropriate value for pump power, which depends on the product of flow rate and pump head, can therefore not be obtained.

Concerning the completion of missing HVAC-related information in BIM models, one can also mention an approach to identify the functions of HVAC components from topological information embedded in IFC files [97].

2.4 Gaps in approaches to automated BPS

This section discusses gaps in existing approaches to automated BPS, focusing on model completeness, design process integration and model resolution.

2.4.1 Automated generation of a complete model

As already mentioned, many research and development activities tackling the transformation of BIM data into BPS models focused on geometry, often eluding other aspects affecting the thermal and energetic behavior of buildings. Internal loads and HVAC systems represent two essential domains for the creation of complete BPS models as intended.

Occupancy and internal loads. Occupancy, internal loads and the related scheduling are important parameters, for which default values are most of the time assumed without further investigation. However, Rodrigues et al. [98], in the context of an automated approach for optimization-based design generation, did examine the robustness of alternative floor plans with regard to occupancy. The role played by expected occupancy in the ranking of different floor plans was found out to be significant. Also, ROBESim, a "retrofit-oriented building energy simulator" [99] based on EnergyPlus, supports detailed occupant positioning information, and can generate multiple building models for comparison and optimization of retrofit measures, including localized heating and self-programmable thermostats. On the other hand, it supports only limited HVAC templates and fixed geometry with four zones per floor. Grouping all non-geometric data inputs assigned to zones in building energy models under the name of "building properties", Cerezo et al. [95] note that only "limited attention" has been paid to the documentation and exchange of these inputs, and advocate the creation of a template format able to encapsulate them.

HVAC systems. Research addressing the use of BIM data for HVAC simulation is rather recent [80, 100]. The wealth of HVAC system and component types proves challenging for BIM integration. Approaches using an intermediate format to transform HVAC-related BIM data for BPS have been presented in the second section.

Apart from these, two promising approaches are co-simulation, which replaces the translation effort by that of defining an interface between simulators, and generative HVAC design, in which automated procedures could be used to create models of HVAC systems suitable for a given building.

Co-simulation. The co-simulation of building and HVAC performance is a promising approach [84]. No occurrence of it being integrated in an automated procedure for building simulation model generation has been found the literature. Co-simulation could save part of the translation effort by enabling the use of an HVAC simulation model for integrated simulation without needing this HVAC model to be expressed in the same format as the building model. However it does not resolve the problem of translating from an HVAC planning tool to an HVAC simulation tool.

Generative HVAC design. Generative design refers to methods in which the role of computers is extended from that of assisting in design (e.g. with draft-ing) to that of actually generating design ideas and solving challenging problems [101]. It has been suggested that generative design has the potential to transform building services, using automated zoning and space load calculations, HVAC system templating, 3D routing, automated coordination of services and libraries of pre-fabricated components [102].

Generative design could be used to create models of possible HVAC systems and simulate their performance, instead of waiting for HVAC models to become available and translating them. Despite this automation step for early-stage performance feedback, engineering professionals would still be responsible for the detailed planning of HVAC systems.

Until now, generative methods for HVAC systems have been mainly restricted to the optimization of system variables, whereby system structure remained fixed. In particular, genetic algorithms have been used to implement such optimization approaches [103]. A recent paper [104] proposed to extend generative methods to more aspects of HVAC design, including zoning, sizing and location of air delivery components (diffusers and return grilles), primary equipment, intake and exhaust louvers, and duct routing and sizing.

Most similar to the approach followed in this thesis, Brahme et al. presented a solution based on “homology-based mapping” and ”generative design agents” [105] to the problem of analyzing building performance in early stages of design. The main steps included the mapping of a shared building representation into a domain representation, and the automated generation of a detailed model from minimal user inputs, using a “design agent”. This strategy was applied to the HVAC domain. The design agent was used to generate a duct layout using heuristic rules emulating the practice of HVAC designers with air-based systems.

With heuristics based on HVAC design practice, expert systems may also be a candidate for the generation of HVAC systems. Maor and Reddy developed a knowledge-based expert system for conceptual HVAC design [106]. The system worked on two levels, configuring subsystems (primary and secondary) from components, and whole systems from subsystems. After the systematic generation of solutions and the pruning of unfeasible ones, each solution could be evaluated in terms of cost, but also in terms of performance, using simulation.

2.4.2 Integration in design process and building life cycle

Consideration of the design process. Building performance simulation, whatever the degree of automation, should take the process context into consideration, as it is required for efficient data exchange and a better interaction between building design and building performance analysis [107].

Following interviews about the use of BPS tools for conceptual design, Hopfe et al. [108] noticed that the synchronization of design stages was one of the biggest issues. Morbitzer [109] developed a concept for “simulation supported design process”, bringing simulation tools directly in the architectural practice. Three design stages from the RIBA Design Plan of Work were chosen, and for each of these stages parameters were selected for inclusion in a constrained interface using the same simulation program (ESP-r). Recently, an international survey [110] was carried out in order to investigate currently used methods for solar design and identify limitations of existing tools. Some conclusions were the requirements that tools "should be able to adapt to specific design phases" and "support comparisons between competing design alternatives".

A model description of the building process and the corresponding information exchanges may be a key to the interoperability issue [111]. To support a particular business process, the buildingSMART organization recommends the use of an Information Delivery Manual (IDM) defining exchange requirements between participants, and a Model View Definition (MVD) specifying which subset of the IFC schema is needed to satisfy these requirements. In the case of building and HVAC simulation, IDM and MVD are still being developed [112].

Result visualization. For building performance simulation to inform the design process, attention should be paid to the visualization of results [113]. The idea has been expressed that "the simulation bottleneck is no more the computer, but the understanding of the user" [114].

The visualization of large multi-dimensional results potentially arising from automated simulation is a difficult issue, calling for the use of interactive tools [115].

When considering the flow of information, one finds that simulation tools typically translate design and context data into performance attributes. "Bi-directional inference" [116] allowing to derive design attributes from the specification of a given performance level is a challenging task, even to define, but architects would probably welcome the resulting "propositions" [24]. Tools for sensitivity analysis and optimization may be used to this purpose, and "support comparisons".

Life cycle. It is reasonable to assume that simulation models for buildings and HVAC systems should "be continuously available, but in different forms" [114] during the design process and after it. Not only would the successive simulation models be based on an evolving set of data, but they would also serve different purposes.

Retrofit. The potential of building retrofits for energy savings is high, especially in industrialized countries. Apart from ROBESim [99] and SEMERGY [117], most building energy simulators are not oriented towards the retrofitting of building, which compels the user to manually modify models to compare different retrofit options. Existing buildings also come with different situations with regard to data availability and design constraints, with implications on possible automated simulation methods that would remain to investigate.

Calibration. Calibration, the adjustment of input data in order to match measured values, is a way to obtain more reliable thermal simulation models for existing buildings. The development of "smart meters" collecting high resolution data offers new possibilities in this direction. While calibration can be considered as an "art" requiring patience, experience and fine judgement, more or less automated procedures have also been proposed to deal with it [118]. However, there does not seem to be any reference to an application of an automated calibration procedure to automatically generated building models.

2.4.3 Level of detail of simulation models

There are several ways in which BPS models may be considered to be more or less detailed. These include spatial resolution (zoning) and the granularity of HVAC system models, and depend on the simulation engines. While the question of the appropriate level of detail is relevant for all simulation endeavors, it deserves a specific discussion in the context of automated model creation. On the one hand, using default values may imply low accuracy and render certain modeling details pointless. On the other hand, automation may make the creation of more detailed models affordable. A consideration of these questions seems to be rare in the reviewed literature. Beltrami et al. [119] introduce simplification protocols, allowing models to be adapted for design at different spatial scales. The design process and the data accumulation along its different phases also call for different levels of detail [120].

Tools and level of detail. In this context, it can be debated if one single tool should be used all along, or if different tools would not accommodate the different phases better. As argued by Morbitzer [109], the first solution improves communication, makes comparisons easier, and allows shared developments of the simulation engine to benefit all parties. Still, a disconnection can often be found between tools running basic analyses and others for more advanced studies [56]. The use of a monolithic simulation engines like EnergyPlus does leave room for a certain customization of the simulation complexity with the choice of objects and simulation options, but within the bounds of a rigid model structure. The component-based structure of TRNSYS, as illustrated by the previously cited article, means more freedom in the implementation of any level of detail.

Zoning. Although fundamental for building thermal and HVAC simulation, zoning has received relatively little attention. Criteria for the combination of architectural spaces in one thermal zone have been proposed to ensure that the assumption of a uniform air temperature remains reasonable, which means the spaces to simulate should exhibit the same dynamic thermal behavior. In order to be lumped together, different spaces should feature [121, p.27]:

- similar internal loads, among other things in terms of occupancy, activity, light and equipment gains;
- similar solar gains, which means rooms without significant solar gains should be kept distinct from rooms with important solar gains, and that the latter should have similar orientation and glazing ratio to be combined;

- similar HVAC operation, starting with temperature set points. When considering HVAC systems in the simulation, and when their layout is known, only rooms served by the same type of systems should be combined.

- similar construction: parts of a building with very different thermal mass should be separated [122].

Standard ISO 13790 [73] gives some quantitative criteria: maximal set point temperature differences of 4 K are allowed between conditioned spaces for them to be grouped together. A relaxation of the rule is allowed to prevent "small spaces like corridors and storage rooms" from leading to extra zones: it is enough for 80% of a zone to be serviced by one system, in which case the whole zone may be modeled with this main system.

Partitions between spaces combined into one zone should be taken into account as heat storage surfaces in the resulting zone [123, 124].

In some cases, it is recommended to subdivide a single space in different thermal zones separated by a virtual boundary through which energy is allowed to flow [123]:

- If different types of HVAC equipment serve different sections of a space [125, p.148], it makes sense to have a zone for each such section.

- In the case of large open spaces, the temperature distribution might not be uniform enough for the space to be accurately represented by one zone, due to the higher influence of solar gains near glazed areas or to thermal stratification (for instance in atria).

- Ensuring that each zone is convex may also require spaces to be subdivided. This is required by EnergyPlus for detailed radiation calculations.

Still, these criteria are not defined univocally. Zoning strategies for simulation mostly seem to be implicit, depending on the personal judgment of simulation users for the application of the above mentioned criteria. The view that this is "somewhat of an art" [124], as the EnergyPlus basic concepts manual puts it, seems to be widespread. Indeed, few systematic studies on the impact of different zoning strategies are found in the literature. One case study on the application of different zoning strategies to a school building with stone walls in Kenya [126] found out relatively low temperature differences, concluding in favour of simplified zoning. A study in the case of an office building in France [127] investigated the impact of different zoning simplifications on annual energy demand, in relation with the variation of other parameters. For this case, the authors concluded on the acceptability of large simplifications, including the grouping of rooms on different floors. A detailed sensitivity analysis [128] showed the importance of thermal zoning for the design and simulation of "solar houses", and in connection with it the essential role of interzonal airflow.

Automated zoning strategies. An appropriate zoning strategy would depend on simulation goals and available information, and take into account the computational cost of finer zoning. Coarser simulation zoning for increased speed is for instance required in simulation-based control [69, p.100]. The information available on space structure and use can be considered to be the first determining factor for zoning strategies.

For existing or already planned buildings, whose interior structure is known, the definition of thermal zones used for simulation should take into account the criteria evoked in the previous paragraphs. The lack of explicitness in these criteria explains why most presented methods for automated BPS either equate thermal zones to rooms or settle for a mono-zone building model. It has been argued that thermal analysis tools should offer more options for zoning, to avoid mixing up simulation zones and architectural spaces [129].

One strategy for obtaining a suitable zoning may be to run a first simulation with a very fine zoning, analyze its results and aggregate zones based on them. Georgescu et al. [130] used a mathematical analysis technique (Koopman mode analysis) on the results of a building simulation with fine zoning in order to create zoning approximations and evaluate them. Giannakis [69, p.100] used the same approach, and also carried out the analysis with hierarchical clustering.

When the interior spatial structure of a building is unknown, the only applicable criteria is that of similar solar gains. In this case, ASHRAE Standard 90.1 [49, appendix G, p.174] recommends to separate interior spaces, "located greater than 5 m from an exterior wall" and perimeter spaces, which in turn are to be considered separately for each orientation. For a rectangular floor plan, this results in the widely used five-zone model illustrated in Figure 2.6. Similar glazing properties are implicitly assumed for all spaces of each orientation. While an exact definition of orientation is not provided, ASHRAE Standard 90.1 specifies that "orientations that differ by less than 45 degrees may be considered to be the same orientation".

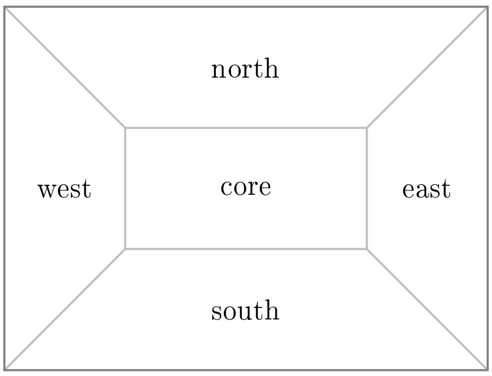


Figure 2.6: Typical five-zone model for a rectangular floor plan (20 by 15 m) according to ASHRAE 90.1 Appendix G [49].

In other sources [125, p.38] [121], a value of 6 m is given for the relevant distance from an exterior wall with glazing. A recently presented algorithm [131] creates a partition of buildings whose interior space definitions are unknown, based solely on the building outline, thus generalizing the five zone model to arbitrary geometries. Core zones are found by offsetting the outline. Perimeter zones with different orientations are derived from the straight skeleton decomposition of the floor-plan polygon [132]. The same authors [133], after a comparison of results obtained with this automated zoning and with real floor plans, revealed large differences.

The two phases - "speculative" and "existing layout" - were considered by de Souza and Alsaadani [134] for an office building. The importance of zoning was established not only for load and temperature distribution, but also for the total heating and cooling loads. De Wilde and Tian, considering zonal resolution in a sensitivity study on the performance of an office under climate change [34], found out that the differences introduced by zoning were small for annual energy consumption and carbon emissions, but much more significant for overheating risk. Thus, the zoning resolution should also be chosen in accordance with the goals of simulation.

Zone data models. Simulation zones also pose the question of their representation in data models. Two types of spatial elements (*IfcSpatialElement*) may come into consideration for the representation of simulation zones in IFC:

- A hierarchical spatial structure element (*IfcSpatialStructureElement*) is used "to define a spatial structure". It is, for instance, a building, a storey or a space. A space (*IfcSpace*) "represents an area or volume bounded actually or theoretically". A space is contained in a building storey (aggregation relation). Elements at a hierarchical level (e.g. spaces) may not overlap.

- A "spatial zone" (*IfcSpatialZone*) is a non-hierarchical element, which offers the possibility of segmenting space according to function. These spatial zones may be used in a variety of domains, including thermal simulation, lighting and construction management. Resulting from the grouping of spaces, these zones do not have an explicit geometry. These zones may overlap, which is not the case of simulation zones (for one simulation).

Level of detail of HVAC systems. The level of detail of HVAC system models can vary along several dimensions. It is primarily defined by the choice of one from the five main approaches presented in the introduction, from conceptual modeling to equation-based modeling. For the more detailed approaches of component-based or equation-based system modeling, the level of detail can be varied in numerous ways.

Individual models for each component may be selected among several possibilities. Component models may be static or dynamic, based on first principles or empirical data. In the latter case, performance curves of various complexities may be considered. Some particular elements may be included in the model, or not. For instance, distribution components such as pipes are often omitted in EnergyPlus models. Actuators and sensors may also be present in the model or not. In general, controls may be modeled more or less explicitly. Finally, there are different degrees to which HVAC simulation can be coupled to the remaining building model.

In addition to eight simplification steps for the building model, including the reduction of constructions to archetypes, zone lumping and the reduction of all floors to a single geometry, Beltrami et al. [119] identified three different simplifications for a heating plant. These included the decoupling of building and system simulation and the use of predefined efficiency values instead of their calculation, as well as simplification and resizing of delivery and distribution subsystems following zone lumping.

Summary

Opening this chapter, an analysis of current interfaces for building performance simulation showed the potential of automation approaches for making simulation more widely practicable. The chapter then presented a literature review of approaches towards automated building performance simulation. The review was organized around the required data, which may be translated from available sources, or completed based on some rules.

The review of user interfaces showed the existence of a trade-off between ease of use, speed of model preparation and comprehensiveness. This certainly corresponds to differences in targeted users and design phases. Still, automation approaches may be instrumental in shifting the lines of this trade-off, allowing more complete and integrated simulation to be prepared and carried out more easily.

Various parts of BPS models can be obtained by automated translation of data from available sources. Such data translation has been explored first and foremost for building geometry. It may also be relevant for material and construction data, time series and HVAC data. Concerning HVAC systems, Section 2.2.5 revealed that current standards - primarily IFC - are not semantically rich enough to contain all the data necessary for the detailed modeling of their performance.

Data not available for translation should be completed in order to obtain a complete model. To that end, approaches for automated BPS often resort to the use of default values. A good documentation of these values is necessary. In the context of HVAC modeling, automated sizing is a frequently used functionality of simulation tools. In combination with templates and zone grouping, autosizing may allow experienced users to create HVAC models rapidly. Still, it is limited to the completion of given property values. In particular, autosizing of pump head is not available in existing tools, as it would imply information about the distribution subsystem which is not there. Producing this information will be part of the present work. The difficulties in creating HVAC models for simulation automatically, as identified in this literature review, lead us to consider the possibility of creating models of possible HVAC systems specifically for performance simulation, which may be realized with generative approaches as presented in Section 2.4.1.

Two other considerations addressed in this work also correspond to identified gaps in approaches presented until now. The reviewed literature provides few answers as to what the appropriate level of detail of simulation should be. By considering different model resolutions and their impact on results, this work may also contribute to answering this question. In fact, the appropriate level of detail depends on the answers expected from simulation. In our case, it can only be defined in the context of the design process. While the importance of the context of use for simulation is generally recognized, approaches to automated model creation often tend to focus on data transformation without clearly defining its context. This work will address this issue with the definition of use cases in the next chapter. These use cases will guide the development of the proposed software system.

Chapter 3

Requirements for automated building and HVAC model creation

This chapter specifies requirements for a method of automatically creating building and HVAC models for performance simulation. These requirements can also be seen as requirements for a software system based on the application of the envisaged method.

To start with, the intended use of the method is presented, and three use cases in building and HVAC design are defined. This is followed by the statement of system requirements accommodating these use cases. Finally, data requirements of two chosen simulation engines are described in more detail, as they play a determining role for the intended system.

3.1 Intended use

This section aims at narrowing down the intended use of the method. We start by describing general conditions of use for the method. Then, we define three main use cases for the method.

3.1.1 Conditions of use

The conditions of use of the method are related to planning processes and the use of simulation. Important aspects are the actors involved and the sequence of events. Conditions of use may be delimited by the following questions, which are developed in the next paragraphs: (i) What is the purpose of simulation? (ii) Who is involved in the simulation endeavor? (iii) When is simulation to be carried out?

Purpose of simulation. As a tool, building performance simulation can be used for various purposes, including decision support for planning, prediction in model-based control, certification, benchmarking and research. This is narrowed down here, as we only consider the objective of providing some indication of the performance of planned systems in order to support decision-making. Thus, we exclude from the present work cases where simulation would be used for certification purposes. The performance aspects considered here are related to energy consumption and thermal comfort.

Actors and roles. Key actors include the entities (persons, teams or institutions) performing simulation, the ones commissioning or calling for simulation, the ones providing data for simulation, and the ones whose decisions may be influenced by simulation. For simulation studies in general, Robinson assumes three roles: the client, the modeller and domain experts [135]. In the context of building design, de Wilde [38] distinguishes three main parties: the principal, the architect and consultants, mentioning consultants for installations (including HVAC) and for renewable energies. These consultants are domain experts. The actual modeller can be represented by such a consultant, or be a consultant specialized in modeling, or coincide with the architect. Focusing on the two roles of "building designer" and "simulationist", de Souza insists on how different their paradigms are [24].

The design processes to be supported by building performance simulation are variable, potentially complex and characterized by multiple interactions between different actors. As already shown in Figure 2.1, the simulationist role may be taken on by architects, design engineers or specialized modeling consultants.

Still, we resort to the simplified workflows of Figures 3.1 and 3.2 in order to exemplify the data flows implied by certain strategies to carry out building performance simulation for design support.

Figure 3.1 illustrates a prototypical workflow for a part of the design process involving three roles. An architect is responsible for designing a building, and a mechanical engineer is responsible for the planning of an HVAC system serving this building. In order for an integrated building and HVAC simulation model to be created, the simulation expert in charge of it needs to obtain data from both planners. The literature review showed that HVAC model translation may represent a bottleneck in this workflow.

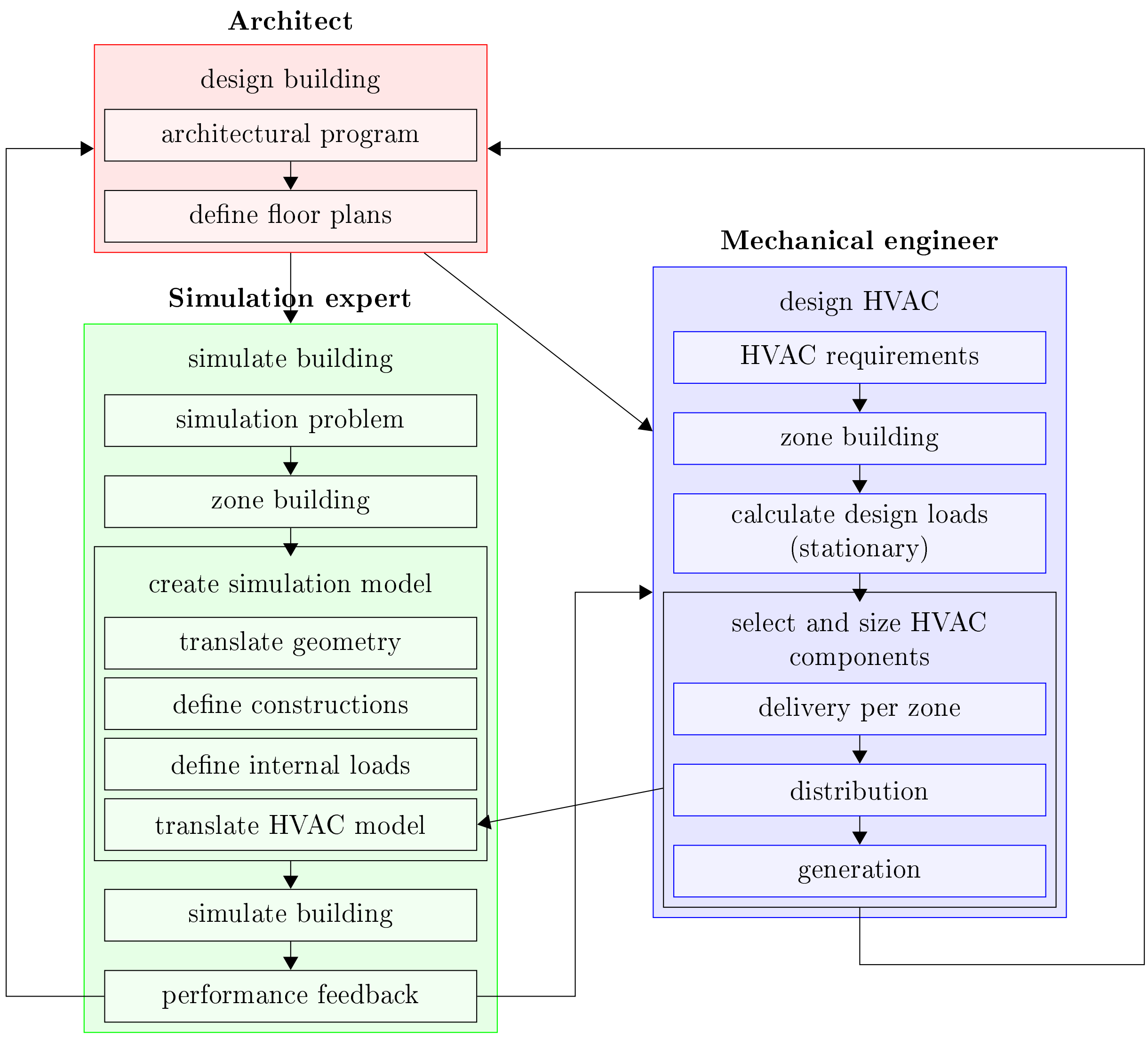


Figure 3.1: Workflow model with three roles: architect (red), mechanical engineer (blue) and simulation expert (green).

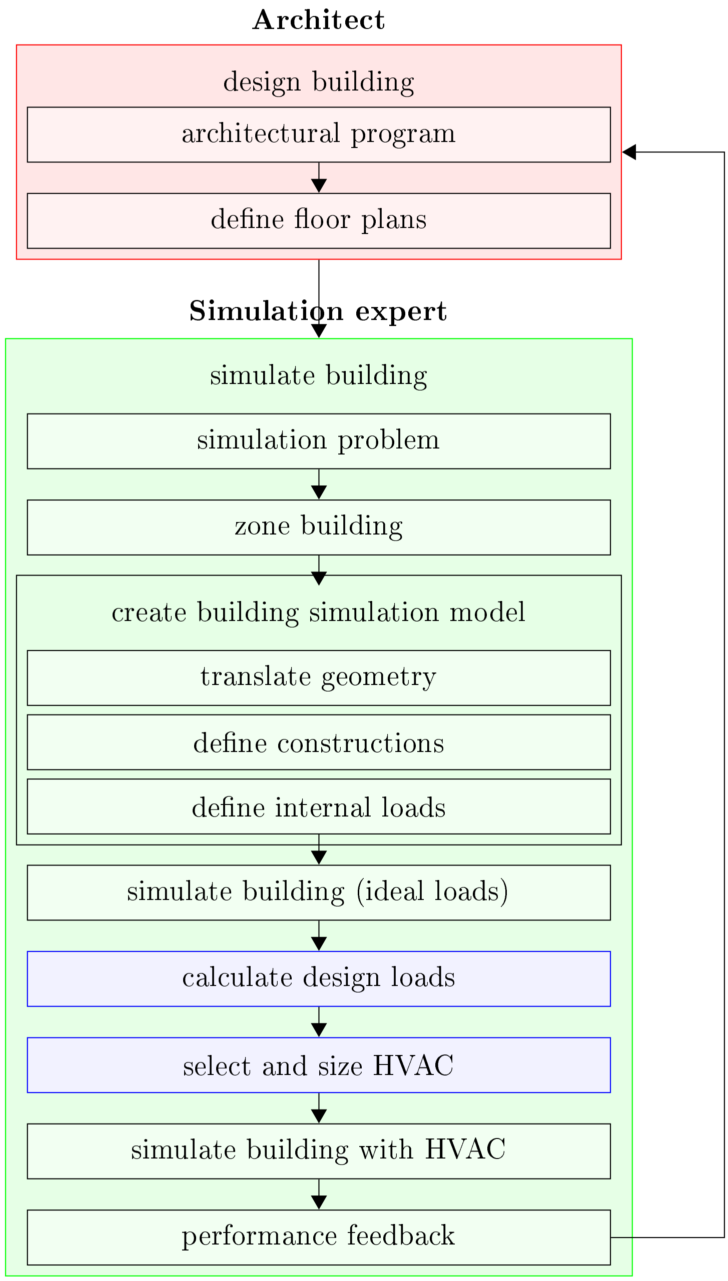


Figure 3.2: Workflow model with two roles: architect (red) and simulation expert (green), with HVAC design emulated by automated procedures (blue).

Figure 3.2 illustrates a two-role workflow where HVAC models are created specifically for simulation by partially emulating HVAC design with automated procedures (in blue), which avoids the HVAC model translation difficulties associated with the three-role workflow. This corresponds to the strategy followed in the present work, starting with the use cases described in the next section. One should note that both workflow models only represent a small part of the design process during conceptual design, in relation with BPS. Other aspects of the mechanical engineer role would remain unaffected. In particular, automated procedures would not apply to the detailed planning of HVAC systems. One should also note that, in both workflows, each role may be played by several actors, or conversely one actor may play several roles.

Concerning the envisaged system, automation cannot spare users some essential tasks: (i) understanding the project in all its energy-relevant aspects, which may be broad; (ii) formulating the simulation problem; (iii) preparing system inputs; (iv) ensuring the system is functioning properly; (v) interpreting simulation results; (vi) communicating results.

As a result, users of the envisaged system should have a knowledge of HVAC systems, building physics, building performance simulation, as well as the communication skills necessary to communicate with planners and decision-makers. Communication is required in both directions, to understand relevant aspects of the project and report on simulation results. This bundle of skills is most likely to be found in HVAC consultants, or maybe even more in multidisciplinary teams.

Situation in planning timeline. The use cases defined below are design use cases, in the sense that their goal is to devise a (building and HVAC) system which does not exist yet. They may take place during the design of a building, before its construction and operation, or before a refurbishment.

There are multiple sequential models dividing the planning and use of buildings in phases or stages separated by more or less clearly defined gate activities [136]. The Royal Institute of British Architects (RIBA) Plan of Work [137] is one such framework, which has been regularly updated since 1963. Figure 3.3 compares the two last versions of the RIBA Plan of Work, as well as another standard timeline [138]. Although displayed linearly in this figure, these stages should be seen as part of a continuous cycle with refurbishment, reuse and recycling, as well as exploitation of feedback from past projects [137, p.4]. Each of the planning stages may correspond to a multitude of design steps and activities, the representation of which would require more detailed models, such as process maps [139].

Dawood et al. [140] have argued that the conceptual design stage (C in RIBA Plan of Work 2007) is the most appropriate for the comparison of various options with regard to energy performance. The RIBA Plan of Work 2013 mentions the importance of a sustainability strategy at the concept design stage (2).

De Wilde showed that, in many cases, computational support is prevented from having an impact on energy efficiency by the mere fact that it is applied (or produces results) after the most relevant choices have been made [141]. These decisions were mostly taken in the conceptual design phase and before (feasibility

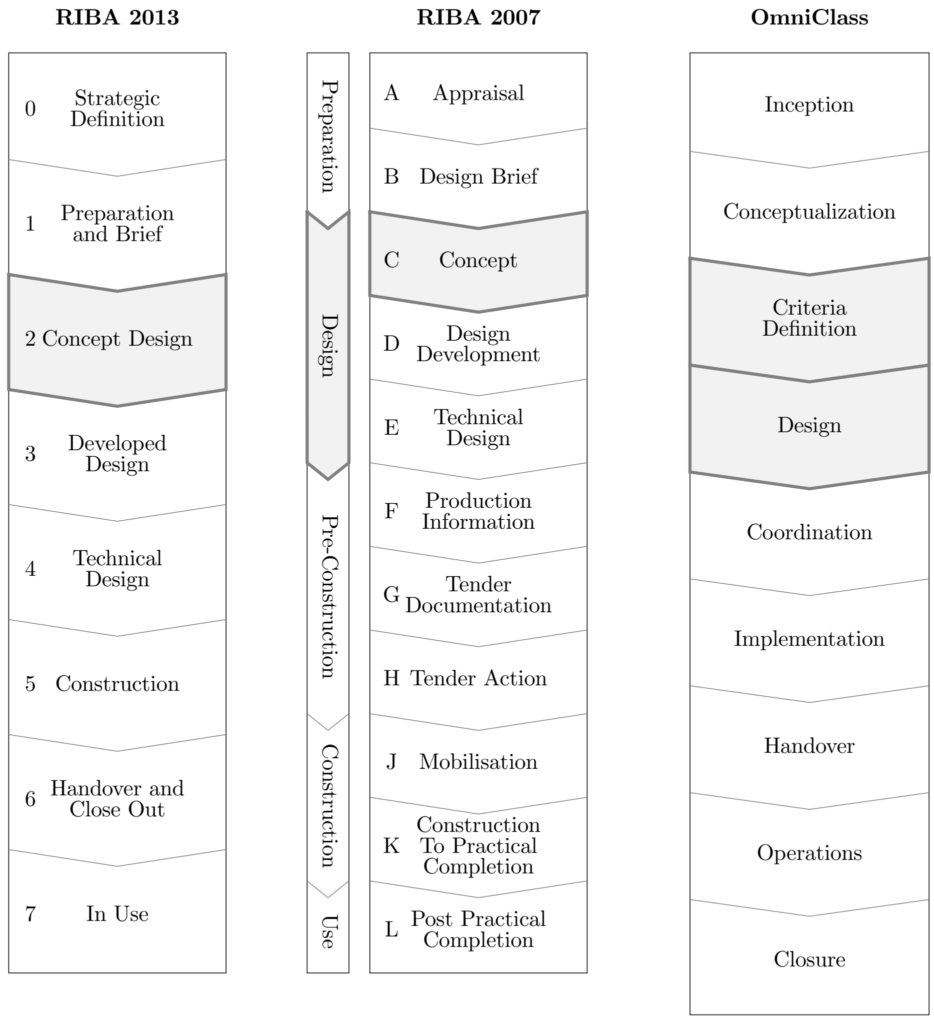


Figure 3.3: Phases and stages in the 2007 and 2013 versions of the RIBA plan of work, and according to the OmniClass definition [138]. The stages relevant for our system are highlighted in grey.

study), whereas computational results were rarely available before the next phases (preliminary and final design). In the same piece of research, it was also found out that architects and consultants often had different recollections of the phase(s) at which design decisions had happened [141, p.56-57].

Process stages may vary for different disciplines. Fee guidelines defined at a national level often play a major role in this regard. The BSRIA Design Framework for Building Services [142] defines design activities in connection with building services for different stages aligned with the RIBA Plan of Work. Activities for the concept design stage include the determination of "mechanical systems philosophy". Deliverables intended for this stage include a building energy model and recommendations for renewables. A more detailed process formalization would be required in order to account for the actual activities and information exchanges taking place during the planning of buildings and HVAC systems. This may be provided by the information delivery manual (IDM) methodology and the use of process maps [143].

3.1.2 Use cases

Use cases are a popular way of describing and investigating business processes and software functional requirements. How formally they should be structured depends on the situation. Whereas formal (fully dressed) use cases reduce ambiguity and enforce homogeneity by following detailed templates, casual use cases are less precisely structured but faster to write [144]. In the present case of gathering requirements for a software system developed by a single person, and given the small number of use cases, a casual use case description appears justified.

We define three main use cases for which the envisaged system can support design by quantifying the performance of buildings and HVAC systems. These use cases are academic: they do not derive from the empirical observation of practice. They correspond to questions, to which BPS is supposed to provide relevant answers: 1. How does the performance of several types of HVAC systems compare? 2. What is the best trade-off between HVAC system and envelope quality? 3. What performance is achievable by changing the generation subsystem?

Common to the three use cases is the comparison of several alternatives. These alternatives correspond to variations in design variables, the definition of which differs with each use case: 1. HVAC system type; 2. HVAC system type and envelope quality; 3. generation component and supply temperature.

Other circumstances may contribute to the definition of use cases but are not explicitly considered here: level of detail of available data, presence and quality of monitoring data for existing buildings, properties of the planning process.

In the three following use cases, we refer to the primary actor interacting with the proposed system as *simulation expert*. The simulation expert interacts with the proposed system and with other stakeholders, which are: (i) an *architect* in charge of building design; (ii) a *mechanical engineer* in charge of HVAC planning; (iii) a *client*, who is supposed to commission planning and simulation activities. The simulation expert's goal is to enlighten decisions made by the other stakeholders by analyzing the performance of several options. A workflow similar to that modeled in Figure 3.2 is assumed.

3.1.2.1 Use case one: HVAC system design

In this case, the building design is given, and an HVAC system is to be determined. This can be for instance because changes in building use or requirements make the installation of a system necessary, or because the previously installed system is obsolete. The question answered by simulation is: *How can we compare the energy performance of different HVAC systems?* More than selecting among a few options, the use case involves the creation and use of detailed models corresponding to each option.

Main success scenario:

1. A client decides on the necessity of installing or replacing an HVAC system in a building.
2. The concept design phase for the new HVAC system is initiated.
3. A list of eligible HVAC system types with their essential characteristics is agreed upon.
4. Data related to major boundary conditions is collected: site, building model, use of building spaces, set points.
5. On the basis of these data, the proposed system creates, runs and post-processes a simulation for each eligible HVAC system type.
6. The simulation expert checks the system outputs, including simulation models and results.
7. System outputs support the choice of an HVAC system type, involving all stakeholders.

Extensions:

1a. The client would like to know if replacing an HVAC system would be worthwhile.

3a. Preferences for given types are expressed by certain stakeholders.

4a. Important data (e.g. infiltration rates or space occupancy) is missing or highly uncertain.

4b. In the case of an existing building, measurements (e.g. of room temperatures) are available which make a calibration of the building model possible.

6a. The simulation expert finds some results to be inconsistent.

7a. Stakeholders would like to compare more options.

7b. The mechanical engineer expresses doubts about simulation results.

3.1.2.2 Use case two: HVAC design and envelope optimization

This case differs from the previous one as additional degrees of freedom are present at the level of the building envelope. Building shape and internal structure are already determined, but the envelope constructions are not defined in terms of material and thickness.

The question answered by simulation is: *What are the best combinations of HVAC systems and envelope quality in terms of energy performance?* A goal is to investigate the trade-off of investing in passive energy-saving measures and in HVAC system efficiency. This also implies determining whether passive measures may allow savings to be made with regard to the HVAC system.

<u>Main success scenario</u>:

1. A client decides on the construction or extensive refurbishment of a building.
2. The concept design phase for the building is initiated.
3. Several passive measures and HVAC system types are considered.
4. Data related to major boundary conditions is collected: building model, use of spaces, set points.
5. On the basis of these data, the proposed system creates, runs and post-processes simulations for various combinations of passive measures and HVAC systems.
6. The simulation expert checks the system outputs, including simulation models and results.
7. On the basis of results, stakeholders make a decision about which passive measures and HVAC system type to select.

<u>Extensions</u>

3a. Costs or other considerations limit the combinations of passive and active measures.

4a. Important data is missing or highly uncertain.

7a. Stakeholders would like to compare more options.

7b. The client changes its comfort requirements, in order to substitute an HVAC component with passive measures.

3.1.2.3 Use case three: HVAC system modification

This use case differs from the first two use cases by the presence of an HVAC system already installed in the building, a part of which should be preserved. More specifically, a modification of the generation subsystem is planned. Delivery and distribution subsystems are expected not to be changed, as this would involve expensive interventions in living areas.

Heating (or cooling) generation components can often be operated more efficiently with lower (or higher) supply temperatures. In this context, the question answered by simulation is: *In which range can the supply temperature be adjusted, and what are the impacts of several modifications of the generation subsystem on energy performance?*

Main success scenario:

1. A client decides on the possibility or necessity of replacing an HVAC generation component.
2. The concept design phase for the HVAC system refurbishment is initiated.
3. A list of eligible generation components is agreed upon.
4. Data related to major boundary conditions is collected.
5. For each generation component, the modifications to apply to the rest of the system are determined and a corresponding scenario is defined.
6. On the basis of these data, the proposed system creates, runs and post-processes a simulation for each scenario.
7. The simulation expert checks the system outputs, including simulation models and results.
8. System outputs support a decision about generation subsystem replacement and corresponding modifications to system temperatures.

Extensions:

4a. Important data is missing or highly uncertain.

4b. Measurements are available which make a calibration of the building and HVAC model possible.

5a. One or several alternatives can be ruled out before simulation.

8a. Stakeholders would like to compare more options.

8b. The mechanical engineer expresses doubts about simulation results.

8c. Stakeholders come to the conclusion that distribution and delivery subsystems should also be significantly altered.

3.2 System requirements

This section describes the requirements set for the system to tackle the previous use cases.

3.2.1 Functional requirements

The expected behavior of the system in addressing the previous use cases is described in the following functional requirements:

- R1: The system shall operate on a structured representation of buildings and HVAC systems.
- R2: The system shall generate a zoned building model from an initial structured building representation.
- R3: The system shall derive a component-based model of appropriately sized HVAC systems from a zoned building model.
- R4: The system shall be able to translate its internal building and HVAC model into input files for chosen simulation engines.
- R5: The system shall derive building performance metrics from simulation results.

Use of simulation engines. The way the proposed system is to assist planning is by leveraging building energy performance simulation tools. Different tools are used because they provide different simulation capabilities. Using more than one tool also ensures that the method is generalizable to a certain extent.

Building performance metrics. Obtaining performance metrics and indicators allowing better decisions to be made can be seen as the end goal of the proposed system. The value of the system will thus depend on selecting and calculating appropriate performance metrics. Simulation results can be aggregated in many different ways, resulting in as many performance metrics [145]. A metric involves the standard definition of a measurable quantity [146]. A performance metric more specifically points to some aspect of performance. Results mattering for us have to do with comfort, energy use and costs.

The main function of HVAC systems being to ensure thermal comfort, results of simulation should be inspected in this regard. At the simplest level, one may look at the frequency of zone temperatures falling below lower set points or exceeding higher set points. The question is complicated by the consideration of radiant temperature along with air temperature, and by the definition of aggregation strategies for temperature indicators over longer periods and in several zones. Comfort values like the predicted mean vote (PMV) and the predicted percentage of dissatisfied (PPD) are closer to the actual comfort issue, but require more unavailable data (such as people clothing and activity levels). This is why we focus of temperature-based comfort indicators following standard EN 15251 [147].

Simulated energy use can be regarded as the main output. Values can be seen at different levels of aggregation (component, subsystem, system, building) and with different system boundaries. A distinction between forms of energy (thermal energy at different temperatures, electricity) should be present, and allow primary energy use and pollutant emissions to be assessed. It is indispensable to define system boundaries for the evaluation of energy use. Following DIN V 18599-1 [148], we distinguish:

- *Useful energy*, including useful heat for heating and useful cooling energy;
- *Final energy*, which is the energy provided to the HVAC system, including auxiliary energy. It is final from the perspective of the energy market;
- *Primary energy* use, which in addition to final energy includes all energy losses before reaching the building, i.e. during production or extraction, conversion and distribution (distribution to the building, not in the sense of the HVAC distribution subsystem).

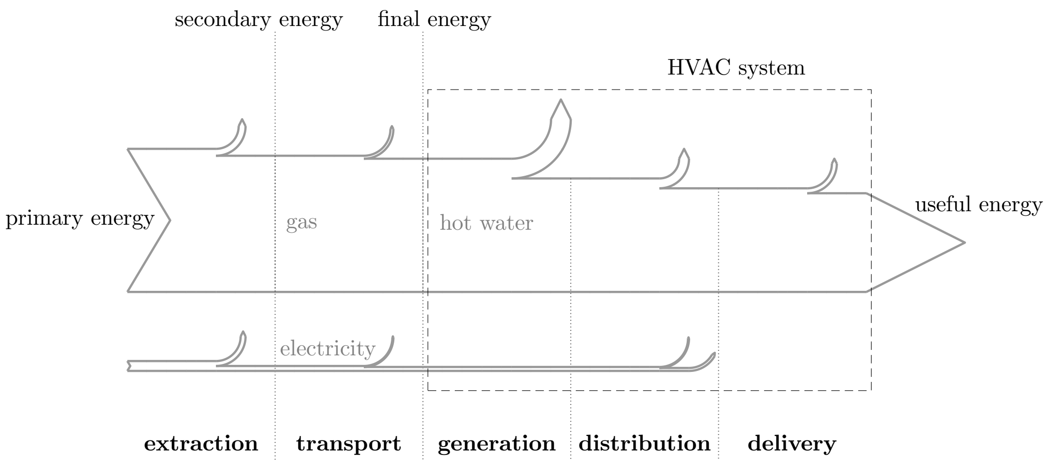


Figure 3.4: Sankey diagram for gas heating as an example of system boundaries from primary energy to useful energy. Auxiliary energy is represented below the main energy path.

As illustrated in Figure 3.4, HVAC systems are provided final energy and deliver useful energy. Sankey diagrams can become much more complex, for instance in the case of renewable energy sources and reusable energy losses (for instance waste heat).

Apart from energy costs, costs (construction, maintenance) and feasibility are not included in this work. It would be the experts' task to evaluate costs from their knowledge of the different system types. System characteristics output by the system, for instance as lists of equipment data, may help them.

3.2.2 Non-functional requirements

The following non-functional requirements define characteristics of the system needed for it to be useful in the defined use cases.

- NFR1: The system shall not need any user intervention between the setting of input parameters and the analysis of results.

- NFR2: The time required by the system for the creation of a building simulation model shall be limited. More specifically, it shall not significantly exceed the running time for a whole-year simulation, or 5 minutes for a 50-zone model on a common personal computer.

- NFR3: In terms of scalability, the system shall be able to handle realistic buildings with up to a hundred zones.

- NFR4: The way the system creates models shall be traceable. Simulation specialists shall be able to follow the main steps of model creation if desired. In other words, the system should not act exclusively as a black box. Also, it is desirable that the methods used should be understandable for HVAC engineers.

- NFR5: The way the system creates models should be deterministic.

NFR1 corresponds to investigating full automation of model creation. A less radical approach would require user intervention to be quantified, which would represent a difficulty in itself. The quantitative requirements NFR2 and NFR3 are assumed to correspond to what can be expected in practice. One can trace back NFR4 to the use cases extensions in which doubts are expressed about the simulation results. In this case, there should be a possibility to check the model creation process, and gain confidence or find out errors. NFR5 is related to the previous requirement of traceability, and to the demand that system behavior should be reproducible.

3.2.3 Non-requirements

Non-requirements, or out-of-scope requirements, contribute to defining the scope of the system, and may be considered in future work.

While requirement R2 implies the use of existing sources for building models, the import of data from specific building information modeling (BIM) formats is out of scope. Consistency with various standards for energy performance assessment would be preferable, especially with regards to the definition of inputs and performance indicators. However, compliance with these standards is not a requirement. Compliance with a specific set of standards would have to be implemented separately for each country and/or standard (e.g. Passive House) aspired to, which would require much additional work.

Optimization of HVAC operation rather than design is not treated here, although it would probably be worth applying similar methods to it. In terms of scalability, the system is devised for the analysis of single multiple-zone buildings. Urban building energy modeling is not part of the ambition.

3.2.4 Data model requirements

The thermal model creation method requires a structured representation of the building and its HVAC systems (requirement R1). The data model used for this is itself submitted to several requirements.

- DR1: The general structure should be able to accomodate the targeted BPS tools (see Section 3.3). This implies that it should contain enough information (in terms of object types and properties) that the tool-specific structures may be derived from it. What is more, this translation should be made as easy as possible.
- DR2: The data model should make it possible to model a majority of central HVAC systems. An appropriate structure should be able to cope with the challenge of connected loops, such as hot water and air loop connected by a water air heating coil.
- DR3: The models should be comprehensible, and possible errors as easy to track as possible.

The structure should consider existing BIM schemes, in particular the leading Industry Foundation Classes (IFC). This should leave open the possibility of a later mapping, keeping in mind that IFC schemes for HVAC do not seem to have reached maturity yet. However, it is out of the scope of this work to develop a full structure accommodating any arbitrary HVAC system, as well as to develop a full mapping with the IFC.

3.3 Simulation model requirements

Given the amounts of resources needed to develop and validate BPS tools, it is reasonable to use existing software for simulation. This section justifies the choice of two specific simulation engines, and presents their input model requirements, which need to be accommodated by the system to be developed.

3.3.1 Choice of simulation engines

The large amounts of resources associated with the development of building performance tools justify the use of existing software, and even the combination of development efforts, for instance through co-simulation [149]. Engines such as ESP-r [1] and EnergyPlus have been developed over several decades, and their source codes contain several hundred thousands of lines [36]. With the necessity of collaborative development for building performance simulation, recently stressed in a paper prepared on behalf of the International Building Performance Simulation Association board [150], it appears desirable to reuse the fruits of such long-standing efforts.

Use of EnergyPlus. EnergyPlus [151] is a popular building energy simulation program, whose development began in 1996 on the basis of two existing programs, DOE-2 and BLAST. These predecessor programs have, on the one hand, supplied the new program with numerous simulation characteristics and routines. On the other hand, it was attempted to overcome their shortcomings, notably by making the code more modular. The simulation engine is composed of three main components: surface heat balance manager, air heat balance manager and building systems simulation manager.

Following the logic of sharing and reuse highlighted above, the use of general-purpose tools, or tools based on these, could also be considered, instead of tools dedicated to buildings. General-purpose codes based on symbolic equations in a general modeling language are a relatively new alternative to traditional "monolithic" codes [46]. The separation of models, data and solvers should make it easier to maintain the code and add new models, potentially coming from different disciplines [36]. The first mature application to whole building simulation of such codes based on differential algebraic equations (DAE) was IDA ICE [46]. It is believed that the object-oriented language Modelica has the potential of allowing equation-based models to be developed for a variety of engineering domains and exchanged between them [36]. In a comparison between Modelica and the procedural modeling language TRNSYS [152], it has been argued that benefits were to be expected from the first kind of tools in terms of model development time and model reuse. The Modelica "buildings library" is still rather recent. The corresponding room and window models have been validated in 2014 [153].

In addition to the mere development of simulation tools, much effort has gone into their validation. This can be illustrated by a review of the history of validation with the ESP-r program [4], from which it becomes apparent that validation is a "long-term and continuous process".

The degree of use of the different engines, and the associated amount of resources spent on maintaining, validating and expanding them, is thus a parameter of great importance for our choice. Figure 3.5 makes it apparent that the number of research contributions dealing with EnergyPlus now exceeds that of concurrent tools such as ESP-r or TRNSYS, and is rising steadily. What is more, these contributions all deal with building performance, as opposed to TRNSYS, where other systems not relevant for our research are considered, and Modelica, for which buildings and energy systems only represent a subset of the possible applications.

The articles cited in the state-of-the-art also mainly make use of EnergyPlus, or take it as a reference. An advantage of EnergyPlus for automated approaches to simulation is its text-based and human readable input file, as opposed to several text-based files for ESP-r, and to non human readable proprietary formats of some other simulation tools.

Use of TRNSYS. Because of the limited flexibility of EnergyPlus for HVAC system modeling, the use of another tool for HVAC modeling is investigated.

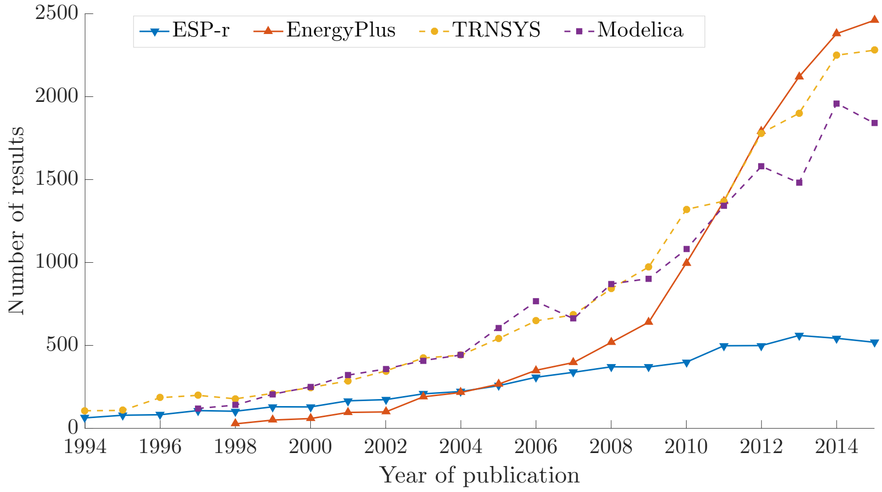


Figure 3.5: Number of contributions referenced by Google Scholar mentioning the different simulation tools for different years (search on 24.05.2017)

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TRNSYS is a software environment for the transient simulation of systems, including buildings with multiple zones [154]. From the first public version TRNSYS 6.0 in 1975, it has evolved into a suite made up of a simulation Studio, a simulation engine, a graphical input program for multizone buildings (TRNBuild) [155], and an editor (TRNEdit) for the creation of stand-alone redistributable programs.

The TRNSYS simulation Studio represents the main visual interface, in which projects can be created by connecting components together and setting their parameters.

Among the arguments presented in Section 3.3.1 for the use of EnergyPlus, that of wide-spread use and consequent validation also applies to TRNSYS. The main reason for the use of TRNSYS is the limited flexibility of EnergyPlus in the simulation of HVAC systems, leading for instance to the impossibility of describing systems with nested loops.

Use of co-simulation. Our use of co-simulation is motivated by several reasons. Co-simulation offers the possibility of using the most appropriate tool for each domain. While EnergyPlus has more capabilities in terms of modeling building envelope and internal processes, it was found that the more flexible HVAC model of TRNSYS can offer more accuracy and be of advantage.

Co-simulation offers the possibility of comparing only HVAC models, the building part remaining the same. Given its focus on HVAC modeling, this appears beneficial for the present work.

Finally, the Functional Mock-up Interface (FMI) standard now makes it easier to carry out co-simulation in a standardized way, without resorting to ad-hoc bilateral links. In future developments, a third HVAC modeling tool could be added with little additional coupling effort.

The rest of this section describes the data required for integrated building and HVAC simulation using the chosen tools. These data requirements follow from requirements for building performance simulation in general, as introduced in the first chapter. Still, they vary significantly with the tools used. The two cases to be distinguished here are single-tool simulation using EnergyPlus and co-simulation using EnergyPlus and TRNSYS. In the first case, the whole building and HVAC model is contained in an input file (IDF). Together with a weather file (.epw), and optionally external files for yearly schedules, the IDF is enough to run a simulation.

3.3.2 Data requirements for EnergyPlus building model

An Input Data File requires at least two types of information to be run: geometry and global simulation information. Global simulation information is provided in the form of unique objects. Each file must contain exactly one of each of the following objects: *Version*, *SimulationControl*, *Building* and *RunPeriod*.

Geometry definition. Geometry definition in EnergyPlus requires at least zones and surfaces. Most of the building definition in EnergyPlus revolves around the concept of zone, which is described in previous chapters and is so omnipresent that it does not even seem to be defined in the documentation. As seen in the following IDF example, the only required field for the definition of a zone is a name, by which other objects refer to the zone.

```
Zone,
      ZoneName, !- Name
      0,        !- Direction of Relative North {deg}
      0,        !- X Origin {m}
      0,        !- Y Origin {m}
      0,        !- Z Origin {m}
      1,        !- Type (unused)
      1,        !- Multiplier
      autocalculate, !- Ceiling Height {m}
      autocalculate; !- Volume {m3}
```

Surfaces can be defined with several object types, the most common and general of which is *BuildingSurface:Detailed*. Surfaces may have different boundary conditions, such as *Outdoors*, *Ground* or *Surface*. The latter case is used to model heat transfer between two zones, and is illustrated in the following IDF example, which defines an interior wall surface. A surface (*ThisInteriorWall*) assigned to the first zone will have another surface (*TheAdjacentWall*) assigned to the second zone as boundary condition, and reciprocally.

```
BuildingSurface:Detailed,
      ThisInteriorWall,      !- Base Surface Name
      Wall,              !- Surface Type
      InteriorWallConstruction, !- Construction Name
      ZoneName,          !- Zone
      Surface,           !- Outside Boundary Condition
      TheAdjacentWall, !- Outside Boundary Condition Object
      NoSun,             !- Solar Exposure
```

```
NoWind,            !- Wind Exposure
autocalculate,     !- View Factor to Ground
4,                 !- Number of vertices
0, 0, 4,           !- Vertex 1 X-, Y-, Z-coordinate
0, 0, 0,           !- Vertex 2 X-, Y-, Z-coordinate
0, 10, 0,          !- Vertex 3 X-, Y-, Z-coordinate
0, 10, 4;          !- Vertex 4 X-, Y-, Z-coordinate
```

The surface geometry is defined through a list of vertex coordinates. As a consequence, only simple polygons (without holes) can be represented. To determine the surface outward facing normal, vertex order should conform to rules defined in the *GlobalGeometryRules* object. By default, vertices are listed in counter-clockwise order (viewed from outside of the zone), beginning with the upper left corner. A surface also refers to a given construction defined elsewhere in the input file. Each construction is defined by the reference to a set of *material* objects, which represent the layers of the construction with their different thermophysical properties.

Openings like windows or doors are grouped under the term *fenestration*. They are considered as *subsurfaces* of a *base surface*, typically a wall, from which they inherit some properties. Like for the base surfaces, their geometry is specified in terms of vertices, but these are limited in number to three or four. The vertices correspond to the glazed part of the window, excluding the frame.

Comparison to the data requirements of other tools: ESP-r. The data requirements of EnergyPlus correspond to the general data requirements for dynamic thermal simulation described in the first section. In order to evaluate the generality of methods developed for this particular tool, it is useful to compare its data requirements with those of other tools.

One of these is ESP-r, a "comprehensive simulation environment" for the assessment of problems related to thermal, air and moisture transport in buildings, fluid flow in HVAC systems, electric power flow and indoor air quality [156]. It contains several modules, for "problem creation", model viewing, database management, climate analysis and manipulation etc.

In place of the EnergyPlus IDF, ESP-r makes use of several files, including a problem configuration file, and for each zone a geometry, a construction and an operation file [157].

- The *problem configuration file* or system configuration file is the main description of a "problem", containing references to the various other files.
- A *configuration control file* contains "the control statements to be obeyed by the simulator at simulation time".
- A *zone geometry file* describes the geometry of a zone in terms of vertices, with their Cartesian coordinates, and surfaces, defined by a list of vertices. Surface attributes include name, type (opaque or not), construction (reference to the zone construction file) and type of environment on the other side.

The location of windows and doors is described as an offset relative to the containing surface. In the case of interzone surfaces, the environment on the other side is specified in terms of another zone, whereas in EnergyPlus it is specified in terms of a surface, which is more precise.

- A *zone construction file* contains thermophysical data for each zone. Constructions are also defined in terms of multiple layers. Apart from air gaps, layers are characterized by their thickness, conductivity, density and specific heat. Emissivity and absorptivity are specified for the inside and the outside face of each surface. Like in EnergyPlus, constructions used between thermal zones should be made of the same layers in reverse order.

- A *zone operation file* describes the patterns of heat gains (sensible, with radiant and convective fraction, and latent), ventilation and infiltration, "with an associated control syntax". In EnergyPlus, similar information would be held in different zone-related objects (*People*, *Light*, *Zone:Infiltration*, *Zone:Ventilation*) linked to schedules.

In conclusion, data requirements for ESP-r and EnergyPlus are similar. Thus, basing the design of our system on the requirements of EnergyPlus should not induce a significant loss of generality.

3.3.3 Data requirements for EnergyPlus HVAC model

EnergyPlus makes it possible to model HVAC systems at several of the levels of abstraction introduced in the first chapter:

- At the conceptual level, ideal air systems represent ideal systems supplying zones with the exact amount of thermal energy they need to maintain a given set point.

- HVAC *templates* corresponding to predefined systems can be defined with only few parameters. The corresponding descriptions are then automatically "expanded" into a more explicit model, in a pre-processing step before the actual simulation run.

- The more explicit simulation of energy systems in EnergyPlus is based on *loops*. Each loop consists of two half loops, formed by the linking of components in a limitedly flexible way, as detailed below. This makes this modeling approach "a hybrid implementation of component-based and system-based environments" [158].

EnergyPlus components correspond to subroutines in the software modules, taking fixed inputs and calculating outputs [159, p.374]. The EnergyPlus plant manager is based on a "flow resolver" rather than on a pressure based flow network. This way, the solution algorithm is simpler (and faster), and the information flow is handled more easily by the program. On the other hand, this restricts the input flexibility and the capability to model complex systems.

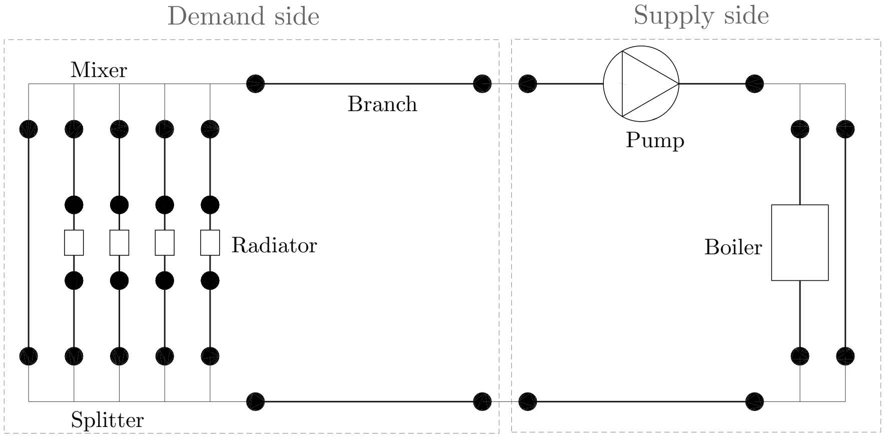


Figure 3.6: Example of EnergyPlus loop structure for hydronic space heating. Black circles represent nodes.

Figure 3.6 shows an example of loop structure in EnergyPlus. Each loop is divided into supply and demand side. Each of the corresponding half loops may contain one splitter and one mixer, between which parallel branches may be listed. A branch is formed by a collection of components in series. Each component has an inlet and an outlet node, at which fluid properties are evaluated. During simulation, the component input corresponds to the conditions at the inlet node, and the output to the conditions at the outlet node. As a result, the output of one component serves as the input to the next component in the branch. Some components, like *HeatExchanger* or *WaterHeater*, may have two pairs of inlet-outlet nodes, which allows them to be connected to two different loops, once on the supply and once on the demand side.

According to this structure, the possibilities of modeling systems with different topologies are limited. Nested loops, for instance, cannot be modeled. As stated in the engineering reference [159, p.389], "EnergyPlus is focused on modeling building energy performance over long periods of time and is not intended as a completely flexible system that can directly model any actual plant system with its full complexity and exact layout". This requires some conceptual effort from the modeler, in order to simplify actual plants into "sets of pairs of closed half-loops with the allowed branch topologies".

EnergyPlus can size systems, or more specifically objects containing fields with the *autosizable* attribute. Based on a heat load calculation for given sizing periods, heat delivery components, and the corresponding plant loops and generation components can successively be sized.

3.3.4 Data requirements for TRNSYS

The restrictions on model structures presented above for EnergyPlus do not apply for TRNSYS. In TRNSYS, a model of an HVAC system, or of any other kind of system, is formed by a combination of components called *units*. This combination can follow almost any arbitrary structure. Attention should only be paid to linking variables with the same physical meaning.

Units represent instances of classes called *types*. Each type is defined by a number of parameters, inputs and outputs. The parameters of a given unit are fixed for each simulation, whereas inputs can refer to outputs of other units or variables defined in equations.

Based on the example presented in Table 3.1, it appears that parameters and inputs can represent control variables as well as physical characteristics of the modeled components. For other types, parameters also include simulation parameters not related to the physical objects (e.g. discretization parameters).

Table 3.1: Parameters, inputs and outputs for TRNSYS type 114 (single speed pump). Default values appear when dragging a new unit from the library in the TRNSYS Simulation Studio. Some of them correspond to plausible assumptions, like the fluid specific heat being that of water. Others, like the default flow rate of 1000 kg/h, are more arbitrary and should definitely be replaced by a value corresponding to the modeled system.

	Name	**Unit**	**Default value**
Parameters	rated flow rate	kg/h	1000
	fluid specific heat	kJ/(kg K)	4.19
	rated power	kJ/h	2684
	motor heat loss fraction		0
Inputs	inlet fluid temperature	°C	20
	inlet fluid flow rate	kg/h	1000
	control signal		1
	overall efficiency		0.6
	motor efficiency		0.9
Outputs	outlet fluid temperature	°C	
	outlet fluid flow rate	kg/h	
	power consumption	kJ/h	
	fluid heat transfer	kJ/h	
	environment heat transfer	kJ/h	

Comparison to the data requirements of other tools: EnergyPlus. There is not always a one-to-one relationship between components in EnergyPlus and TRNSYS, and very rarely between parameters in equivalent components of both programs, as exemplified in Table 3.2 for the components modeling pipe segments and Table 3.3 for the components modeling radiators.

Table 3.2: Comparison between two components representing a pipe in TRNSYS and EnergyPlus. Double-headed arrows stand for an equivalence between two fields. A single-headed arrow from a field F_1 to a field F_2 means that F_1 contains more information and the value of F_2 can be derived from the value of F_1.

	TRNSYS		**EnergyPlus**
Component name	Type31		Pipe:Indoor
Parameters	Pipe length	$\Leftrightarrow$	Pipe length
	Inside diameter	$\Leftrightarrow$	Inside diameter
	Loss coefficient	$\Leftarrow$	Construction Name
Inputs	Inlet temperature	$\Leftarrow$	Fluid Inlet Node Name
	Inlet flow rate	$\Leftarrow$	Fluid Inlet Node Name
	Environment temperature	$\Leftarrow$	{ Environment Type +Ambient Temperature Zone Name
	Fluid density		hard-coded
	Fluid specific heat		hard-coded

Table 3.3: Comparison between two components representing a radiator in TRNSYS and EnergyPlus.

TRNSYS		**EnergyPlus**
Type1231 (TESS library)		Baseboard:RadiantConvective:Water
Design capacity	$\approx$	Rated Capacity
		Rated Average Water Temperature
		Rated Water Mass Flow Rate
		Maximum Water Flow Rate
Design surface temperature		
Design air temperature		
Design Delta T exponent		
Number of pipes		
Pipe inside diameter		
Air pressure exponent		
		availability schedule
		Fraction Radiant
		Fraction of radiant energy incident on people
		Radiant surfaces
Room temperature	$\Leftrightarrow$	zone to which baseboard is attributed
Room air pressure		
Inlet water temperature	$\Leftarrow$	Fluid Inlet Node Name
Water flow rate	$\Leftarrow$	Fluid Inlet Node Name

Summary

This chapter presents the intended use of a method allowing building and HVAC models to be derived automatically for simulation, and requirements for a system applying this method. It is proposed to use the method in the conceptual design phase, as it is assumed to be the most promising time for simulation to support planning. The proposed method would involve the automation of simulation preparation steps. Still, its application would rely on skilled users with sufficient knowledge of building performance simulation and HVAC systems.

The requirements are based on three use cases. Common to these use cases is the use of simulation to compare the performance of several variants. Differences between these variants may consist in the whole HVAC system, in a combination of HVAC system and envelope quality, or in a subsystem (generation) of the HVAC system.

To support these use cases, the system shall derive component-based models of well-sized HVAC systems from existing building models and allow building performance simulation to be carried out based on these models. These operations also involve an appropriate data model for buildings and HVAC systems. As simulation is to be carried out by existing simulation engines, the data requirements of these tools must be taken into account.

Thus, the envisaged system is based on the possibility of deriving models of pertinent HVAC systems from building models. Methods achieving this are presented in the next chapter.

Chapter 4

Creation of HVAC system models

Because of the difficulty to translate HVAC-related BIM data into a detailed HVAC simulation model, as explained in the literature review, the present work investigates the possibility of generating such a model from general building information. This chapter presents procedures developed to this aim. Using them, delivery, distribution and generation subsystems can be successively created, as pictured in Figure 4.1. The same order is followed in this chapter. To a large extent, it also corresponds to that used by HVAC engineers for the manual definition of heating systems [16].

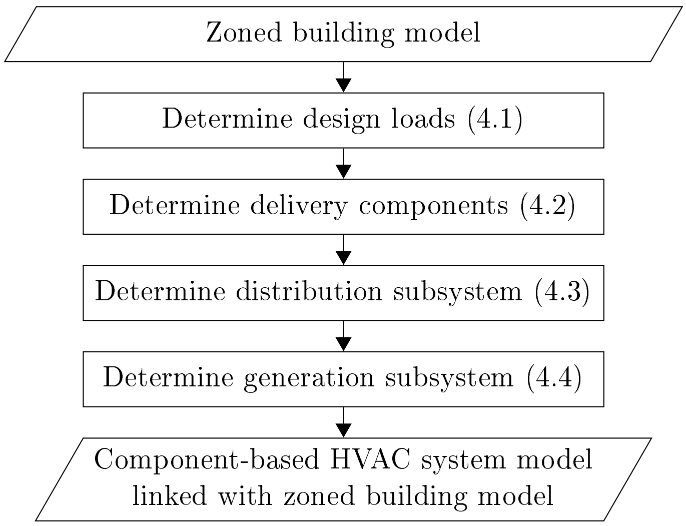
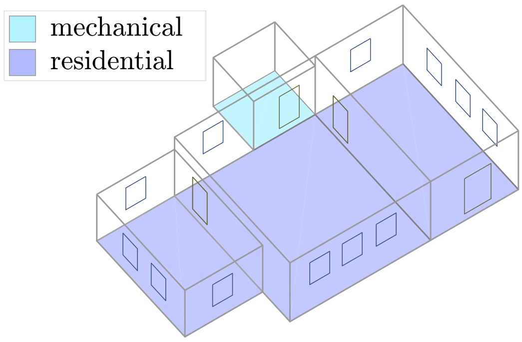
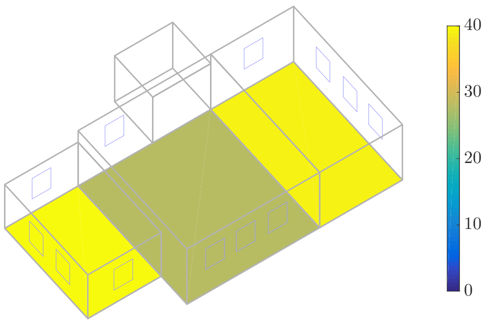


Figure 4.1: HVAC model creation steps.

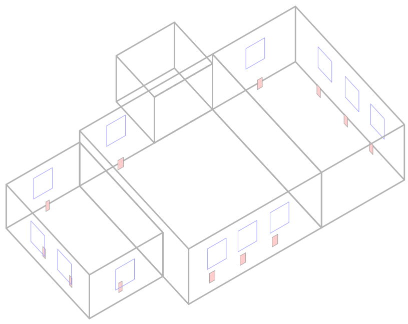
The general input for these procedures is a zoned building model comprising zones, space boundaries, constructions and materials, internal loads and set points. The data model chosen for such a model is introduced in the next chapter (Figure 5.3). In the following, an example one-floor building with three residential zones and a mechanical room is used as a minimal running example. Figure 4.2 shows an architectural view (input) for this example (4.2a), and corresponding results of the main model creation steps.



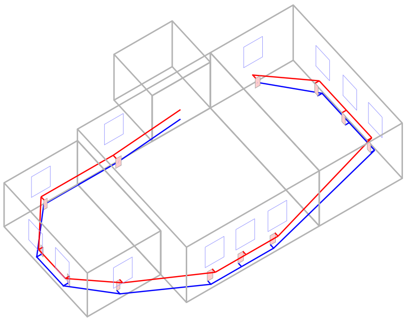
(a) Architectural view.



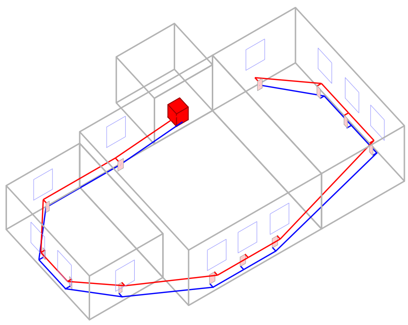
(b) Design heat load density (W/m^2).



(c) Delivery.



(d) Distribution.



(e) Generation.

Figure 4.2: Overview of the model creation procedure for an example building with three residential zones and a mechanical room.

The general output of the presented procedures is a component-based HVAC system description, the main part of which takes the form of a network of components. This HVAC model is based on general objects, which later in the workflow are translated into tool-specific objects (for EnergyPlus and TRNSYS). Also part of the output, the input building model is linked to this general HVAC model, enriched with some information on zone sizing, and if needed modified to take into account certain delivery systems.

4.1 Determination of design loads

In a general way, the design load of a system may be defined as the maximum amount of a quantity that this system is designed for. For HVAC systems, the relevant quantities are heating and cooling powers, as well as ventilation rates. The determination of design heating and cooling loads may be seen as the first step of HVAC system design. The maximum air ventilation rate may also be considered as a design load, having an influence on the first two loads and on the design of ventilation and air-based systems. These three quantities are defined at the level of a zone. Heating and cooling loads are the maximum amounts of thermal energy that should be supplied, respectively taken away from a zone, in order for acceptable thermal conditions to be maintained in the zone under given boundary conditions. Accordingly, standards for the determination of design loads have to define acceptable zone conditions, as well as exterior weather and other influencing conditions to consider. An example is European standard EN 12831 [29], which defines a method for the calculation of design heat loads.

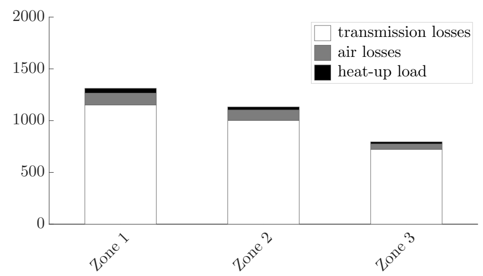
4.1.1 Design heat loads

The determination of design heat loads is the first step in determining and sizing a heating system. For this, two approaches can be considered.

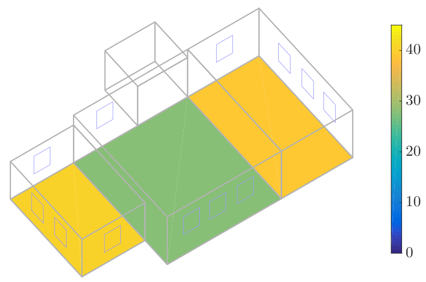
Use of a simulation period with ideal loads under specific sizing conditions. Ideal load simulation means that instead of modeling the HVAC system explicitly, only the amounts of energy necessary to maintain set-point conditions in each thermal zone are calculated, without consideration of how this energy would be delivered. This is also the procedure behind the *autosizing* feature of EnergyPlus. A sizing period typically corresponds to one week. Special conditions are assumed for this sizing simulation period, which differ from those used in other simulations and reflect conservative assumptions. Internal heat gains are typically reduced to zero. Examples of sizing run results are illustrated in Figure 4.4.

Use of a steady-state (non-dynamic) calculation with extreme weather conditions. This may correspond to the standard method used for the sizing of the actual equipment. The calculation mainly consists in the addition of several transmission and ventilation heat losses. According to the EU standard, the impact of thermal bridges is to be considered, whereas they are neglected in the rest of our workflow, as in most dynamic simulations to date. As buildings become better insulated, thermal bridges may actually play a more important role in thermal losses. However, their study requires information about constructive details that is usually not available in early design stages. Also, truly dynamic modeling of multidimensional thermal bridges is a challenging endeavor, for which new methods have been proposed in the last years [160]. For situations in which set-point temperatures vary (for instance after a night or weekend setback), dynamic effects linked to thermal mass (heat-up loads) are approximated, based on set-point temperature difference and the expected time to reach the new set-point.

Both approaches have distinct pros and cons. Sizing with ideal load simulation may ensure consistency with later simulations. Steady-state calculations are more straightforward to carry out and interpret. They allow design loads to be simply decomposed according to loss type, as illustrated in Figure 4.3. They may also yield divergent results, as exemplified by the comparison of Figures 4.3 and 4.4. As a consequence, it may be useful to compare sizing results obtained with the two methods.

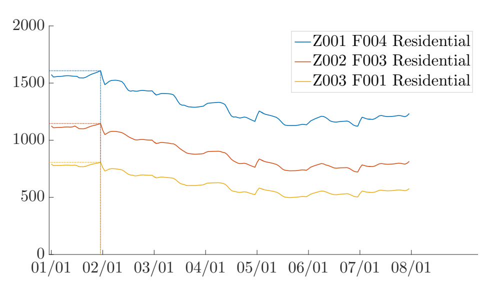


(a) Design heat load (W) per zone and loss type.

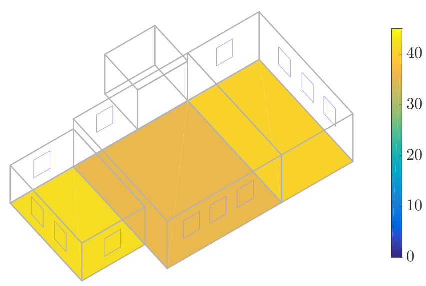


(b) Design heat load density (W/m^2).

Figure 4.3: Examples of steady-state sizing results.



(a) Heat load (W) during simulation run.



(b) Design heat load density (W/m^2).

Figure 4.4: Examples of sizing results obtained with sizing run.

4.1.2 Design cooling loads

Greater daily temperature swings in the cooling period than in the heating period, together with the influence of solar radiation and intermittent internal heat gains, contribute to making the determination of design cooling loads more involved than for heating. The consideration of operative temperature instead of mere room air temperature also contributes to making a computer-based dynamic calculation indispensable, as argued for the new version of guideline VDI 2078 [2].

Guideline VDI 2078 also proposes a simplified static procedure (Annex D), the result of which should only be seen as a “rough estimate” of the cooling load. The estimated cooling load $\dot{Q}_{c,max}$ for a zone is defined in Equation 4.1:

$$\begin{aligned}\dot{Q}_{c,max} = -1\Bigg[&0.9\left(\dot{Q}_{source,max} - \dot{Q}_{sink,max}\right)\left(1 + 0.3\ \exp\left(\frac{-\tau}{120\,\mathrm{h}}\right)\right) \\ &- C_{eff,env}\frac{A_{env}}{t_{ref}}\ (\Delta\theta - 2\,\mathrm{K}) + C_{eff,env}\frac{A_{env}}{40\,\mathrm{m}^2}\left(\frac{12\,\mathrm{h}}{t_{c,op,d}} - 1\right)\Bigg]\end{aligned} \tag{4.1}$$

where τ is a time constant (in h) and $C_{eff,env}$ a value of effective heat capacity for the zone, A_{env} the zone envelope area, $\Delta\theta$ the permissible oscillation of the indoor temperature, t_{ref} a location-dependent reference time between 60 and 85 h, and $t_{c,op,d}$ the daily duration of the cooling system’s operation. This equation demonstrates the difference in complexity between the cooling load estimation and the calculation of the heating load, which would correspond to the sole $\dot{Q}_{sink,max}$ term. Still, like the static procedure for design heat loads, this simplified calculation has the advantage of clearly apportioning the design load between various contributions.

4.2 Determination of delivery components

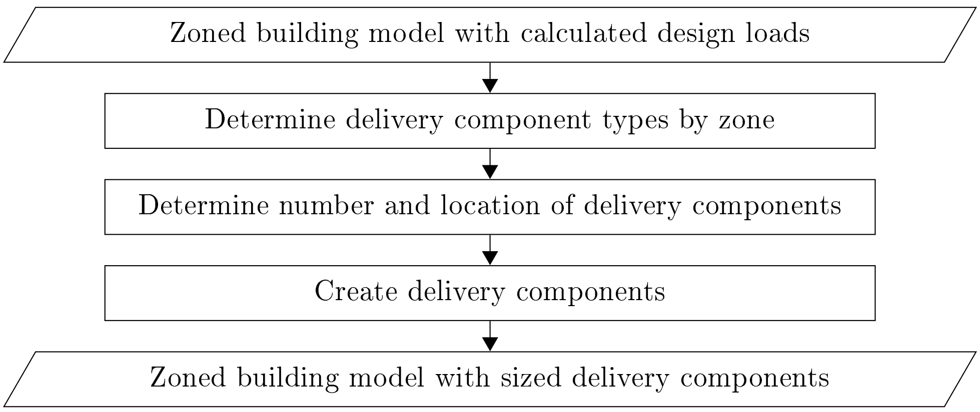


Figure 4.5: Delivery subsystem model creation steps, unfolding step *determine delivery components* of Figure 4.1.

Delivery components are responsible for supplying thermal energy to the zone, or extracting it from the zone for cooling systems. We assume that each delivery component is assigned to a unique zone. This section shows how delivery components may be selected and sized, and their geometry determined, taking into account zone characteristics.

4.2.1 Selection of delivery component types

Based on the calculation of design heat loads (or cooling loads), delivery components may be selected and sized. Constraints to the capacity of delivery components include the following:

- Underfloor heating is limited in its heat output because of maximum floor temperature. It is recommended to keep floor temperature under 29 °C in occupied areas [161, p.953]. Higher floor temperatures, and therefore higher heat outputs, are possible in non-occupied areas.
- Air heating is limited by the air temperature at the entry point, which should not exceed a limit of about 50 °C [161, p.585]. Increasing volume flow rate above the required hygienic flow rate is usually not economically acceptable.
- The high heat output of radiators and convectors will generally be sufficient for any zone. However, considering their usual position, the (free) length of walls in the zone may be considered to be a limiting factor.
- For surface cooling, surface temperatures are limited for comfort reasons, and because of the risk of condensation.

Thus, the capacity of each type of component in a zone is bounded. The maximum capacity is a function of the zone characteristics (volume, area, use type), for which typical values are listed in Table 4.1. The resulting limits might suffice to meet the design heat loads or not.

Table 4.1: Typical domains of capacity upper limits for different heat delivery component types. The capacity of radiators and convectors depends on their length, height and breadth. The capacity of air heating depends mostly on the maximum air flow rate, specified for instance as air change per hour (ACH).

Component type	Limit domain	Unit	Reference	Source
Underfloor heating	80..175	W/m^2	floor area	[161, p.953]
Flat panel radiator (h=900 mm)	1000..3000	W/m	wall length	[161, p.934]
Convector (h=210 mm)	700..2000	W/m	wall length	[161, p.944]
Air heating (2..4 ACH)	16..40	W/m^3	zone volume	

Delivery component type selection procedures. Three possibilities of automated component type selection are considered and summarized in Table 4.2. Each of the procedure operates on the basis of a list of component types ordered by preference, and on design loads calculated for each zone.

Table 4.2: Possible procedures for the selection of delivery component types.

Procedure	Description
SeveralByZone	In each zone, the first component type is chosen to meet as much load as possible, followed by the next component types by order of preference, until the total design load is covered.
OneByZone	In each zone, the first component type with the ability of supplying the whole zone design load is selected.
OneForSystem	The first component type with the ability of supplying design loads in all zones is selected.

The selection of a given delivery component should not be guided only by the design load, but also by the room use. For instance, convectors should not be used in dining areas or hospitals, for hygienic reasons. Air delivery components are constrained by considerations of acoustics and comfort, which are subject to various requirements depending on space use. Space use frequency may also be a significant factor to consider. For instance, the necessity of fast warm-up times in intermittently used spaces such as sport halls makes air heating a favored option. However, this level of reflection is not implemented in the present work. Required air flow rates, dependent on space use, also have a more or less direct impact on the choice of delivery component. For delivery components in air-based systems, another decisive factor is whether they are located in a perimeter or a core zone [106].

4.2.2 Determination of delivery component instances

Table 4.4: Reference objects by types of delivery components.

Component type	Reference object	Display geometry
radiator	wall or window	vertical surface
convector	wall or window	vertical or horizontal surface
fan coil	wall or ceiling	vertical or horizontal surface
floor heating	floor	horizontal surface
chilled ceiling	ceiling	horizontal surface
air inlet and outlet	floor and/or ceiling	two points

After the choice of one or several types of delivery components for a zone, and the determination of their respective capacities, the actual instances should be determined, along with their geometry. Aspects to consider when determining the location and geometry of heat delivery components include their impact on thermal comfort and distribution subsystems.

Heat delivery component location and geometry may play an important role in thermal comfort. It is current practice to place radiators near windows, in order to avoid or mitigate cold draft. In well-insulated buildings, radiation asymmetry is limited and the importance of radiator location for thermal comfort is reduced [161, p.1014-1015]. For energy performance simulation as such, they only matter when detailed attention is paid to the radiant fraction of delivered heat. With the assumption of a single air node per zone, the location and geometry of a heating appliance inside of a zone are not relevant for convective heat transfer. For these reasons, it may be argued that several delivery components of the same type present in one zone can be grouped into one component for simulation.

The role of distribution subsystem being to connect generation and delivery components, the subsequent creation of their model will depend on the location of the latter. In particular, the simplification of delivery components to one component per zone may lead to unrealistically short distribution routes, all the more with a coarse zoning.

Finally, the visualization of the HVAC model is made more intuitive if heat delivery components are assigned a location and a geometry that one may expect in reality. This makes visual checks of model correctness possible.

Considering these aspects, and depending on the component type, various methods may be used for the determination of delivery component geometry. According to Table 4.4, radiators, convectors and fan coil units share similar reference objects and may approximately be represented with rectangular surfaces in a vertical plane, so the same method can be applied to all of these types. Underfloor heating or chilled ceilings represent another case, where reference objects are floor or ceiling objects. We will assume such delivery components extend over the whole floor or ceiling object, and use the corresponding surfaces to display them. Air inlets and outlets represent yet another case. In their case, the reference object is typically a floor or a ceiling, but the geometry of the inlet or outlet itself should rather be considered punctual (although their actual shape is generally rectangular or circular). In a general way, one should try to find n points as uniformly spread as possible on the reference surface.

In the following, radiators will serve as an example of how heat delivery components may be created relative to architectural objects, such as walls and windows. Radiator geometry is assumed to be rectangular, on a plane parallel to that of the reference object (wall or window), and placed near this reference surface. A typical radiator height may be assumed, for instance 60 cm, or provided as input parameter. The area, and with this the length of the rectangle, are considered to be proportional to the radiator design capacity.

Reference objects. Reference objects may be chosen in different ways, where the necessary information may be extracted from the architectural view. Possible reference objects may be exterior windows, exterior walls or interior walls. They would typically be chosen in this order of priority, which means radiators would preferentially be located near exterior windows, and near interior walls only if there is no exterior wall. If taking only one component per zone, the reference surface is typically the largest exterior wall of the zone, if there is one, or the largest interior wall of the zone otherwise.

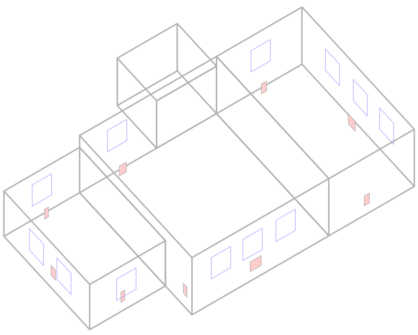
Given one type of reference object available in the zone, the simplest possibility is to create one delivery component for each object (wall or window). Inside of each zone, the capacities of each component are proportional to the areas of their reference surfaces, and such that the sum of the capacities corresponds to the design load. Some windows (e.g. French windows) may not be able to serve as reference surfaces. To determine if this is the case, the distance between the bottom of the window and the floor can be compared to the component height.

A refinement of this method may ensure that the resulting components all have capacity values within realistic bounds:

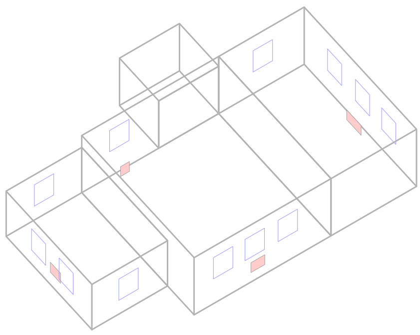
- Reference surfaces which are so small that the resulting component capacity would fall under a given limit P_{min} are not selected.

- Reference surfaces which are so large that the resulting component capacity P_s would exceed a given limit P_{max} are divided into n portions of equal size, with $n = \lceil \frac{P_s}{P_{max}} \rceil$.

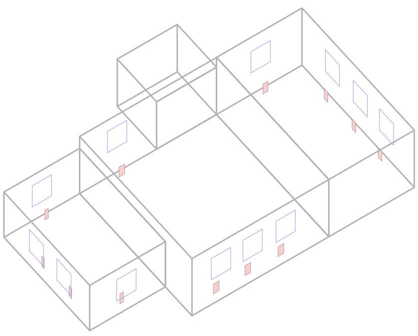
A further sophistication of the method could be imagined, to account for the fact that, for economical and organizational reasons, uniform sizes tend to be preferred.



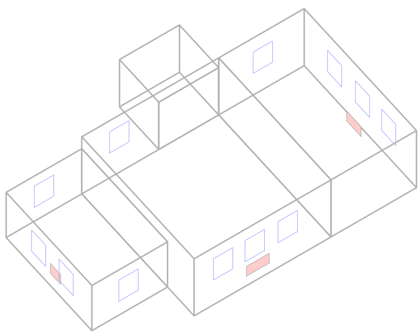
(a) Wall references without capacity limits.



(b) Wall references with capacity limits.



(c) Window references without capacity limits.



(d) One component per zone.

Figure 4.6: Geometry of heat delivery components with different types of reference objects. The lower capacity limit, when applied, is $P_{min} = 300\,\mathrm{W}$. The higher limit $P_{max} = 1500\,\mathrm{W}$ is not active here, in the absence of large walls or windows.

Figure 4.6 illustrates sizing and attachment of delivery components to architectural elements applied on an example building floor. In this example, the enforcement of capacity limits has an influence when walls are chosen as reference surfaces. Since windows in the example are mostly of the same size, capacity limits do not play any role when windows are the reference surfaces.

The level of detail of the input building model matters. For instance, one should not mistake simplified window components obtained from window area ratios for the actual geometry of windows. Also, mounting particulars are not considered, as the available geometric level of detail of the building model is not assumed to be sufficient (e.g. recesses).

In addition to their surface geometry, delivery components are assigned two pairs of points, representing the location of their inlet/outlets ports, and the location where the connection segments are connected with the supply/return distribution subsystem. An example of such points is presented in Figure 4.7.

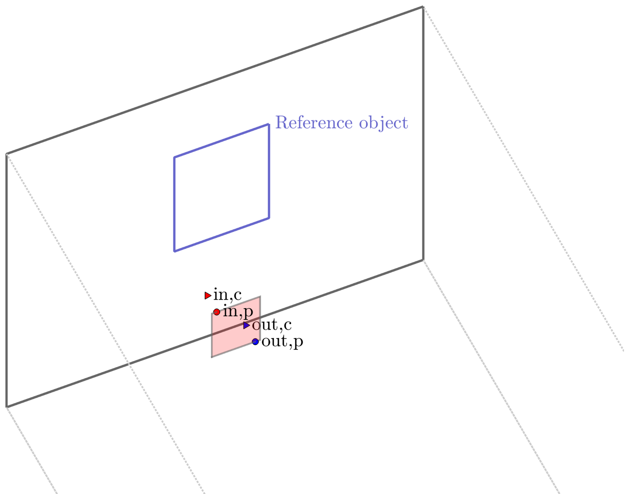


Figure 4.7: Reference points for a radiator: inlet port (in,p), outlet port (out,p), inlet connection point (in,c) and outlet connection point (out,c).

Thermally-activated building systems represent a special case, as with them HVAC delivery components are embedded in building elements. From the model point of view, this also means the HVAC model creation procedure modifies the input structure, which is otherwise not the case.

4.3 Determination of the distribution subsystem

Once heat delivery components are set, it is the role of the distribution subsystem to link them into a network, ultimately connecting them to the generation subsystem. This is done through the use of distribution segments (pipes in the hydronic case), through which an energy carrying fluid flows, circulated by flow moving devices (pumps in the hydronic case). In the present method, the generation of a distribution subsystem starts with the determination of structures (*group distributions*) linking demand components to an inlet and an outlet component through

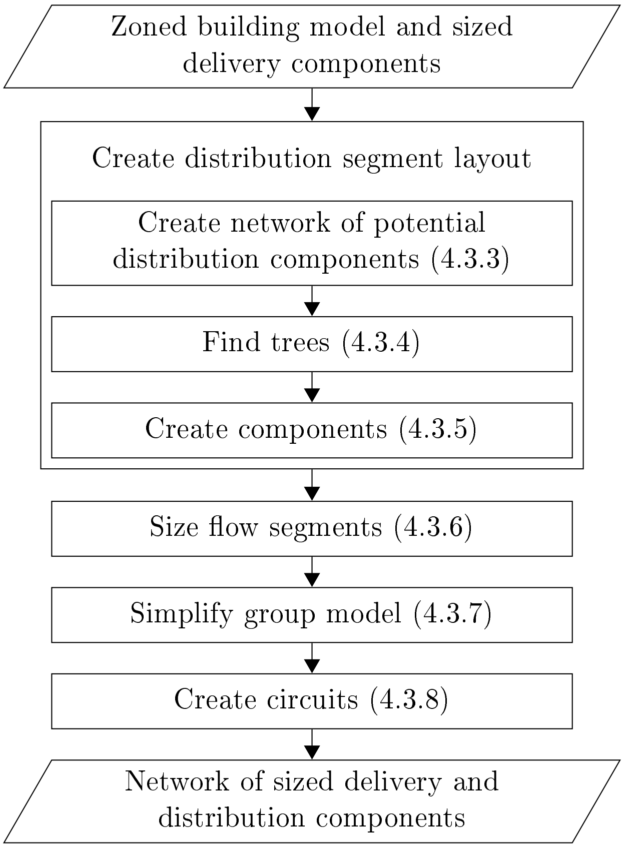


Figure 4.8: Distribution subsystem model creation steps.

two trees of distribution segments. The resulting group distributions are then completed to form circuits, possibly including bypass segments and flow moving devices.

Demand components are, in the cases illustrated here and for hydronic systems in general, delivery components. They may also be heating or cooling coils, which are demand components for the respective hot water or chilled water loops, or air delivery components, when considering mechanical ventilation systems.

This is done at the level of a *group distribution*, which is a part of the system which we define with: (i) a group of (one or more) demand components which are designed to get the same fluid at the same temperature. Generally, these demand components will be of the same type. (ii) an inlet component, possibly a placeholder, for which at least a 3D position and a zone are specified. (iii) an outlet component, defined in the same way as the inlet component. According to the case, inlet and outlet components may correspond to ports connected to various kinds of objects, according to Table 4.5. In most cases, these objects are defined at a later step, so that placeholders have to be used for inlet and outlet.

Table 4.5: Meaning of group distribution inlet and outlet in different cases.

Case	Inlet	Outlet
throttling circuit	generation subsystem outlet	generation subsystem inlet
mixing circuit	circuit mixing valve outlet	circuit diverting valve inlet
diverting circuit	circuit diverting valve outlet	circuit mixing valve inlet
air heating loop	heating coil air outlet	heating coil air inlet
ventilation	supply fan outlet	exhaust fan inlet

An example of group distribution is illustrated in Figure 4.9. This part of the distribution subsystem can be decomposed into two directed acyclic graphs (DAG, or trees), with the inlet/outlet component at the root, and the demand components as leaves. The energy carrier flows from the inlet to the demand components in the supply tree, and from the demand components to the outlet in the return tree.

4.3.1 Group distribution structure requirements

The structure of a group distribution will have to satisfy some general requirements, the consideration of which may guide its creation. These requirements include topological requirements, geometric requirements, modeling requirements and engineering requirements.

Topological requirement

- There should be a unique path from the inlet to each demand component, and from each demand component to the outlet. Indeed, bypass segments are not included in group distributions, but added outside of them at the level of circuits (see Section 4.3.8). This corresponds to having two tree

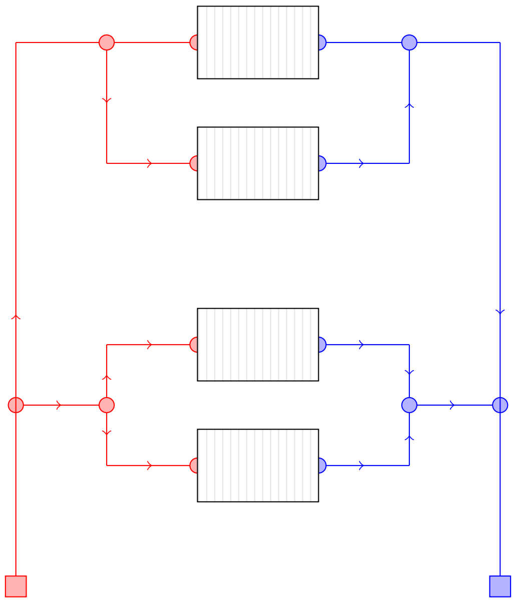


Figure 4.9: Group distribution for four radiators. Supply tree in red. Return tree in blue. Red square: inlet. Blue square: outlet.

structures, for supply (linking the inlet to the demand components) and return (linking the demand components to the outlet).

Modeling requirement

- Each component should be assigned to a unique zone. This is necessary for thermal losses from distribution segments to be modeled later.

Geometric requirements

- GR1: An open polyline geometry should be assigned to each distribution segment.
- GR2: The geometry of a distribution segment should be contained in the solid defined by the zone.
- GR3: The geometry of a distribution segment should remain near the space boundaries of the zone.

These last two requirements are soft requirements. We do not check mathematically that they are met, as the computational effort would be too high. Instead, this can be checked visually.

Engineering requirements

- ER1: Thermal losses to the environment depend on the total exposed surface of distribution segments. Installation costs are often considered to be approximately proportional to the lateral surface of pipes or ducts. Because of the relation between pipe or duct radius and flow rate, direct minimization of this quantity is difficult, but it might be approached from two border cases: If segment diameter is fixed irrespective of flow rate, minimizing total segment exposed surface amounts to minimizing the sum of segment lengths. If segment diameter is proportional to flow rate, or equivalently if segments leading to and from demand components run parallel and separately, minimizing total segment exposed surface amounts to minimizing the segment length between inlet/outlet and each demand component. In real cases, one may consider that segment diameter is a concave increasing function of flow rate - putting aside the fact that actual distribution segment diameter can only assume discrete values - and we may consider the minimum of exposed surface to be reached for some intermediate structure.

- ER2: Pressure drop in the system depends on the most unfavorable path between inlet and outlet through a demand component, which typically corresponds to the maximum path length. Keeping pressure drop low helps to reduce the size, cost and noise levels of pumps or fans, and to limit the amount of energy consumed by these flow moving devices.

- ER3: The minimization of openings through building elements (e.g. walls, ceilings, floors) may be a significant factor to consider when planning a distribution layout.

- ER4: In cases where shaft spaces or plenum spaces are included in the input model, distribution segments should be placed preferably in those spaces.

More local aspects of geometry, such as bends, kinks, enlargements and narrowings, also affect pressure drops and costs. In a first view, these are not explicitly considered. Other possible influences on distribution segment layout not considered in the present work include self-avoidance, avoidance of other building elements and the preference for a rational grid-like structure.

Computational requirements

- The computation of the distribution subsystem should be deterministic, as this is a general requirement for the developed methods.

- In agreement with requirement NFR2 defined in Section 3.2.2, the determination of the distribution subsystem should not be too computationally expensive. In particular, it should not take more time than running a yearly simulation of the corresponding building.

The general requirements to minimize quantities related to total or maximal path length lead to the use of graph-based optimization algorithms to determine the distribution structure of a group distribution. Generative HVAC design with the use of similar optimization methods may have potential in engineering [102]. However, in the present work, optimization is used with the following objectives: (i) meeting the previously mentioned requirements of HVAC design; (ii) leading to realistic values for system properties such as pipe lengths, pipe sizes and pressure drops; (iii) leading to realistic variations of these values for given changes of assumptions and inputs, such as design loads, delivery component type and system temperatures; (iv) general applicability, for any zoned building model; (v) acceptable computational complexity for typical building models. These objectives, along with the graph structure of the HVAC system model, motivate the use of graph-based algorithms with a limited run-time complexity, rather than more complex algorithms with a potential to tackle more ambitious problems. It may also be remarked that we resort to optimization only for the determination of the distribution components. Simultaneous optimization of demand equipment position and distribution configuration could be considered, but it would be computationally more challenging and would disrupt the linearity and traceability of the method.

4.3.2 Overview of method for group distribution model creation

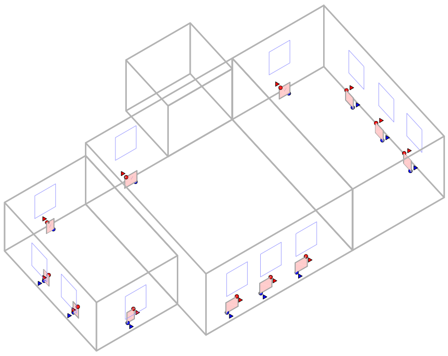
It is proposed to create the distribution components for a *group distribution* along the following steps (Figure 4.10):

1. Determine the network of potential distribution components (NPDC) for supply.
2. Determine the supply tree on this graph.
3. Create the supply distribution components.
4. Determine the network of potential distribution components for return.
5. Determine the return tree.
6. Create the return distribution components.

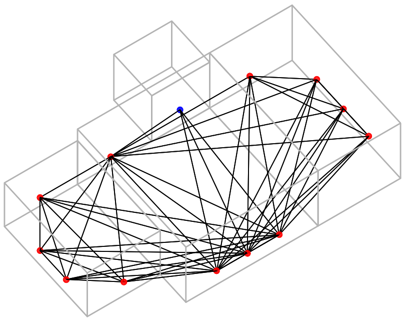
4.3.3 Network of potential distribution components

We introduce the network of potential distribution components (NPDC), a graph $G = (V, E)$ defined in the following way:

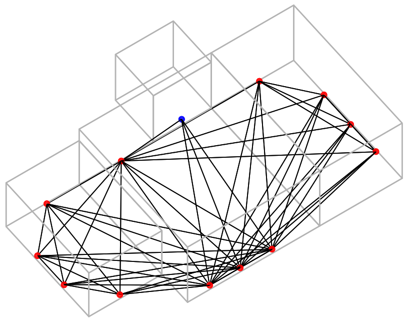
- Nodes V correspond to components (demand components, inlet and outlet), and possibly intermediate nodes. Each node has a three-dimensional position, a zone identifier, and optionally a component identifier. The position of a node corresponding to a demand component is not the position of the component (corresponding to the center of its geometric representation), but rather its (supply or return) connection position. Distinct nodes should have distinct geometric positions.



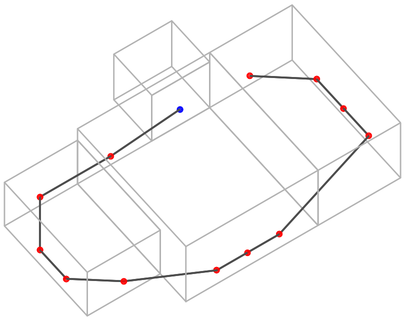
(a) Input: demand component with port locations and connection locations.



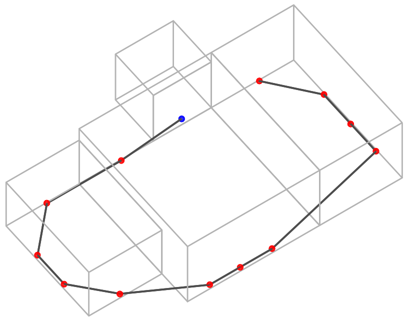
(b) NPDC (supply).



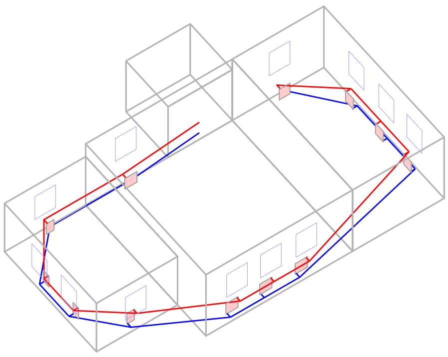
(c) NPDC (return).



(d) Supply tree.



(e) Return tree.



(f) Output: supply and return distribution components linked to demand components.

Figure 4.10: Main steps in the creation of group distribution components for a hydronic heating system.

- Edges E correspond to potential distribution segments. Each edge connects a pair of nodes, and is the only edge for this pair of nodes (the graph is not a multigraph). They are weighted with a distance measure.

Intermediate nodes. Intermediate nodes may be required or useful for several reasons. They can ensure that the network of potential distribution components is connected. Without intermediate nodes, this might not be the case if some zones do not contain any demand component of the corresponding group. They are required in order to meet requirement GR2: to prevent distribution segments from taking illogical routes, such as through the building exterior, or in and out of a zone, which may happen whenever zones are not convex. They make it possible to find networks with a lower total cost, as they make the design space larger.

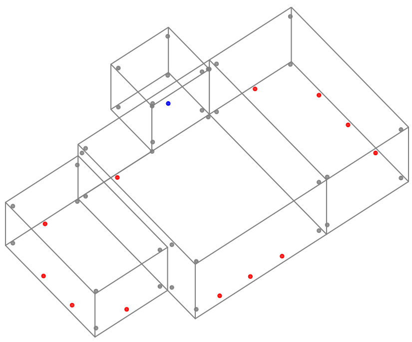
On the other hand, the size of networks grows with the number of intermediate nodes, and so does the computational cost of the used procedures.

We consider two possibilities for the creation of intermediate nodes, based on either space boundary vertices or zone centroids.

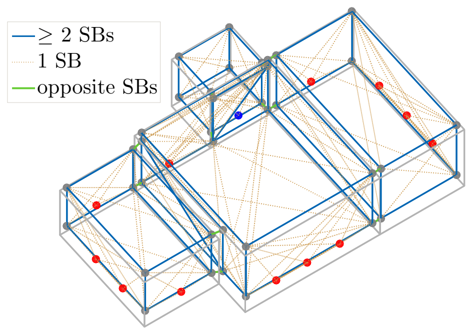
Offset zone space boundary vertices can be used for intermediate nodes. In combination with specific configurations of edges and distances explained below and illustrated in Figure 4.11, these intermediate nodes allow geometrically correct paths to be found along space boundaries. If the building elements have no thickness in the geometrical model, the original vertices of the zone space boundaries are offset towards the zone center, so that nodes in different zones have a different geometric position. The (typically one to three) space boundaries to which each node belongs are kept in memory. Edges are then created between two nodes if they share: (i) two space boundaries or more (in which case they share an edge in the input geometry), or (ii) one space boundary (in the case of rectangular space boundaries this corresponds to a diagonal), or (iii) a pair of space boundaries between adjacent zones. These three types of edges are illustrated in Figure 4.11b. Compared to the definitions proposed in the next paragraph, distances can be defined as higher in the second case (to penalize segments not following an edge) and in the third case (to represent the cost of going through a building element, as in requirement ER3). Edges corresponding to the second case may even be left out altogether, which may substantially reduce the number of edges.

Zone centroids are defined for each zone as the centroid of its space boundary centroids. For convex zones, the centroid is contained in the zone. With non-convex zones, it may lie outside of the zone, which would lead to the geometric requirement not being met. In any case, to meet requirement GR3, the intermediate node should be a projection of the zone centroid on a horizontal plane including other nodes of the same supply or return side.

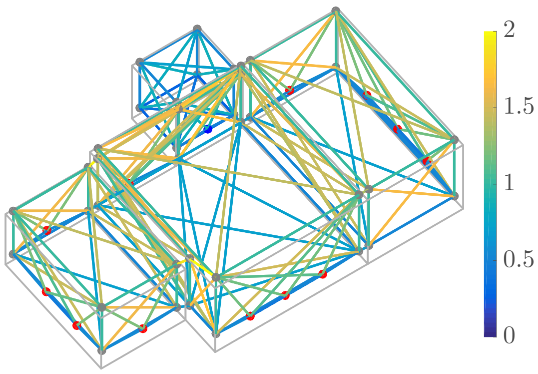
Distances. The weight assigned to an edge in the network of potential distribution components roughly corresponds to the distance between the two nodes. Given two nodes v_1 and v_2 with respective Cartesian coordinates (x_1, y_1, z_1) and (x_2, y_2, z_2), the distance $d_{1,2}$ between them might be defined following Equations 4.2 to 4.4.



(a) Network nodes: inlet (blue), demand component connection (red) and intermediate nodes (gray).



(b) Edge types, according to the space boundaries (SBs) shared by the two edge nodes.



(c) Weighting of edges: edge color scale represents edge weight divided by Euclidean edge length.

Figure 4.11: Network of potential distribution components with intermediate nodes from offset space boundary vertices.

$$d_{1,2} = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2 + a_z(z_1 - z_2)^2} \tag{4.2}$$

A weight a_z on the z-dimension in weighted Euclidean distance 4.2 allows vertical segments to be favored or penalized. A low value of a_z will favor a distribution structure with several risers, while a high value may lead to a single riser.

The Manhattan distance 4.3 may reflect the fact that pipes and ducts are often connected at a right angle. However, it would only really make sense if the coordinate system was aligned on the main or preferred orientation of the building or zone, which is not straightforward to define. The necessity to determine distances between nodes in adjacent zones represents an obstacle to the use of a local coordinate system for each zone.

$$d_{1,2} = |x_1 - x_2| + |y_1 - y_2| + |z_1 - z_2| \tag{4.3}$$

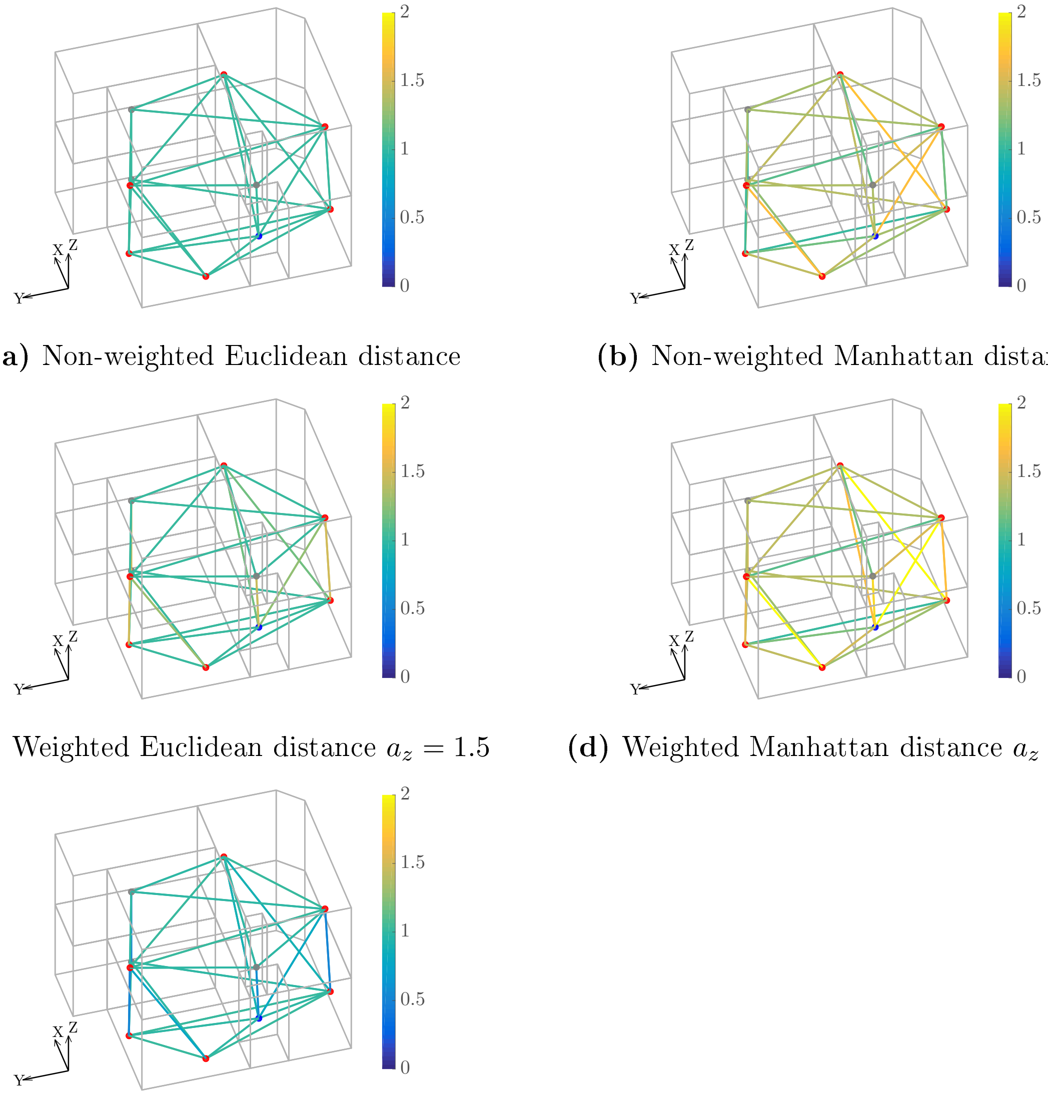
The hybrid distance 4.4 penalizes oblique segments, favoring horizontal segments in any orientation or vertical segments.

$$d_{1,2} = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2} + a_z|z_1 - z_2| \tag{4.4}$$

Figure 4.12 shows how possible connections are favored or penalized by the choice of one of these distance functions. Figure 4.14 shows the resulting minimal spanning trees for two of these distance functions. Not satisfactory in some of these results is the fact that horizontal segments are located on different floors. In fact, the weight of matching segments on different floors is exactly the same, which leads to several minimum spanning trees. A solution to this issue is to assign segments located in distinct floors slightly different weights, for instance by assigning a slightly lower weight to segments in the lowest floor.

The previous distances may also be modified (at the risk of contradicting the triangular inequality) in order to favor segments in or between zones marked as containing technical conduits (*shaft* space use property).

Border points. Furthermore, a border point should be determined between two nodes situated in different zones, since segments between two zones will have to be divided into two components for simulation purposes. The distance between two such nodes may then be taken to be the sum of the two distances to the border point. When zones are not convex, it is not always possible to find a border point such that each distribution segment remains geometrically in its zone, and intermediate points may be required inside of a zone. If both zones are convex, a border point can be found on a space boundary between the two zones, such that each segment remains geometrically in its zone. However, it is not trivial to define the most appropriate border point. A simple choice consists in taking the intersection of the geometrical edge with the plane of a common space boundary pair. However, this intersection may fall outside of the common boundary, as shown in Figure 4.13a. Fortunately, the determination of border points is only an issue in the case of simple networks with few intermediate nodes. In the case of detailed networks with intermediate nodes based on space boundary vertices, as



(a) Non-weighted Euclidean distance

(b) Non-weighted Manhattan distance

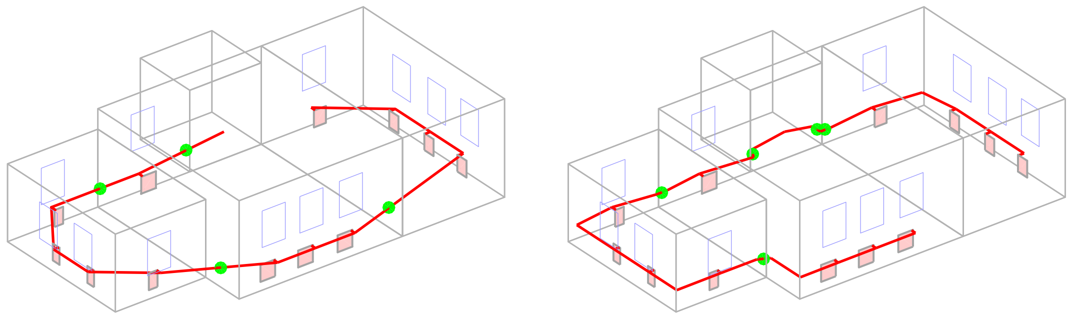
(c) Weighted Euclidean distance $a_z = 1.5$

(d) Weighted Manhattan distance $a_z = 1.5$

(e) Weighted Euclidean distance $a_z = 0.5$

Figure 4.12: Network of potential distribution components (NPDC) with various distance definitions. Zone centroids are used as intermediate nodes. Edge color scale represents edge weight divided by Euclidean edge length.

in Figure 4.13b, edges between different zones are limited to short edges through construction elements, so that taking the middle of each edge is acceptable.



(a) With simple NPDC. **(b)** With detailed NPDC.

Figure 4.13: Border points between zones (in green) in the supply half of a distribution group.

4.3.4 Tree finding algorithm

After determining the network of potential distribution components, supply and return trees are found using one of the following tree finding algorithms, summarized in Table 4.6. These algorithms find trees minimizing the total sum of edge weights or the sum of weights for each path, which corresponds to engineering requirements ER1 and ER2.

Table 4.6: Considered tree finding algorithms. For the cycle algorithm, each cycle spans all nodes of the respective subset of the NPDC nodes, corresponding for instance to a given floor.

Name	Minimized quantity	Constraint on tree
Minimum spanning tree	total sum of weights	tree spanning all nodes
Steiner tree	total sum of weights	tree spanning necessary nodes
Shortest path	sum of weights for path	tree spanning necessary nodes
Cycle	sum of weights for cycle	cycle spanning all nodes
Steiner cycle	sum of weights for cycle	cycle spanning necessary nodes

Minimum spanning tree. Given a graph $G = (V, E)$ and a weight function $w : E \mapsto \mathbb{R}^+$, the minimum spanning tree (MST) problem [162] consists in finding a spanning tree $(V, T \subseteq E)$ of G with the minimal weight $w(T) = \sum_{e \in T} w(e)$. We take this graph to be the network of potential distribution components defined in the previous section, with V its nodes, E its edges, and their weights w. The resulting spanning tree is in itself not directed, but it can become univocally directed if we fix the root node $v_0 \in V$ as the inlet (or outlet) of the NPDC. As the obtained tree spans all nodes in V, including intermediate nodes, it may contained unnecessary edges, defined as those edges having only intermediate nodes downstream of them. These edges are subsequently identified and deleted, as illustrated in Figure 4.15.

(a) Non-weighted Euclidean distance **(b)** Weighted Euclidean distance $a_z = 1.5$

Figure 4.14: Minimal spanning trees obtained with two edge weight definitions varying in the z-weighting.

Steiner tree problem. Considering the fact that intermediate nodes do not actually need to be spanned by the distribution network, one can formulate the problem as a Steiner tree problem. Given a graph $G = (V, E)$ and a weight function w as above, as well as a subset S of V, the problem consists in finding a tree of minimal weight spanning all nodes in S. The subset S would correspond to the required nodes, which are the non-intermediate nodes. Unlike other versions of the Steiner tree problem such as the Euclidean Steiner tree, the set of possible nodes V is fixed and finite. Still, this Steiner problem is NP-hard, so considerably more expensive to solve exactly than the minimum spanning tree problem [163]. An algorithm for finding Steiner trees has not been implemented in the present work. Instead, we use the suboptimal approximation of finding a minimum spanning tree and deleting unnecessary edges afterwards.

Shortest path. An alternative approach consists in finding the shortest path (SP) between the inlet/outlet and each demand component. The base network is defined in the same way as above. The supply tree is made of the union of shortest paths from the origin to delivery components. With the same definition of $G = (V, E)$ as before, the shortest path tree is a tree $(V, T \subseteq E)$ such that for each $v_i \in V$ the weight of the path from the root v_0 to v_i is minimum.

Return tree. With the options above, the return side might be obtained in two ways, either by copying the supply-side tree and inverting vertex direction (and offsetting or modifying locations), or by using the same algorithm as for the supply side (with return locations instead of supply locations). The first possibility presents the advantage of sparing a second run of the minimum spanning tree algorithm, and of always having parallel supply and return components. Conversely, the second possibility may accommodate more complex or asymmetrical

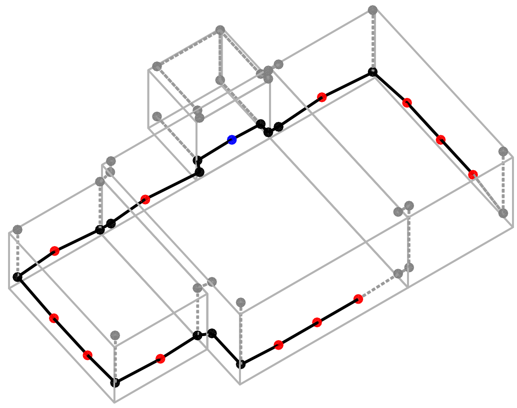


Figure 4.15: Minimum spanning tree for the NPDC illustrated in Figure 4.11. Unnecessary (subsequently deleted) edges are displayed as gray dotted lines.

distributions, including air distribution networks, where inlet and outlet may lie far apart.

Ring layout. Sometimes, piping or ductwork has (at least locally or at the floor level) a ring-like structure. Such cases can be modeled by solving a traveling salesman problem.

For a graph $G = (V, E)$ and a weight function w defined as above, the traveling salesman problem (TSP) [164] consists in finding a path visiting each vertex in V exactly once (Hamiltonian circuit) in such a way that the sum of weights on this path is minimized. As above with the minimum spanning tree and Steiner tree problems, we are also interested in a variant of the TSP called Steiner traveling salesman problem (STSP) [164] in which only some required nodes $S \subseteq V$ must be visited.

A cycle obtained with TSP or STSP may be used to create one-pipe distributions or two-pipe distributions with reverse return, as opposed to two-pipe distributions with direct return as have been assumed above. Two-pipe distributions with reverse return (also called Tichelmann system) are a type of distribution layout in which the sum of supply and return lengths is the same for all components, which makes hydronic balancing easier [165, p.1277]. The determination of these ring-like layouts differs from the previously considered options in two respects. An important conceptual difference is that a hierarchy has to be introduced between nodes. Secondly, the return tree cannot be computed independently. Instead, it is derived from the supply tree (Tichelmann), or it is not to be distinguished from the supply tree (one-pipe distribution). However, the result still consists of one or two tree structures, on which the later steps of the methods can be applied similarly.

One may create a two-pipe distribution with reverse return (Tichelmann) with the following steps (Figure 4.16):

1. Create the network of potential distribution components for the supply side.
2. Divide the building in n groups of zones $g_0, g_1, ..., g_n$, each of which should

be supplied by one ring-like structure. A simple division corresponds to building floors, in which case there will be a unique riser linking the ring structures. Arrange these groups of zones on a tree structure. In the case of building floors, the tree structure will be a directed path where each floor is linked to the adjacent floors (in ascending direction, assuming technical rooms are located on the lowest floor).

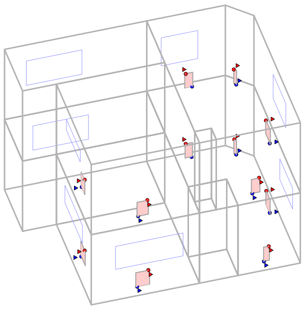
3. For each zone group g_i, get the corresponding nodes V_{g_i} and define the root node $r_i \in V_{g_i}$ of the group. Typically, the root node of the group is located in a zone through which a riser pipe segment runs (e.g. *shaft* space use). Get the subgraph $G_{g_i} = (V_{g_i}, E_{g_i})$.
4. For each zone group, solve the Steiner traveling salesman problem on subgraph G_{g_i}. If there are only few intermediate nodes, as in the case of Figure 4.16, the standard TSP may also be used. The result can be written as a directed path on nodes V_{g_i} beginning with r_{g_i}: $P_i = (v_{g_i,1} = r_i, v_{g_i,2}, ..., v_{g_i,|P_i|})$.
5. Create the supply tree by linking the directed paths $P_1, ..., P_n$ created for each group through their root nodes, according to the group-tree structure.
6. Create the return tree in a similar way, but changing the direction of paths for each group, still starting from the root node:
$(v_{g_i,1} = r_i, v_{g_i,|P_i|}, v_{g_i,|P_i|-1}, ..., v_{g_i,2})$
7. Create and size distribution components as in other cases.

4.3.5 Creation of distribution components

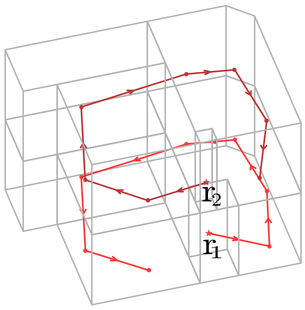
With this section, we create the actual distribution components. The outcome of this step is a group of distribution and delivery components (GDDC), in which the newly created distribution components are linked to already determined delivery components. These components of both types can be seen as the nodes of a network of HVAC components. This network should be distinguished from the NPDC and its tree subsets on which the previous steps have focused. A significant difference is the fact that distribution segments, which correspond to edges in the NPDC, become nodes in the resulting network, since they correspond to components modeled on their own. The rules governing component creation, illustrated in Figure 4.17, can thus be seen as graph transformation rules from supply and return trees (subgraphs of the respective NPDCs) to the network defined by distribution and delivery components as nodes and outlet/inlet relations as edges. The following rules are applied to nodes and edges of supply and return trees:

- Supply (and return) tree nodes are transformed into distribution components with a point-like geometric representation. These components are either valves or turn components, according to the following rule. Let v be a node, $n_{c,v}$ the number of its children in the tree to transform, and

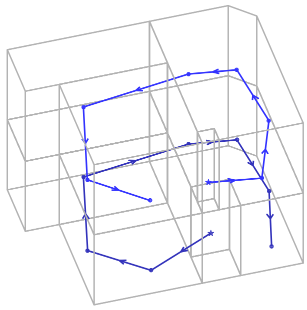
$$d_v = \begin{cases} 1 & \text{if a demand component is associated to } v \\ 0 & \text{otherwise.} \end{cases}$$



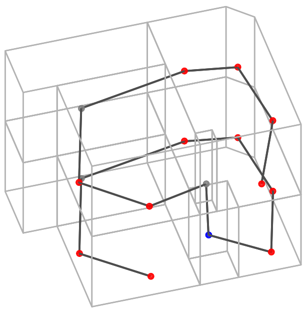
(a) Input: delivery components with connection nodes.



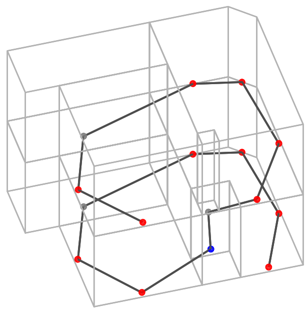
(b) Floorwise paths (supply).



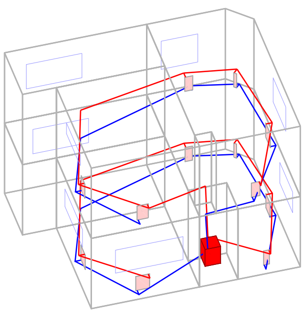
(c) Floorwise paths (return).



(d) Supply tree.

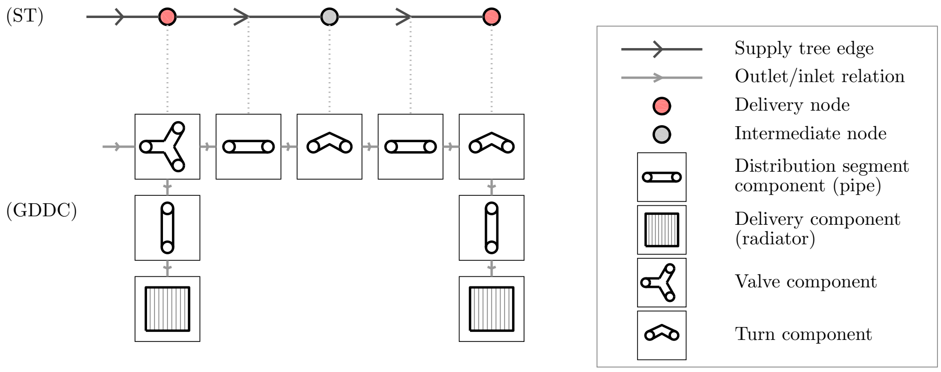


(e) Return tree.

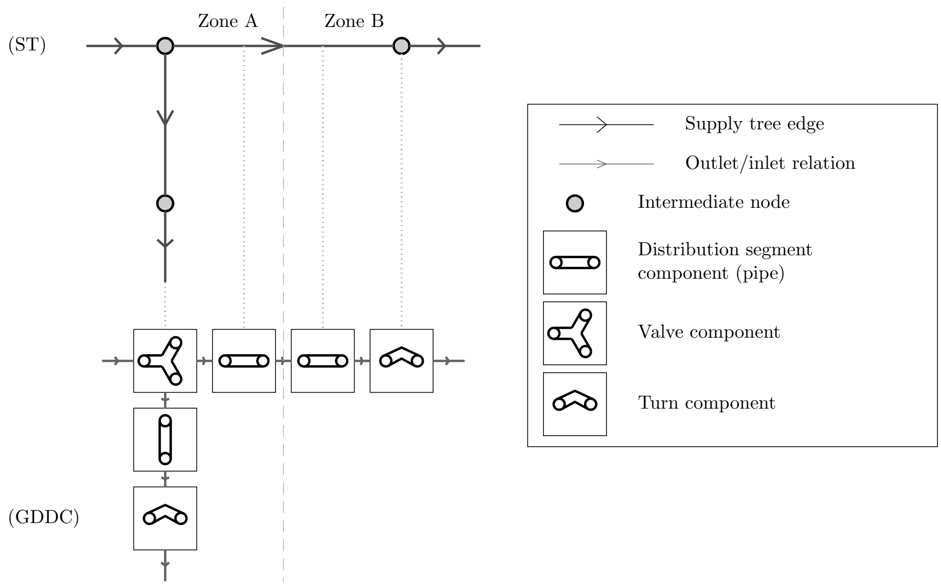


(f) Resulting distribution structure.

Figure 4.16: Model creation steps for a floorwise double-pipe distribution with reverse return (Tichelmann). r_1 and r_2 are the respective roots of the zone groups corresponding to first and second floor.



(a) Transformation of supply tree portion with a leaf (ST) to distribution and delivery components.



(b) Transformation of supply tree portion (ST) to distribution and delivery components situated in adjacent zones.

Figure 4.17: Transformation from supply tree (ST) to group of distribution and delivery components (GDDC).

Node v is transformed into a valve component if and only if $n_{c,v} + d_v \geq 2$ (e.g. upper left node in Figure 4.17b). Otherwise, it is transformed into a turn component (e.g. middle node in Figure 4.17a).

- For delivery nodes, a distribution segment component is created and added between the valve or turn component (geometrically at the delivery component connection point) and the actual delivery component. The purpose of this connection distribution component, which is generally very short, is to consistently have a distribution segment between two punctual components, and to obtain a model that is visually similar to real distribution subsystems. It may be superfluous in the case of air distribution, where air diffusers are often directly integrated in ducts distributing air to several terminals.

- Edges of the supply and return trees are transformed into distribution segments with a length property. An edge is transformed into one distribution component if the two nodes are in the same zone, or into two components if the two nodes are in adjacent zones.

These rules can be applied as well for the supply side as for the return side, where valves are diverting valves and mixing valves, respectively, and the flow direction varies, either from the vertex to its children for supply, or from the vertex to its parent for return. The same rules are also applied for water and for air loops, whereby the component types differ (pipes and ducts, water valves and air valves).

The distribution segment components are instantiated with given length, position and flow direction information, but they are not sized yet at this point.

4.3.6 Distribution segment sizing

The simplest case for distribution segment sizing is when maximum loads for all demand components are simultaneous. In this case, the maximum flow rate through a supply (return) component is equal to the sum of maximum flow rates through the demand components downstream (upstream) of it. Determining these can be done recursively, beginning with demand components, as in Equations 4.5 and 4.6. For a component with index c, the set $dc(c)$ of demand components downstream of c is

$$dc(c) = \cup_{k \in o_c} dc(k) \tag{4.5}$$

where o_c are the indices of components at the outlet of c. The mass flow rate $\dot{m}_c$ through c is

$$\dot{m}_c = \sum_{k \in o_c} \dot{m}_k = \sum_{d \in dc(c)} \dot{m}_d \tag{4.6}$$

where the mass flow rates through demand components $\{\dot{m}_d\}_{d \in dc(c)}$ are known. Knowing which delivery components are downstream of valve components is also useful for controlling the latter.

In the case where maximum loads for all demand components are not simultaneous, the summing rule still applies to instantaneous flow rates, but not to maximum flow rates. One can calculate instantaneous flow rates through a component at several critical times, and select the maximum thereof.

The determination of pipe or duct diameters depends on a variety of parameters, the main physical criteria being related to maximum pressure gradient and maximum water velocity. The maximum pressure gradient (decreasing with diameter) has a direct impact on the energy used by the flow moving device to circulate the loop medium. High water velocity increases flow noise, but too low velocity increases the warm-up time [161, p.987]. Pipe dimensioning mainly results from a compromise between investment costs (rising with diameter) and pump energy use [166, p.30].

Table 4.7: Proposed criteria for pipe dimensioning, applicable to pressure drop (R_{max}) and water velocity (ν_{min} and ν_{max}).

Source	**Pipe type**	R_{max}	ν_{max}	ν_{min}
VDI 2073 [166, p.30]				
	connecting pipes	100 to 150 Pa/m	0.7 m/s	
	branch pipes	100 to 150 Pa/m	0.7 m/s	
	riser pipes	200 Pa/m	1.0 m/s	
	main distribution	200 Pa/m	1.0 m/s	
[161, p.987-988]				
	main distribution		1.0 m/s	0.3 m/s
	traditional values	80 to 200 Pa/m		
	newer values	20 to 50 Pa/m		

Several methods are thus conceivable for the determination of pipe section diameters in our framework for automated HVAC system model creation, with increasing complexity: (i) assumption of a default value independent of water flow rate, based on pipe type and possibly building area (e.g. ÖNORM H 5056 [167]); (ii) use of a tabulated value depending on water flow rate and pipe type, e.g. from tables in guidelines VDI 2073 [166, p.31-32], derived from criteria of pressure drop and velocity; (iii) iterative finding of a value satisfying given criteria at best.

Figure 4.18 illustrates how tabulated values can be used in the context of the proposed model creation procedures. Note that the appropriate table should be used, depending on pipe material and pipe location. The latter determines the acceptable level of flow noise and thus the allowed velocity.

A more detailed and flexible way of sizing distribution segments is illustrated in Figure 4.19. It involves possible iterations, in which the diameter is modified until criteria for both pressure gradient and maximal velocity are satisfied. Still, sizing each segment separately represents an approximation, as total pressure drops along each path would have to be considered for pressure balancing and optimal sizing.

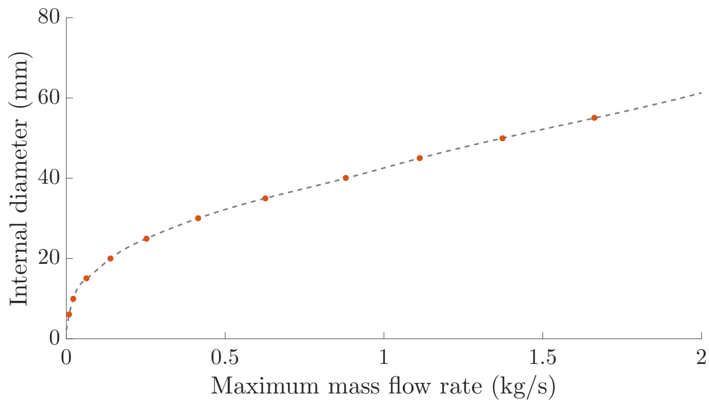


Figure 4.18: Pipe internal diameter as a function of maximum mass flow rate, for smooth pipes: standard values at discrete mass flow rates from VDI 2073 and interpolation.

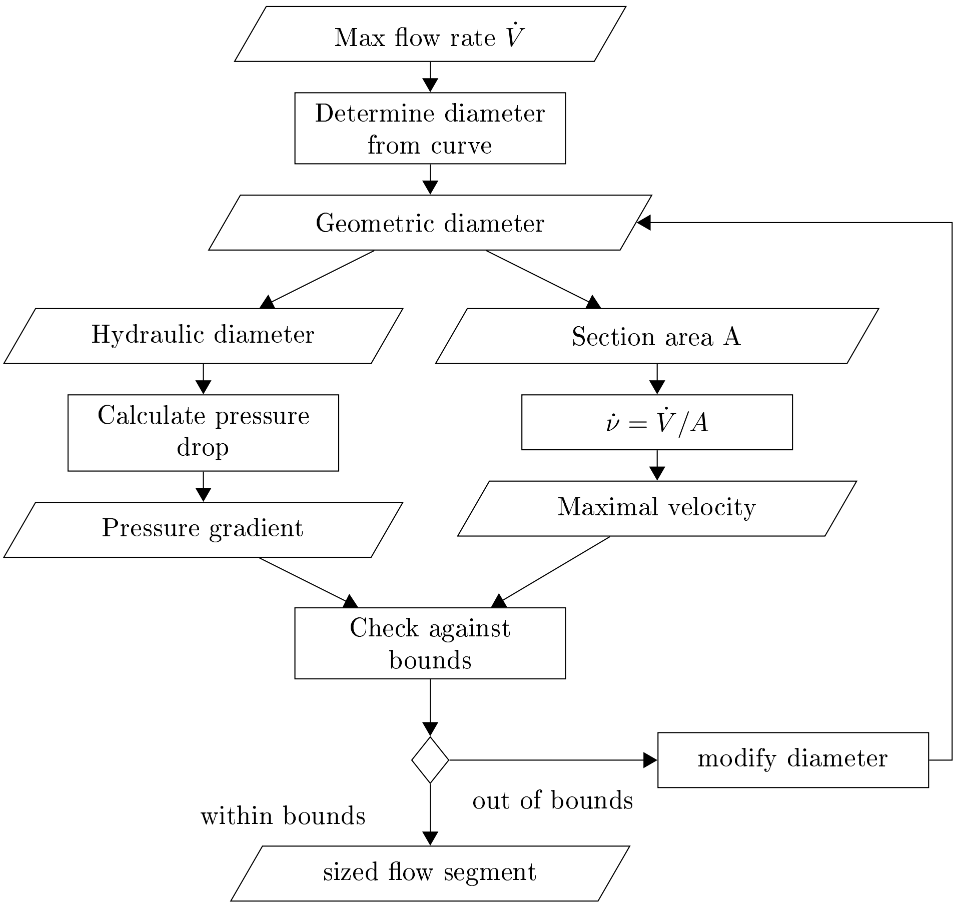


Figure 4.19: Sizing workflow for a distribution segment, inspired by VDI 2073 [166].

4.3.7 Distribution model simplification

The models of distribution subsystems obtained with the procedures presented above may turn out to be too complex for the intended purposes. The high number of components may be counterproductive, by slowing down simulation and making the model difficult to check. What is more, the model structure, with several levels of diverting and mixing valves, cannot be used in one of the target simulation tools (EnergyPlus). The following paragraphs present ways of simplifying these models while attempting to preserve system properties.

Determination of equivalent distribution segment. By merging distribution segments, we mean replacing several distribution segments by a single potentially *equivalent* component.For a set of n distribution segments, the characteristics of the equivalent segment component can be defined in the following way:

- Length l_{eq} is equal to the sum of lengths $l_{eq} = \sum_{i=0}^{n} l_i$.
- Diameter D_{eq} such that the lateral surface area $\pi\ D_{eq}\ l_{eq}$ is equal to the sum of lateral surfaces areas, so $D_{eq} = \frac{\sum_{i=0}^{n} D_i\ l_i}{l_{eq}}$.
- Construction U-value such that the total loss factor is equal to the sum of component loss factors $\pi\ D_i\ l_i\ U_i$. A new construction with an insulation factor corresponding to this equivalent U-value is determined.

Choosing to keep the total lateral surface area equal implies that the total volume may change, as keeping it constant would amount to choosing $D_{eq,vol} = \sqrt{\frac{\sum_{i=0}^{n} D_i^2\ l_i}{l_{eq}}}$, which is usually different from D_{eq}.

Merging of consecutive distribution segments. It seems justified to merge consecutive distribution segments into a single component, as the fluid in these segments is bound to present similar temperature conditions, as long as heat losses to the environment are not too high. Differences to the original model are, physically, a slightly different fluid volume, as mentioned in the previous paragraph, and computationally a coarser discretization of the pipe and fluid. Groups of consecutive distribution segments that can be merged this way are illustrated in Figure 4.20.

Merging of zone distribution segments. The simplification may be pushed further, so as to retain only one level of branching, while trying to modify global system characteristics as little as possible. This structure simplification is required for detailed HVAC simulation in EnergyPlus. It affects primarily distribution segments, that is pipes and ducts. Although it would apply to any type of distribution segment, the following description is made for pipes. We distinguish two types of segment, according to whether they are located in a zone with a delivery component or not. Several segments of the first type are merged into one component when they: (i) belong to the same group; (ii) are located in the same zone, in

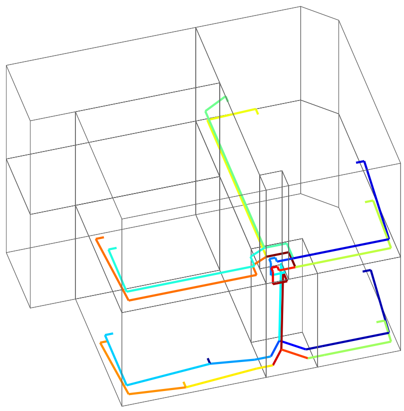


Figure 4.20: Groups of consecutive pipes to be merged, represented with one color per group.

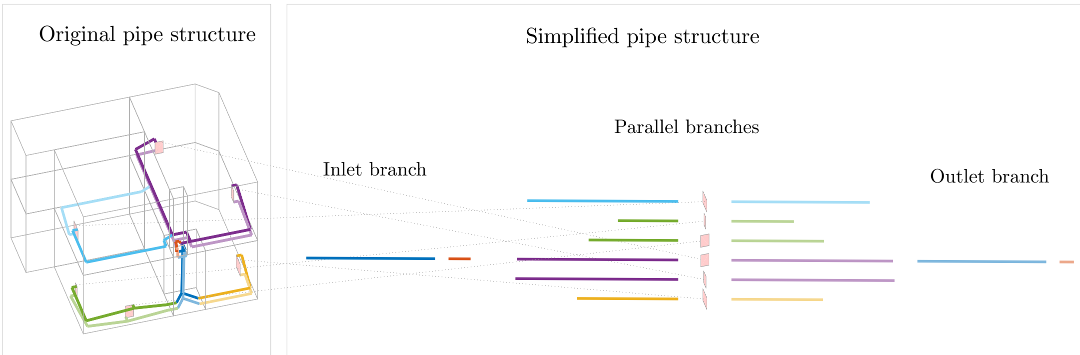


Figure 4.21: Comparison of original pipe structure (left) and simplified pipe structure after merging of zone distribution segments (right). Pipes are colored according to their containing zone, with a lighter shade for return pipes as compared to supply pipes. The simplified structure cannot be represented in the spatial context of the building.

which a delivery component is also present; (iii) are on the same side of the delivery component (either supply or return). This ensures merged pipes have similar temperatures. Indeed temperature differences between the original pipes and the merged pipes may result from differing heat losses due to the configuration, but not from heat delivery, which changes temperature more abruptly. Depending on its supply/return position, the equivalent component is inserted in the model before or after the delivery component that belongs to the same group and zone. If there are several delivery components in one zone, an equivalent pipe component may be attributed to each delivery component, with a length ratio corresponding to the capacity ratio of delivery components.

Pipes located in zones with no delivery components (typically non-conditioned zones) are to be treated differently. They cannot be assigned to a parallel branch corresponding to a delivery component. As a consequence, the easiest way to account for them is to place equivalent components in the inlet or outlet branch, according to whether they are supply or return pipes. These equivalent components for the different non-delivery zones are placed in series. Figure 4.21 illustrates this model simplification with pipes from non-delivery zones placed in series in inlet and outlet branches, and pipes from delivery zones placed in parallel branches on each side of the delivery components.

Whether one of these simplification procedures is applied or not, the next step is to embed distribution groups in circuits.

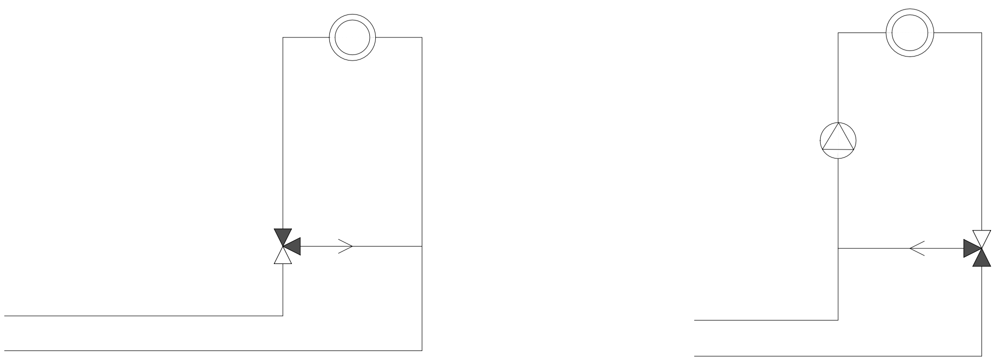
4.3.8 Circuits and flow moving devices

The group distributions, the creation of which is described above, finally have to be completed with eventual bypass sections and flow moving devices to obtain circuits. Different circuits vary the amount of energy distributed to a group of demand components by, either, varying the flow rate in the demand side at a constant temperature, or varying the supply temperature to the demand side with a constant flow rate, or varying both flow rate and supply temperature [166].

The following discussion is limited to hydraulic circuits. Varying the temperature supplied to the consumer side of the circuit (mixing and injection circuits) requires a bypass pipe and a circuit pump allowing more or less return water to be mixed back. Conversely, the fluid in throttling and diverting circuits is circulated by the main pump.

Table 4.8: Basic types of hydraulic circuits and their characteristics [168]. The return temperature information is meant particularly at partial load.

	Throttling	**Diverting**	**Mixing**	**Injection**
consumer flow rate	variable	variable	constant	constant
source flow rate	variable	constant	variable	constant
consumer supply temperature	constant	constant	variable	variable
return temperature	rather low	high	high	rather high



(a) Diverting circuit

(b) Mixing circuit

Figure 4.22: Diagrams for two types of hydraulic circuits.

Flow moving device selection and sizing generally depends on two main criteria: maximal flow rate ($\dot{V}$ in m^3/s), and maximal pressure drop (Δp in Pa). The maximal pressure drop on the demand side is calculated at the level of a group distribution. For main pumps, one should add the pressure drops on the source side, typically from main distribution pipes and generation equipment.

4.4 Determination of the generation subsystem

The generation subsystem does not generate energy in the physical sense. Rather, it converts energy from an energy carrier into a form of energy than can be distributed and delivered to the building spaces. This energy provided by the generation subsystem thus has to cover the sum of energy demands from the various delivery components, in addition to potential distribution losses.

We start by presenting different types of generation components, and the characteristics that are relevant for building performance simulation. This is followed by a discussion of how one or several generation components can be sized in order to obtain an appropriate generation subsystem. Finally, the possibility of a storage subsystem is presented.

4.4.1 Generation components

Overview of generation components. As already mentioned, generation components in HVAC systems are energy converters. Table 4.9 accordingly summarizes some of the main classes of HVAC generation components with regard to the types of energy they use and produce. HVAC applications obviously require the supply of energy in the form of heat and cold. Electricity is also needed for various purposes, mostly as auxiliary energy used in flow moving, measurement and control devices.

Table 4.9: Classes of generation components based on used energy and produced energy.

<table>
<tr><th>To / From</th><th>Heat</th><th>Cold</th><th>Electricity</th></tr>
<tr><td rowspan="2">Fuel</td><td>boilers</td><td></td><td></td></tr>
<tr><td colspan="3">co-generation</td></tr>
<tr><td>Electrical</td><td>resistance heating
heat pump</td><td>compression chiller</td><td></td></tr>
<tr><td>Solar</td><td>solar collectors</td><td></td><td>photovoltaics</td></tr>
<tr><td>Heat</td><td>direct use</td><td>desiccant wheel</td><td>sorption heat pump</td></tr>
<tr><td>Cold</td><td></td><td>direct use</td><td></td></tr>
</table>

Fuels may be separated into fossil fuels (natural gas, oil, coal) and biomass (primarily wood products and biogas). With cogeneration, also referred to as combined heat and power (CHP), thermal energy and electricity are produced simultaneously, at efficiency levels significantly higher than those reached with separate production [169]. Temperature plays an important role in the quality of thermal energy and its potential for use. The “direct use” of heat and cold usually implies some sort of heat exchanger. Waste heat from various sources can be used for heating. In particular, air heat recovery allows part of the thermal energy present in exhaust air to be recovered.

One can make a further distinction between generation components according to the medium to which heat or cold is supplied. In the following, we mostly focus on water-based generation components, that is those using energy in order to heat or cool water. Air heaters (furnaces) have the disadvantage that air is a much less efficient thermal energy carrier than water. They are practically not used in Europe.

Boilers. Burning fuels in boilers is still the predominant way of making thermal energy available for heating systems. Boilers may differ in various aspects, including their fuel type, size, type and material of construction, and operation mode [165, p.921]. With regard to the intended operation of boilers, which plays a particularly important role for the modeling of their performance, one can distinguish standard (high-temperature), low-temperature and condensing boilers [170]. Water temperature in standard boilers is restricted by design, and condensation of the exhaust water vapor should be avoided, whereas it is possible in low-temperature boilers. In condensing boilers, condensation is explicitly pursued, as it allows the latent energy of the released vapor to be used, which can result in efficiency gains in the order of 10%.

Renewable energy generation. Renewable energy is called to play an increasingly important role in the energy supply of industrialized countries. In the context of buildings, the urge to use renewable sources of energy is particularly obvious with the concept of zero energy building (ZEB). Even though several definitions exist for ZEB, a common principle is to meet reduced energy needs with renewable energy generation, which can take place on-site or off-site. Off-site renewable generation may play a role in building operation in that the availability and cost of energy may vary with time, calling for demand response approaches. However, modeling on-site generation is a more immediate challenge for building performance simulation. Renewable energy sources relevant for direct use in buildings are primarily solar energy and ambient thermal energy.

Solar thermal collectors can be used for domestic hot water (DHW) and space heating. Because of the divergent annual courses of solar thermal supply and space heating demand, the use of solar thermal technology for space heating is limited to a supporting role in combination with DHW. Covering more than 30% of the yearly space heating demand with solar thermal energy is not considered to be profitable [165, p.1070]. Photovoltaic (PV) systems transform light into electricity. They may be integrated in buildings to various degrees, from freestanding over rooftop systems, up to the incorporation into the building envelope. Orientation and shading are significant factors for all solar energy technologies.

Several technologies also allow solar energy to be used for cooling.

Heat pumps. A heat pump makes thermal energy present in the environment useful for heating by bringing it to a higher temperature level, thus transferring thermal energy from a colder to a warmer place. In typical vapor-compression heat pumps, this is achieved with a cycle in which a fluid (refrigerant) absorbs heat from a heat source by evaporating, and later releases this heat into a heat sink by condensing. This requires the use of some auxiliary energy, for instance in the form of compressor power in a traditional compression heat pump as illustrated in Figure 4.23. This inversion of the spontaneous direction of heat transfer can also be used for cooling.

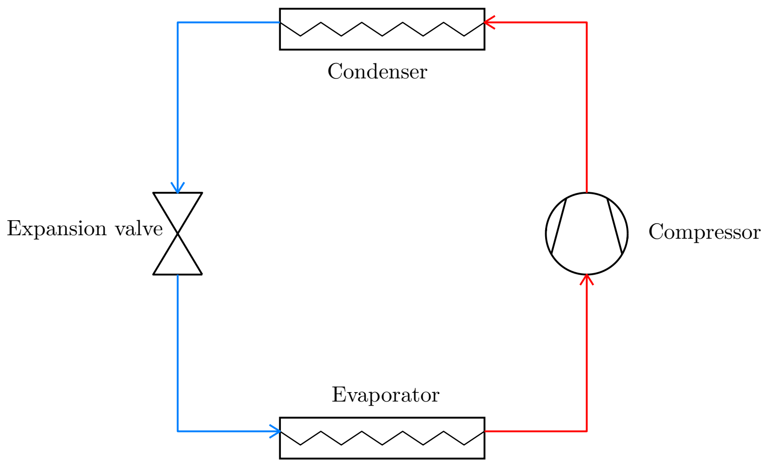


Figure 4.23: Principle diagram of a compression heat pump.

The most common heat sources to which heat pump evaporators can be connected are found in outside air, ground (geothermal energy) as well as groundwater and river water. The number of installed heat pumps has been rising sharply in the last year, and it is predicted to continue to do so. The share of air-water heat pumps is increasing, and is expected to replace ground-source heat pumps as the most frequent type in Germany [171]. In Austria, it is already the most frequent type [172, p.168].

A majority of cooling generation equipment is based on the heat pump technology. Reversible heat pumps can be used for heating and cooling alternatively.

Performance curves. At the level of detail relevant for the present work, the behavior of generation components will generally not be modeled according to physical first principles, but characterized by empirically derived performance curves.

These performance curves can be provided by manufacturers. Information in graphical or tabular form may require some transformation. Some are also available in libraries for use with simulation tools, avoiding the need to translate them.

The exchange of performance data for simulation purposes is still a challenging task, currently addressed by ASHRAE Standard Project Committee 205 [173].

Boiler efficiency depends mainly on part load ratio and input temperature (return temperature of the heating loop). Part load ratio is defined as the ratio of the instantaneous heat load to the design heat load. Figures 4.24 and 4.25 show examples of performance curves for two types of boilers. Figure 4.24 reflects the particularity of condensing boilers that their efficiency is higher for lower return temperatures. Figure 4.25 shows the strong dependence of wood pellet boiler efficiency on part load ratio [174].

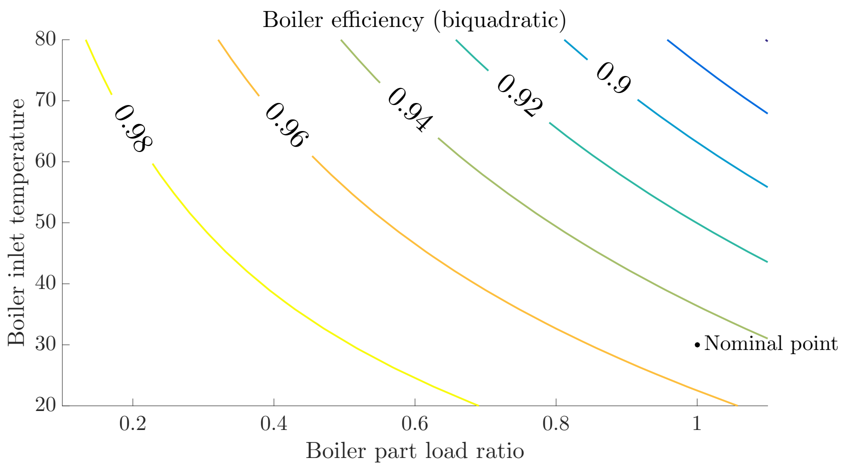


Figure 4.24: Gas condensing boiler efficiency as a function of part load ratio and inlet temperature ($°C$).

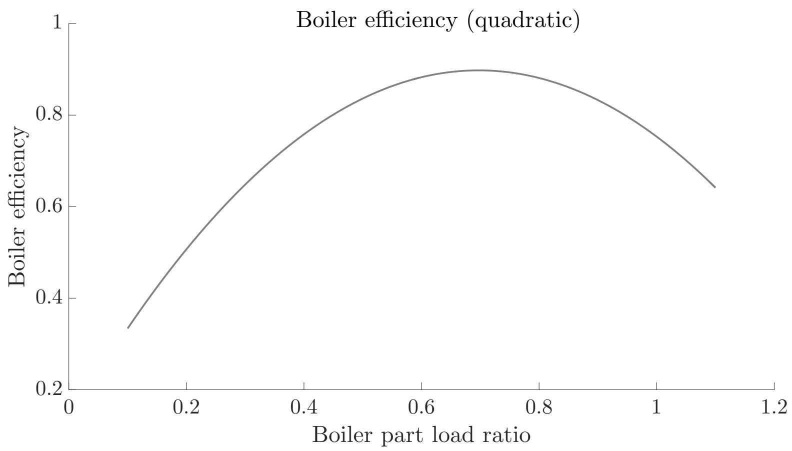


Figure 4.25: Wood pellet boiler efficiency as a function of part load ratio.

The limitation to polynomials of low order (bi-quadratic curves for boilers in EnergyPlus) may be an obstacle to modeling exact performance. For instance, the typical efficiency of condensing boilers as a function of inlet water temperature has a curvature discontinuity at the limit between condensing mode and non-condensing mode [12, p.507].

The efficiency of heat pumps (for heating) increases with higher source temperatures and decreases with higher demand temperatures, hence the advantage of combining a heat pump with a low temperature delivery subsystem.

The capacity of heat pumps depends on the conditions at which they are operated. The nominal (or rated) capacity of a heat pump is defined for nominal conditions which may differ from the design conditions for which the heat pump is to be sized. Thus, we start by fixing the design capacity (as for other generation capacity), and then determine a nominal capacity corresponding to this design capacity at design conditions.

Generation component selection. Criteria for the selection of generation components include the loads to meet, the availability and cost of energy sources at the building location, space requirements, and the interplay with other HVAC subsystems. Supply temperatures are an essential factor for the latter aspect. For heating, the outlet temperature of the generation subsystem should be greater than or equal to the supply temperature of all distribution circuits. Conversely, for cooling systems, the generation outlet temperature should be lower than the supply temperatures of distribution. Since each type of generation component can only supply water within a certain temperature range, the preceding definition of delivery and distribution subsystems constrains the choice of generation components.

4.4.2 Generation subsystem sizing

Based on the previous criteria, components can be selected and sized to form the generation subsystem.

Generation subsystems with multiple components. In the simplest case, the generation subsystem of a central HVAC system may consist of a single generation component. However, several considerations may make it desirable to combine multiple generation components. Planning and controling systems with multiple boilers in an optimal way is considered to be a demanding task [175, p.29]. Some of the challenges are to operate each component at a load ratio for which it is efficient, while avoiding cycling and ensuring stable supply temperatures.

Planning and control strategies should take into account the fact that some component types (e.g. traditional boilers) are more efficient near full load, others (e.g. condensing boiler) in the partial load range. For systems known to work at part load most of the time, one may use a generation component of the former kind for base load, working closer to its peak load than a single component sized for the total design heat load, and another component providing for the residual load when needed. Multiple components may be connected in series or in parallel. The latter is generally preferred [175].

The capacity and efficiency of an air-source heat pump strongly depends on air temperature. By combining it with another generation possibility, one can limit its operation in unfavorable conditions, and reduce investment costs as compared to a monovalent system sized for the lowest air temperatures. In bivalent systems, the heat pump meets the whole heat demand as long as air temperature remains above a certain limit, the bivalent temperature. Below this temperature, the heat pump either switches off (bivalent alternative operation) or continues working alongside a supplementary component (bivalent parallel operation) [165, p.1027].

Sizing. Sizing the generation subsystem implies the determination of a total capacity and, if applicable, its allocation to multiple components.

The size of a hydraulic generation component can be defined with its maximum water volume flow rate $\dot{V}_{max}$ and the design temperature difference between inlet and outlet, from which its maximum heat capacity $\dot{Q}_{max}$ follows according to $\dot{Q}_{max} = \dot{V}_{max}\ c_{p,water}\ (\theta_{out,design} - \theta_{in,design})$.

The flow rate in the generation subsystem may be coupled to that in the distribution subsystem, or not [166]. In the first case, $\dot{V}_{max}$ can be obtained by summing the maximum water flow rates for the distribution circuits. In case of circuits with fixed remixed or diverted fractions, this might differ from the sum of maximum water flow rates for the delivery components. For heating systems, $\dot{Q}_{max}$ can be related to the sum of delivery component capacities, with the addition of a factor accounting for distribution losses. A higher bound to these losses can be calculated from the available distribution subsystem model. However, one needs to evaluate the (typically high) proportion of these potential losses that may be reused to heat the rooms and thus need not be taken into account for the sizing of generation components.

As opposed to heating, cooling loads may not have their peak at the same time in all zones. To avoid oversizing, this load diversity should be taken into account for the sizing of chiller equipment.

Until here, each subsystem of the generation subsystem capable of converting energy into the required form on its own is modeled as a generation component. Ground source heat pumps represent an exception to this approach, as simulation tools model the actual heat pump and the ground heat exchanger as two components. In a first step, we consider a macro-component including both heat pump and heat exchanger. This makes the selection of a ground-source heat pump compatible with the selection of other types of generation components, notably in terms of connection with other subsystems. In a second step, the macro-component is split into its two components, according to the simulation model. The sizing of ground heat exchangers should take into account ground thermal properties (which are subject to local variations) and annual load distribution. One should make sure that ground heat can be regenerated over the years [176].

Spatial aspects. The ASHRAE handbook [12, 1.6] sees in space requirements for mechanical and electrical systems an important aspect of integrated building design, and estimates them to between 4% and 9% of gross building area. Primary equipment rooms housing generation components and pumps represent an important part thereof. One can estimate the space requirements of a generation subsystem according to its type and capacity, e.g. [177].

Since, in the present approach, the building model is an input, one can only compare available spaces to estimated requirements. The potential mechanical rooms are expected to be identified in the input model. What is more, their position is used for the determination of inlet and outlet nodes of the distribution subsystem.

4.4.3 Storage

Storage can be considered as a part of the generation subsystem, in particular when storage is physically incorporated in a generation component. It can also be considered as a fourth subsystem distinct from generation, allowing generation and delivery energy rates to be decoupled to a certain extent. Storage allows to smooth demand peaks, or to generate energy when it is the most efficient or available.

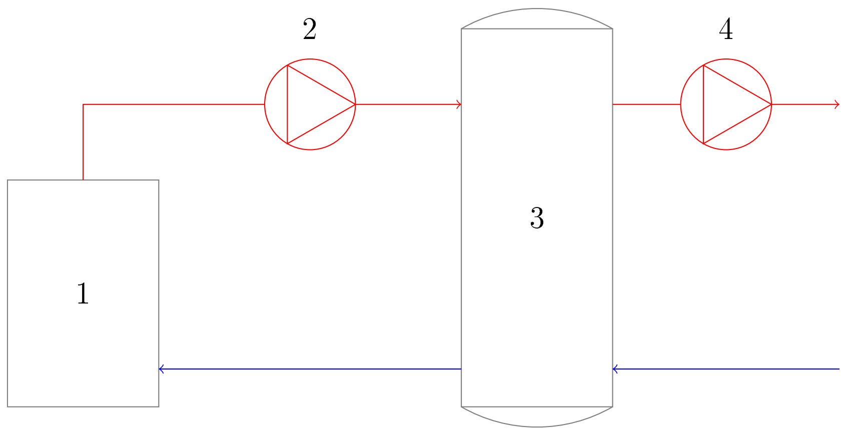


Figure 4.26: Generation and storage system. 1: boiler. 2: pump to storage. 3: storage tank. 4: pump after storage.

Energy can be stored in multiple forms. The main methods of thermal energy storage are sensible heat storage (e.g. hot water tank, ground heat storage), latent heat storage (e.g. phase change materials, ice storage) and thermochemical heat storage.

Not only should the sizing of storage components take into account the characteristics of the remaining subsystems, but it strongly depends on the actual purpose of storage. According to the intended time scale, one distinguishes peak load shaving, load balancing, seasonal storage.

We focus on sensible heat storage, as it remains the most viable technology for thermal energy storage [178]. Main sizing parameter for a hot water tank can be the tank volume divided by the maximum generation capacity. This parameter will depend on the targeted discharge time and on the relevant temperature difference.

4.5 Application to general HVAC systems

Like the bulk of this thesis, the previous sections of this chapter focused on hydronic heating systems. This section aims at discussing how the proposed method or similar methods may be applied to a variety of other HVAC systems, and what difficulties can be expected in doing so. These other HVAC systems include all kinds of decentral systems, cooling systems (starting with hydronic cooling systems), ventilation systems and air-conditioning systems.

Decentral and electric systems. This thesis focuses on central HVAC systems. In some applications, the benefits of decentral systems may make them preferable. These benefits include the absence of distribution losses and energy use for circulation, a more flexible operation, and often lower initial costs. These benefits can be related to the fact that decentral systems are generally simpler than central systems. It may be assumed that this lower complexity would be reflected in a lower effort for modeling and simulation. While the present method is not really relevant for decentralized systems, the procedures for the determination of delivery and generation subsystems may be combined to treat them.

Examples of decentral heating systems are stoves for solid fuels or for gas, and electric heating. As we generally do not model electricity distribution, electric HVAC systems would amount to decentral systems, consisting only of delivery components. Electricity can be used directly for heating (resistance heating) or in decentral heat pumps. Electric storage heaters, a form of eletric resistance heating, was popular in Germany in the 1970's [165, p.1106]. An appropriate model for these devices would have to take into account thermal storage. Decentral systems are also used for ventilation and air-conditioning. [12, Ch. 2], for instance in window-mounted air-conditioners.

Cooling. Cooling systems have been evoked in the previous sections. Hydronic cooling does not differ much from hydronic heating, as far as the system structure is concerned. The proposed method can be applied, based on the determination of design cooling loads, and the successive determination of delivery, distribution and generation subsystems.

An additional difficulty can be found in the determination of design loads, as explained in Section 4.1.2. For accurate modeling, a distinction between sensible and latent cooling loads should be observed, and humidity effects should be considered. In terms of information required in the building model, shading systems should be represented in a way allowing solar loads to be calculated with enough accuracy.

Components for heat extraction are very similar to heat delivery components. They include ceiling panels, chilled beams and fan-coil units. In addition to cooling energy, active chilled beams and fan-coil units use electric energy for forced convection. The risk of condensation should be taken into account when designing radiant cooling panels.

Distribution subsystems for hydronic cooling have the same structure as for hydronic heating. In some cases, the same delivery components can be used for heating and cooling. In these cases, one distinguishes four-pipe configurations, with independent heat and cold distribution, and two-pipe configurations, where warm and chilled water are circulated in the same pipes. The latter configuration limits the possibility of simultaneous heating and cooling in different zones. It also implies that sizing should take into account both heating and cooling cases. An additional difficulty for the sizing of cooling distribution subsystems lies in the fact that peak cooling loads do not happen in all zones at the same type. As a consequence, the maximum flow rate through a pipe may be less than the sum of design flow rates for downstream terminal components.

$$\dot{m}_c^{(max)} = \max\left(\dot{m}_c(t)\right) = \max\left(\sum_{d \in dc(c)} \dot{m}_d(t)\right) \leq \sum_{d \in dc(c)} \max(\dot{m}_d(t))$$

Generation components in hydronic cooling systems are typically chillers functioning on the heat pump principle.

More than for heating, air-based distribution is often used for cooling, which brings us to the topic of ventilation systems.

Ventilation systems. Ventilation and air-conditioning systems do not strictly follow the scheme used for hydronic systems. Still, the procedures developed in this thesis may be reused to a large extent for the creation of models of ventilation systems, based on a correspondence between components in hydronic and air-based systems (Table 4.10).

Table 4.10: Correspondence of components in hydronic and air-based systems.

Entity	Hydronic systems	Air systems
terminal component	delivery component	air terminal
distribution segment	pipe	duct
flow moving device	pump	fan
energy conversion device	generation component	air handling device

Fresh air requirements are related to indoor air quality and occupant comfort. They may be based on multiple criteria and specified in a variety of ways. Eventually, the design ventilation rate for each zone is the main quantity of interest, corresponding to design heating or cooling loads for hydronic systems.

The provision of fresh air and the extraction of contaminated air can be ensured by natural ventilation or mechanical ventilation, or a combination of both. Mechanical systems may be limited to supply or exhaust ventilation, or combine both.

Each of these systems may be central or decentral, or limited to parts of buildings. For instance, one may have one ventilation system (one air handling unit) per building floor. Bathrooms or kitchens may have decentral exhaust systems separate from the main central system. The proposed method does allow for the creation of several HVAC systems in a single building. Building zones are partitioned in subsets, each of which is assigned to one system.

Air terminals correspond to both supply air outlets and return air inlets. These may take on many forms, including grilles, registers and (round, square or slot) diffusers [179]. Depending on the modeling approach chosen, the actual air terminals may be represented more or less explicitly. The modeling of these air terminals is closely linked to the modeling of air flow in the building.

- At the simplest level, one may consider a zone in which mechanical ventilation provides for the same amount of incoming and outcoming air. In this case, the combination of air outlet and air inlet can be considered as a single terminal component for which incoming and outcoming air have the same the mass flow rate but different conditions.

- In reality, air supply and exhaust may happen in different spaces. If simulation zoning is to distinguish between these spaces, one has to account for the flow of air from supply air zones (possibly over overflow zones) to extract air zones. This may be achieved with airflow network models.

- An even higher level of detail may be required, for instance if air stratification is to play a significant role. This is the case in underfloor air distribution (UFAD) systems [180].

The model creation method presented in Section 4.3 may be applied to the determination of air distribution networks. As already mentioned, an important difference is the greater independence of supply and return in mechanical ventilation systems. There may be (i) ducted return; (ii) a return plenum; (iii) no return. This is not problematic, as the method is based on the determination of separate networks of potential distribution components (NPDC) for supply and return. Instead of delivery components, NPDC nodes will correspond to supply air outlets and exhaust air inlets. Root nodes corresponding to the ductwork extremity will be connected to a fan or an air handling component.

The sizing of air ducts may be done with procedures similar to those described in Section 4.3.6, but the importance of pressure drops for fan energy consumption may require the use of more involved methods. The ASHRAE handbook [20] mentions several duct sizing methods with varying complexity, from the equal friction method in which ducts are sized for a constant pressure gradient to the T-method, which iteratively determines the best pressure for each section under consideration of pressure balancing.

Air-conditioning systems. In air-conditioning systems, mechanical ventilation can be combined with some or all of the following services: heating, cooling, humidification and dehumidification. This can be achieved in many possible configurations, which may differ in terms of air distribution structure, air flow control and zoning. In terms of the air distribution structure, one distinguishes between single-duct systems, in which a common air temperature arrives at all terminals, and dual-duct systems, in which cold and warm air are mixed at the terminals.

Each of these systems can be designed for constant air volume (CAV) or variable air volume (VAV). In the former case, the system responds to loads in a space by varying the supply air temperature, in the latter case it does so by varying the quantity of supply air. In terms of zoning, some systems are designed for the conditioning of a single zone and others for multiple zones. Systems for multiple zones are characterized by decentral air handling components (heating coils, cooling coils or humidifiers) or flow regulators allowing the air condition or flow rate to be adjusted for each zone. For instance, in multiple-zone single-duct constant volume systems, air is usually centrally conditioned to meet the highest cooling load, and then reheated for zones requiring higher supply air temperatures, which may result in high energy consumption. A distinction is often made between perimeter zones requiring alternatively heating and cooling, and core zones requiring only cooling.

As air is not only used for ventilation, but also for cooling and maybe heating, the critical path is not unique but dynamic. As already mentioned for cooling, this complicates the sizing procedure. For similar reasons, controls are potentially more involved, and their modeling accordingly difficult.

Model creation may also be complicated by the combination of several systems. While some air-conditioning systems ensure all ventilation and thermal control on their own, dedicated outdoor air systems (DOAS) only handle the air quantities necessary for ventilation, and rely on a parallel (typically hydronic) system for thermal control. The sizing of such systems implies to split the thermal loads into those needed to treat outdoor air, and those (building envelope and internal loads) handled by the parallel system.

More generally, air-conditioning systems can be connected to other systems on which they rely in order to treat air. For instance, an air heating or cooling coil operated with hot or chilled water represents a link between an air system and a water system. In such cases, the system creation and sizing procedure would follow the same direction from demand to supply as with hydronic systems. For instance, one would start from ventilation and supply air condition requirements to determine and size air terminals, then air distribution and air handling components. In a second step, one would consider the water system, for which air handling components (e.g. preheat and reheat coils) are demand components.

Summary

This chapter has presented a general four-step method to derive detailed component-based HVAC system models from a general building model. While the automated determination of design loads is frequent in existing methodologies and tools, as well as the sizing of delivery and generation elements based on it, the present method goes further with the determination of a distribution subsystem based on the explicit location of components.

A limitation of the presented method is its linear character, which makes it faster but may not reflect actual workflows. For instance, it has been argued that component positioning and pipe routing are interconnected problems which require repeated iteration [181]. Such a linear workflow has the benefit of being more transparent, and computationally less expensive.

Another significant difference between the presented method and the design of real HVAC systems lies in the assumption of exact calculated values for component properties, whereas real components are only available in discrete sizes. This issue is present for all three subsystems, with a potentially multiplying effect. In real system engineering, there is even a preference for uniform sizes, which cannot be considered with these procedures as presented in this chapter.

The method is illustrated for hydronic heating systems. It may also used for hydronic cooling systems following the same steps. The application of the same approach to other types of HVAC systems, such as air-conditioning systems, is discussed in the fifth section of this chapter. Its implementation and validation is future work.

For the HVAC system description to be complete, the whole control definition should be added to the output of the method presented in this chapter, which encompasses all subsystems. Since the description of control differs greatly with the simulation tool, it is not set out in this chapter. The procedures described in this chapter allow for static system models to be created. Their dynamic control, as well as the choice of input values (e.g. selected component types), method alternatives and parameters is treated in later chapters, as is the translation of the general HVAC system model into a tool-specific simulation model.

Chapter 5

Design of a system for automated simulation model creation

This chapter follows Chapter 4 on the creation of an HVAC model based on a building model. It shows how the proposed algorithms can be used in a software system for automated simulation model creation. We start by describing the system architecture, based on five main modules. This is followed by a presentation of the data model shared by these modules, and by a description of how an actual simulation model can be created based on an internal model. Finally, an implementation of the proposed system is presented.

5.1 System architecture

5.1.1 Overview

The general workflow supported by the system is illustrated in Figure 5.1. The generation of input files for simulation is distributed in several steps. In related work, this has been refered to as the preparation of "platform-neutral building thermal view", followed by "platform-specific building thermal view" [182].

It has been argued [183] that different workflows and requirements are best addressed by a modular environment. In our case, modularity is desirable due to the consideration of different use cases, the use of different data sources and different simulation engines. The system architecture illustrated in Figure 5.2 reflects the linear workflow, with a module for each main step. Accordingly, interactions between modules are mainly unidirectional. Next, the functions of these main modules are summarized.

5.1.2 Building Zoner

This module corresponds to functional requirement R2, which is to generate a zoned building model from a structured building representation. It is responsible for getting building data and returning it in a form usable by the other modules.

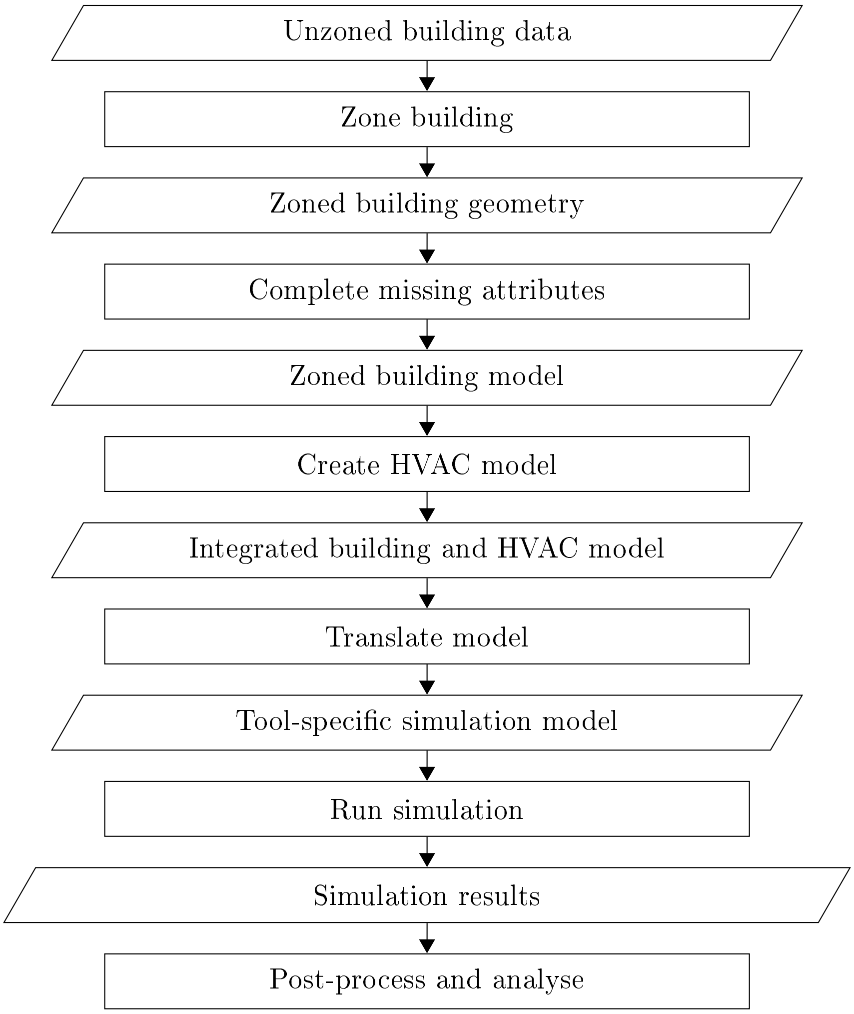


Figure 5.1: General workflow realized by the proposed system.

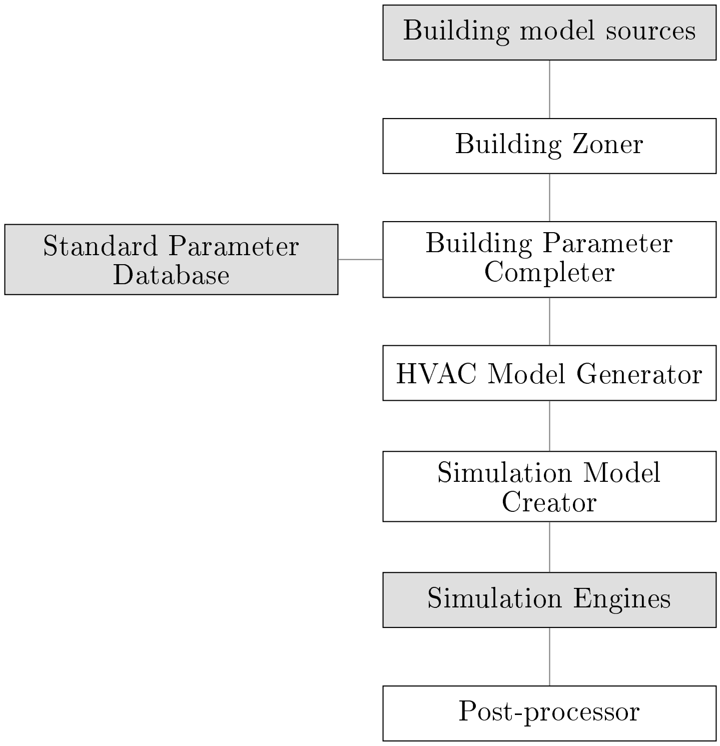


Figure 5.2: System architecture, with internal modules in white and external modules in gray.

It automatically transforms spaces into zones. This building data is first and foremost geometry. Additional information is also included, depending on availability. Construction data may be present or not. If not, at least main building use and year of construction should be known, which will allow default constructions to be retrieved in the Building Parameter Completer module.

Zoning method. Zoning is carried out as a space aggregation operation on a network-based space layout. It has already been proposed to use such operations for modeling multiple views of buildings [184]. The aggregation operation merges spaces based on their properties and connectivity. Geometrically, space merging is realized by the solid union of space volumes, which are modeled as solids. Different simulation zone views are obtained by considering different space properties for space aggregation. The explicit modeling of external spaces is used for perimeter/core space classification and the determination of orientation. A perimeter space is adjacent to at least one external space, whereas a core space is not. Orientation of internal spaces is defined in terms of their connectivity with external spaces through transparent openings, following a convex decomposition of external spaces. Functional zones result from the aggregation of spaces belonging to the same functional group [185], that is having the same primary space property or sharing certain secondary space properties. Examples of functional groups are service spaces, which include bathrooms and storage rooms, and primary circulation spaces, which include publicly accessible staircases and elevators.

5.1.3 Building Parameter Completer

This module is responsible for completing the model returned by the Building Zoner module with parameters necessary for simulation. These parameters refer to static properties, including constructions for opaque and transparent building elements, and dynamic properties, including internal loads and set points. This is done by accessing a database containing standard values. The completed model can then be used for the creation of an HVAC model with the HVAC Model Generator. It can also directly be translated into an input for ideal load simulation.

5.1.4 HVAC Model Generator

This module corresponds to functional requirement R3. It uses the methods described in the previous chapter to derive models of HVAC systems from completed zoned building model. The HVAC model is added to this building model. The existing elements of the building model (such as space boundaries, internal loads) mostly remain unchanged, with a few exceptions: (i) In the case of floor heating, floor surfaces are assigned a modified construction object, indicating the location of active elements among the construction layers. (ii) Zone objects are enriched with system information, e.g. which delivery components serve them. This is mostly for practical reasons in intermediate steps of HVAC model creation, and is not reflected in the produced input files.

5.1.5 Simulation Model Creator

This module corresponds to functional requirement R4. It is responsible for the translation of an integrated building and HVAC model, as can be produced by the HVAC Model Generator, into inputs for the selected simulation engines. Additionally to translation, this also involves some model completion for parts of the model which are very different in the two simulation engines. This is especially the case of HVAC control. The design of this module is described in the third section of this chapter.

5.1.6 Post-processor

This module corresponds to functional requirement R5. It is responsible for processing simulation results, calculating and presenting the desired performance metrics. Post-processing tasks depend on the questions underlying simulation, and thus on the use cases defined for our system. Moreover, comparable results obtained with different simulation tools should be treated in a unified way. Information necessary for post-processing includes not only simulation results, but also simulation input models, for instance for 3D result visualization, or area and volume calculation. In some cases, the post-processor module must resort to the system-internal building and HVAC representation. For example, in order to check that heating control works as expected, one needs to determine which delivery components are present in each zone, and consider the corresponding delivered heat rates, as well as simulated temperatures and zone set points. The calculation of subsystem losses makes it necessary to match subsystems with each other and with their respective components. As a consequence, no existing post-processor could perform all the required tasks.

All these modules interact by exchanging structured data describing buildings and HVAC systems, hence the need for a well-defined data model, which is presented in the next section.

5.2 Data model

The creation of a simulation model requires a structured representation of the building and its HVAC systems. This section presents a data model developed to this aim.

Motivation. There are several reasons to develop a data model for the present work instead of reusing existing ones. To start with, an existing data model could not be used without modifications. As mentioned in the literature review, not all data required for simulation can be contained in IFC and other existing BIM standards. A domain data model like SimModel has been developed for building and HVAC simulation while being in alignment with IFC [79]. SimModel supports data transfer to EnergyPlus. For simulation with TRNSYS, a whole model transformation system would be needed, as has been developed for instance for Modelica [186]. The two main arguments for not attempting such a development were simplicity and the alignment of the model with procedures applied to it.

The following data model can be seen as a minimum structure supporting the requirements of simulation model creation. By comparison, a data model based on IFC would be considerably more complex. One may consider the example of a window in a wall. In EnergyPlus and in the proposed data model, this would be modeled as a subsurface (*Fenestration*) refering to a parent surface (*SpaceBoundary*). In IFC, one would need an intermediate opening element (*IfcOpeningElement*) linked to the wall (*IfcWallStandardCase*) with an *IfcRelVoidsElement* relationship and to the window (*IfcWindow*) with an *IfcRelFillsElement* relationship.

What is more, the presented data model is aligned with the procedures used to create and modify HVAC system models based on the building model. These procedures - and functions checking the validity of these models - can thus be realized as methods in the object-oriented implementation. We use class diagrams of the unified modeling language (UML) [187] to represent subsets of the data model.

5.2.1 Building structure

The internal representation of a building in the proposed system is close to that in simulation tools. In particular, simulation zones play a central role, as may be apparent from Figure 5.3. A building is composed of a number of zones. Each zone is assigned a type of space use, corresponding to definitions of internal loads and set points.

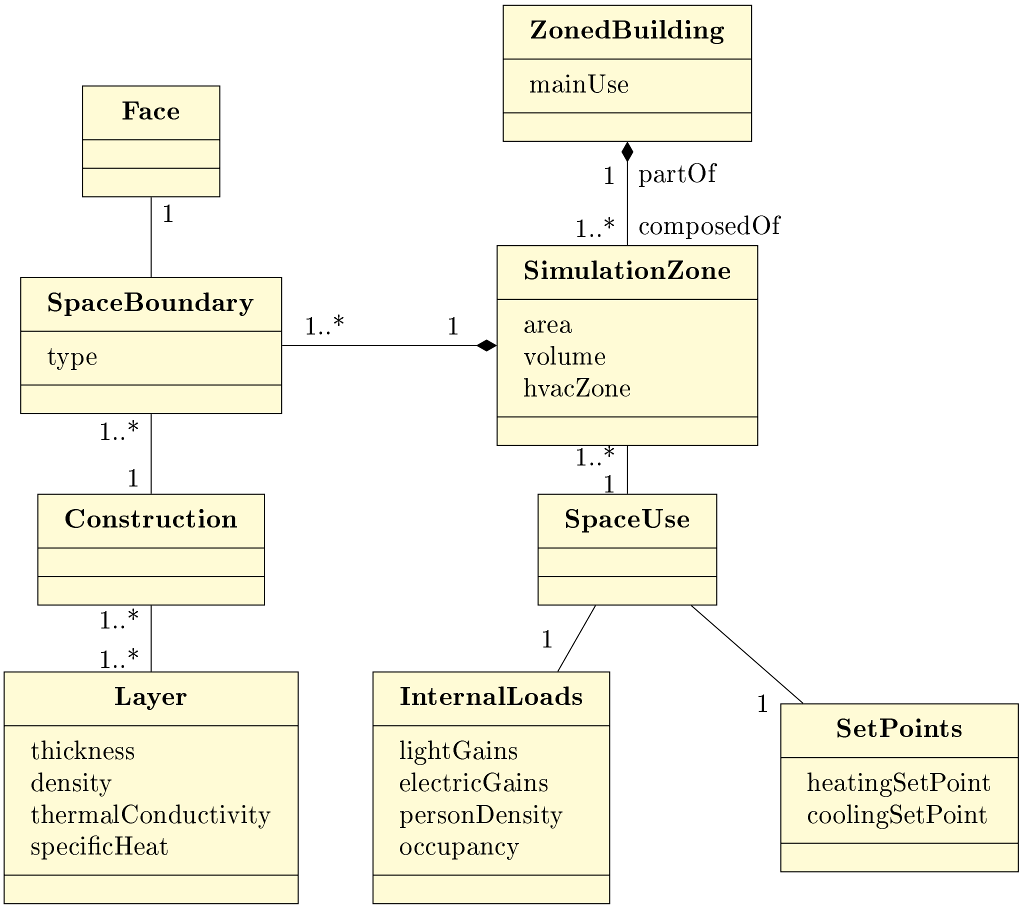


Figure 5.3: Partial class diagram for the representation of a building (*ZonedBuilding*) in the proposed data model.

The representation of the building geometry, presented in more detail in Figure 5.4, corresponds to that most frequent in thermal simulation, where zones are bounded by planar space boundaries, and windows are subsurfaces of space boundaries (Section 1.1.3).

Table 5.1 presents a correspondence of objects in our system data model, IFC, EnergyPlus and TRNSYS. IFC, EnergyPlus and TRNSYS objects are chosen as the semantically closest entities to objects in our model. However, for most rows of the table, there is no strict equivalence between the listed objects.

In IFC, the spatial structure of a building is described hierarchically using instances of *IfcSpace*, which represents a bounded area or volume. By contrast, an

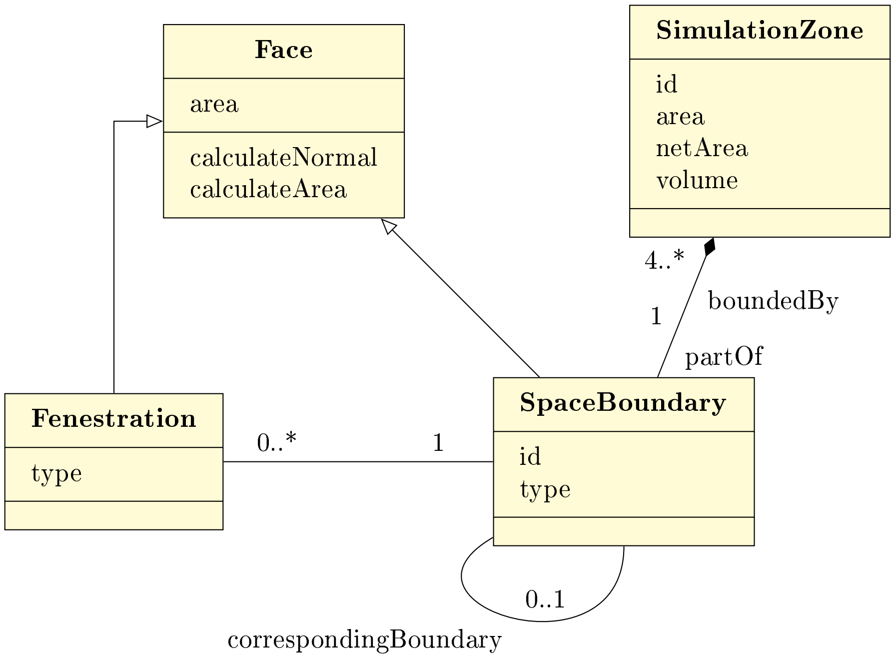


Figure 5.4: Partial class diagram for geometry: *SimulationZone* and *SpaceBoundary*.

Table 5.1: Correspondence of objects with IFC and EnergyPlus.

System data model	IFC4	EnergyPlus
ZonedBuilding	IfcBuilding	Building
SimulationZone	IfcSpace	Zone
SpaceBoundary	IfcRelSpaceBoundary2ndLevel	BuildingSurface:Detailed
Construction	IfcMaterialLayerSet	Construction
Layer	IfcMaterialLayer	Material
Fenestration	IfcOpeningElement	FenestrationSurface:Detailed

IfcZone is a non-hierarchical group of spaces or other zones, thus quite different from zones in an energy simulation model.

In IFC, constructions are defined for building elements (*IfcBuildingElement*), related to spaces using *IfcRelSpaceBoundary*. In EnergyPlus and in our data model, constructions are directly assigned to space boundaries of level two.

The *Layer* object contains both physical data and the thickness of the actual construction layer, like the EnergyPlus *Material* object. In comparison, an *IfcMaterialLayer* refers to an independent *IfcMaterial*, which may also be an inhomogeneous material.

There is no equivalent of *IfcBuildingStorey* in EnergyPlus. Our data model uses a *floor* field in zone objects.

The *Fenestration* object, following the EnergyPlus terminology, represents windows or doors, directly referring to a parent space boundary. As mentioned above, IFC uses three objects and two relationships for this situation.

Space boundaries in the present model correspond to *IfcRelSpaceBoundary2ndLevel*. The attribute *CorrespondingBoundary* allows two space boundaries on each side of a building element to be linked, with the difference that there is no explicit representation of building elements in our model.

5.2.2 HVAC system data model

The first attempts at automated generation of HVAC models followed a template-based approach, requiring a separate implementation for each simulation tool. The use of a general HVAC model structure makes it possible to handle a wider variety of HVAC systems in a more efficient and flexible way.

HVAC component classes. Both selected tools have a component-based HVAC structure with inlets and outlets. Hence a similar structure is adopted for our internal model. The basic class thus represents an HVAC system component, which would correspond to *IfcDistributionFlowElement* in IFC. It should be noted that these components correspond to physical components with an actual flow of energy and matter, as opposed to more general elements present in HVAC systems (*IfcDistributionElement*), which also include electrical and communication elements.

Inheritance is used to define subclasses corresponding to different component types, as illustrated in Figure 5.5. As appears from Table 5.2, the data models of the two selected simulation tools do not have abstract classes.

IfcBoiler is a new entity in IFC2x4. The associated property set *Pset_BoilerTypeCommon* contains almost all properties that would be needed for energy simulation, including energy source, nominal energy consumption and operating mode, but efficiency curves can only be specified as a function of part load ratio (*PartialLoadEfficiencyCurves*).

Control elements like actuators, controllers and sensors (*IfcDistributionControlElement*) are not present in this data model, for they are not represented individually in the used simulation tools. Instead, control is represented by equations and variables in TRNSYS, and by set point values and other fields or objects

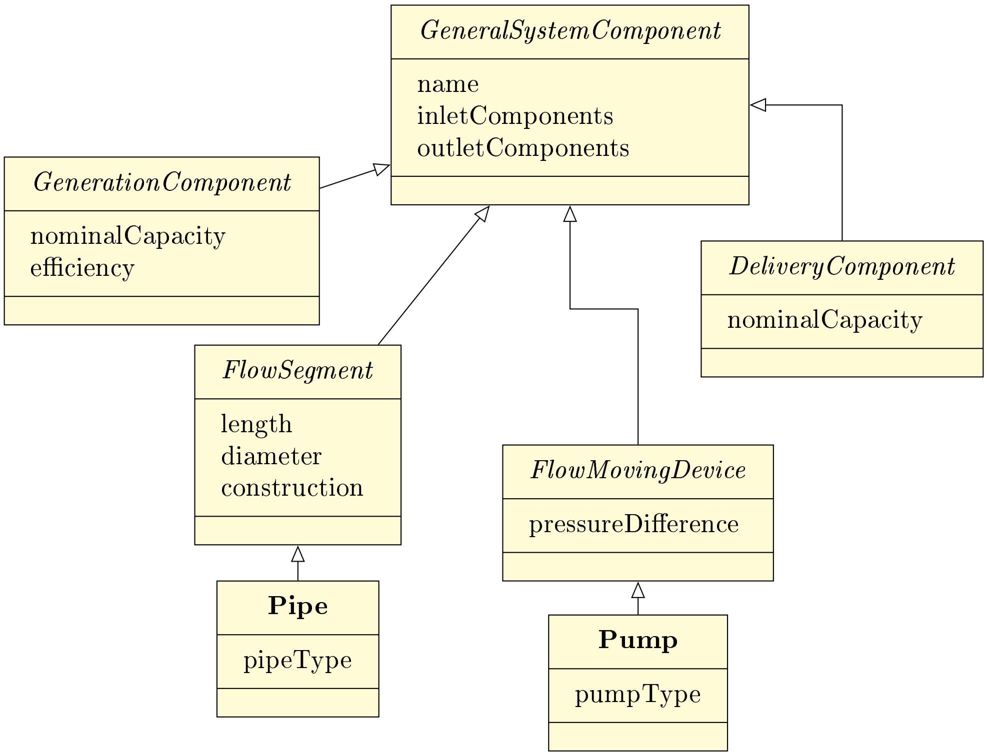


Figure 5.5: Partial class diagram for HVAC system components in the proposed data model.

Table 5.2: Data model comparison with IFC, EnergyPlus and TRNSYS for HVAC system components. IfcPipeSegment and IfcPump are new entities in IFC4.

System data model	IFC	EnergyPlus	TRNSYS
Abstract classes			
SystemComponent	IfcDistributionFlowElement	-	-
FlowSegment	IfcFlowSegment	-	-
FlowMovingDevice	IfcFlowMovingDevice	-	-
GenerationComponent	IfcEnergyConversionDevice	-	-
DeliveryComponent	IfcFlowTerminal	-	-
Component classes			
Pipe	IfcPipeSegment	Pipe:Indoor	Type 31
Pump	IfcPump	PumpVariableSpeed	Type 3b
Boiler	IfcBoiler	Boiler:HotWater	Type 751
MixingWaterValve	IfcValve	-	Type 649

in EnergyPlus. Since possible control schemes are different with these two codes, defining them at a general level would be difficult.

HVAC system structure. The static part of an HVAC simulation model (for instance in TRNSYS) could simply be described by a network of such HVAC components linked by inlet/outlet relations. However, modeling the behavior of HVAC systems, starting with their control, requires additional information on the structures of these systems. Dynamic supply and demand relations can only be defined with a hierarchy of circuits and systems.

Figure 5.6 shows classes related to groups of components forming HVAC systems. Two main types of HVAC systems are considered: hydronic (heating or cooling) systems, and ventilation systems. A hydronic system can supply heat to (or extract heat from) a ventilation system through a heating (or cooling) coil. Different systems can serve different groups of zones in a building. We assume one zone is served by at most one hydronic system and one ventilation system.

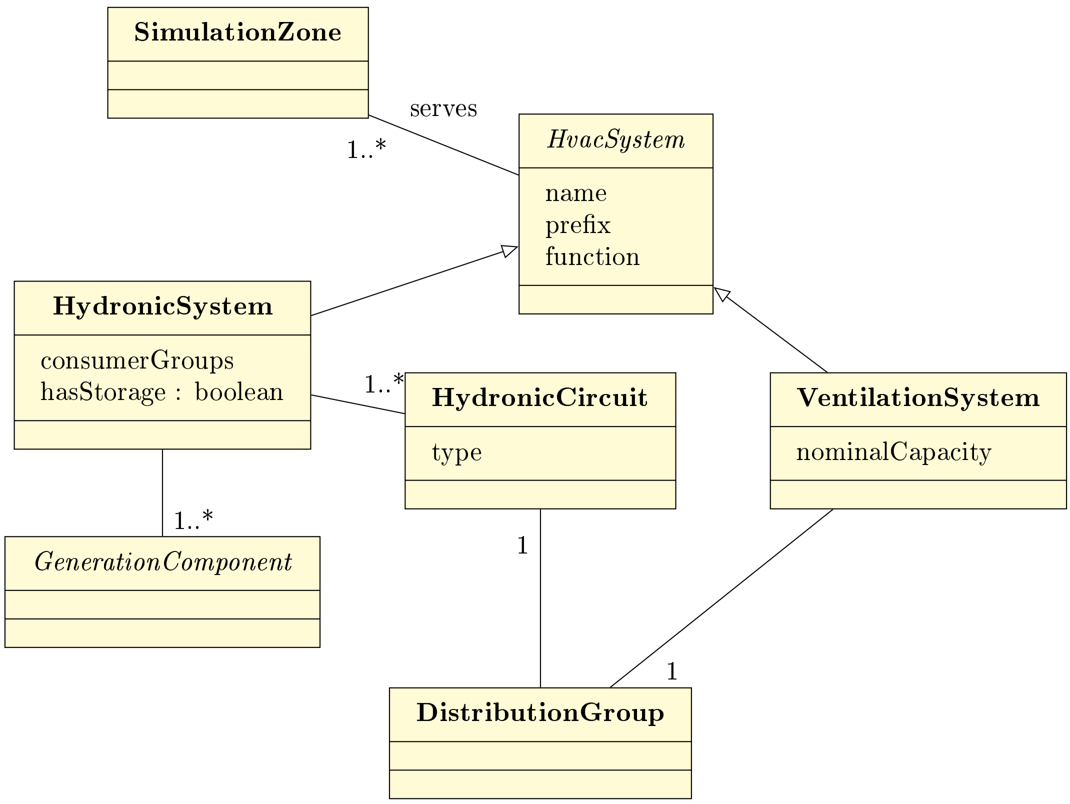


Figure 5.6: Class diagram for HVAC systems in the proposed data model.

A hydronic system may include several hydronic circuits, each corresponding to a separate distribution group (Figure 5.7).

The data structure depends on the range of system types to be accommodated, and on model assumptions. The proposed data structure was developed to represent most common central HVAC systems. Complete HVAC systems combining water-based and air-based systems can be represented with several instances of

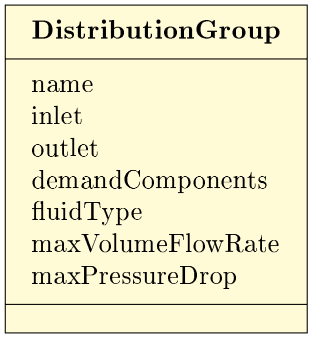


Figure 5.7: Class diagram for a distribution group.

HvacSystem. An instance of *HydronicSystem* can be linked to one or several instances of *VentilationSystem* via a heating or a cooling coil. In such cases, the coil also acts as a logical link, indicating that the hydronic system should provide heat to (or extract heat from) the ventilation system according to the latter's demand.

Chapter 4 described how such an HVAC system model can be created starting from a building structure. The next section shows how such a model can be transformed into an input model for two state-of-the-art simulation engines.

5.3 Simulation model creation

This section describes the Simulation Model Creator module. It deals with the issue of how to create ready-to-use simulation models on the basis of HVAC models already created according to the algorithms described in Chapter 4. This is achieved through data mapping and completion.

5.3.1 Model mapping

Building and HVAC models following the structure described in the previous section should be mapped into tool-specific models for actual simulation.

As far as HVAC modeling is concerned, all three models (internal model, EnergyPlus model and TRNSYS model) are more or less component-based, so that part of the model transformation can be reduced to the mapping of a general component to a tool-specific component (unit for TRNSYS). However, the way these components are organized into a system varies strongly between the three models, so that a transformation of their structures is also necessary.

The structural difference is more pronounced for EnergyPlus, because of the strong hierarchy of HVAC models with plant loops, half plant loops, branches and components. We focus on the translation of the HVAC system model, although non-HVAC objects also require some translation.

Object mapping. The most straight-forward aspect of creating tool-specific simulation models is the one-to-one mapping of single objects from the system data model to that of simulation tools.

At the level of object properties, one may distinguish several situations. Properties in the general object and in the tool-specific object may be equivalent.

Data in the general object may be mapped with loss of information to properties in the tool-specific object. For instance, a construction object describing the walls of a pipe is translated in a single R-value field in the resulting TRNSYS object.

A property in the general object may remain unused in the tool-specific object. This may be the case because the general object contains information used only during model creation or when translating for another tool.

A property in the tool-specific object might have no equivalent property in the general object and be filled with a default value. This may be the case either because the tool-specific object is only used in some of the cases for which it is conceived, or because the property is expected to have a negligible impact. For instance, the TRNSYS air-source heat pump component (type 941) has a parameter for the specific heat capacity of the demand-side liquid. We fix it to a value typical for (liquid) water (4.18 kJ/(kgK)), as we only consider this type in the case of air-water heat pumps. As this is a parameter rather than an input, the variation of heat capacity with temperature is neglected.

A rather trivial but necessary aspect of object mapping is unit conversion for parameters expressed in different units. System-internal and EnergyPlus parameters use SI units with W, kg and s, whereas rate parameters in TRNSYS units are usually expressed per-hour, as shown in Table 5.3.

Table 5.3: Common variable units in EnergyPlus and TRNSYS.

Physical quantity	EnergyPlus	TRNSYS	Conversion factor
power	W	kJ/h	3.6
mass flow rate	kg/s	kg/h	3600

Performance curves. Performance curves attributed to a component represent a special case, treated differently in the two tools. Such curves are used, for instance, to indicate how the efficiency of a boiler depends on inlet temperatures and part load ratio, or how the electric power used by a pump depends on the flow rate. For TRNSYS, they are mostly written down in an external (.dat) file, referred to through a unit parameter. This file contains punctual values of the performance parameter(s) for discrete values of the input variable(s). Interpolation between these discrete values is carried out by TRNSYS at runtime. In simpler cases, performance coefficients are passed as parameters or as inputs, e.g. motor and overall efficiency in Table 3.1. For EnergyPlus, performance curves are usually objects of their own, which may pertain to different types representing polynomial functions, e.g. quadratic, bi-quadratic or cubic curves. The system-internal representation of performance curves is, like in EnergyPlus, based on polynomial functions. This has two advantages. Translation from this representation to the TRNSYS representation is as simple as evaluating a polynomial at discrete points on a grid. The representation is also lighter. A performance curve is encoded with $n \leq 6$ polynomial coefficients, whereas the number of values for the TRNSYS representation is equal to the product of the numbers of input values for each input variable, which can easily exceed 10^2. Sensitivity analysis is all the easier. On the other hand, translation from discrete values (for instance from TRNSYS default data or from a manufacturer's catalogue) to a polynomial curve is a case of curve fitting. As curve fitting leads to some loss of data, doing it before (for the general model) rather than after (for tool-specific models) ensures the same data is used with both tools.

Mapping to EnergyPlus loop structure. As already mentioned, the loop structure imposed by EnergyPlus for HVAC system models is not homomorphic to the data structure of the proposed system.

Limited flexibility of the distribution structure in EnergyPlus requires the distribution subsystem model to be simplified. Simplifications procedures to this aim are described in Section 4.3.7 and evaluated in Section 8.2.

In contrast to the TRNSYS case, inlet and outlet data of general components are only used when several components are situated on the same branch, that is in series. Some additional information is needed to place the components in the appropriate half loops and branches. Some components are retrieved through the use of fixed references, others based on their class. Bypass branches are automatically added, as required by EnergyPlus. Valve components disappear. Instead, splitter and mixer elements are created for each half loop. Splitter and mixer elements are derived from the content of branches.

An HVAC system is transformed into one or several connected loops according to whether there is a storage subsystem, and whether there is a heat pump with a heat exchanger. Resulting plant loops are summarized in Table 5.4.

Table 5.4: Cases of HVAC plant loops considered. A condenser loop is needed for brine-water or water-water heat pumps but not for air-water heat pumps.

Case	**Loop name**	**Supply**	**Demand**
No storage	main loop	generation	delivery components
Storage	consumer loop	storage tank	delivery components
Storage	source loop	generation	storage tank
Heat pump	condenser loop	heat exchanger	generation

Components at the interface of several loops represent a special case, illustrated in Figure 5.8. Such a component is typically present in two different branches, of which one belongs to the demand side of a loop and one to the supply side of another loop. It also has two inlet and two outlet ports, with one pair of inlet/outlet ports for each branch. The component description itself should only be written once.

Mapping to TRNSYS structure. The internal model is transformed into a TRNSYS .dck file used for HVAC system simulation. This file may be divided in

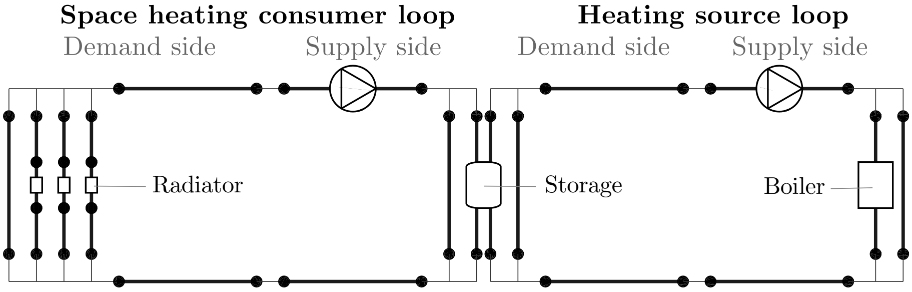


Figure 5.8: EnergyPlus HVAC model structure in the case of a hydronic heating system with storage. The storage component, a hot water tank, realizes the connection between the consumer loop and the source loop.

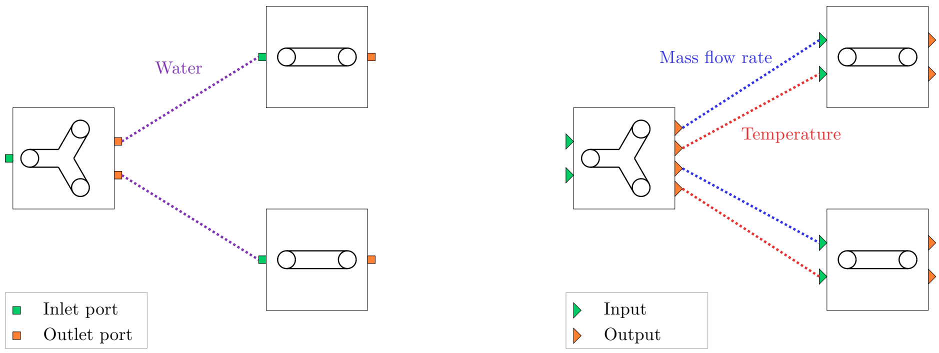
separate parts:

- *HVAC system components.* They are derived from the translation of general components. Each components is represented by a TRNSYS unit of a given type and identified by a unique number.
- *HVAC control part.* It consists mainly of equations defining control variables referred to by the HVAC system components. It may also contain some TRNSYS units representing certain controllers and hysteresis. Since these equations are not explicitly included in the HVAC model, their determination is explained in the next section (simulation model completion).
- *Interface part.* It contains the definition of input and output variables, including unit conversion as well as reading and writing operations.
- *Building response part.* It uses output variables of the HVAC model (primarily energy flows) as inputs and returns as outputs the input variables of the HVAC model (primarily zone temperatures).

In the implementation, these parts of the model can be written by distinct functions. This division allows the same TRNSYS HVAC model to be written in two versions: one for co-simulation, and one for standalone checking and debugging. The same input and output variable names are used in both cases. The only difference is the building response part, which defines how the outputs of the model are treated to return inputs. For co-simulation, the building response part consists of the FMU input (type 6139a) and output (type 6139b), realizing the interface with the EnergyPlus FMI [188]. In the standalone model, the building response is modeled with simplified zone components (type 88). Both HVAC system components and HVAC control parts are written successively for each system.

The HVAC system components in TRNSYS are organized in a flat structure. A challenge in flattening the original model (with a hierarchical structure in systems, circuits and groups) is to make sure that all elements (units) have distinct names and identifiers, while keeping the length of these names within the limits imposed by TRNSYS. Translation of HVAC system components is realized with the following steps:

1. Translation of general components into units based on component class. This is the object mapping described in the previous section.
2. Addition of port numbers to inlet/outlet references, based on the order of outlets in input unit.
3. Determination of unit numbers. This step is carried out for all systems at once, ensuring there is no duplicate unit number.
4. Likewise, determination of external file identifiers, which should also be unique.
5. Derivation of unit inputs related to state and flow variables (e.g. temperature) from inlets, as illustrated in Figure 5.9.
6. Determination of unit 2D positions for readability in TRNSYS simulation studio, based on projection from 3D position, system topology or other rules.



(a) Fluid ports

(b) Data exchange

Figure 5.9: Derivation of unit inputs related to state and flow variables (5.9b) from inlets (5.9a) for 3 hydronic components. For each outlet/inlet relation, 2 inputs of the outlet unit are specified as outputs of the inlet unit. For air flow, additional variables (air humidity and pressure) would be be exchanged.

The interface part defines general inputs and outputs for the TRNSYS simulation. Without output definition, simulation remains useless, as results are not made available. The minimum results to retrieve are zone temperatures and energy consumption. The latter is obtained by summation over all energy-consuming units in the model. To do this, output information is predefined for each TRNSYS component class (type), including the output number it should be read from, and the corresponding energy source. To better characterize the system's performance, the amounts of energy delivered by delivery components are also retrieved, as well as those made available by generation subsystems. For a deeper insight in the system's behavior, mass flow rates and temperatures in various components may also be needed. In this regard, more effort is needed with TRNSYS than with EnergyPlus, as no aggregation is carried out by the simulation tool, and physical units need to be translated.

5.3.2 Simulation model completion

This section discusses the missing parts needed for the transformed model to become a simulation-ready input file. These missing parts are mainly related to (i) controls simulation, that is the representation of HVAC system controls in simulation, and (ii) simulation control, that is parameters and options related to the simulation itself rather than pertaining to the simulated system.

Controls simulation. Controls represent an essential aspect of HVAC systems. However, their consideration in the two selected engines is so different that they cannot be described in a tool-independent way. Having it separately here is also justified by the fact that control could be simulated by a separate program.

Among control functions in HVAC systems, one usually distinguishes local control, dealing with actuators at a low level, and supervisory control, which aims at optimizing HVAC operation at a higher level. Considered here is supervisory control, as opposed to local control. The modeling of local control would require another level of detail and the explicit modeling of physical control components.

EnergyPlus control schemes. HVAC system control in EnergyPlus is modelled with groups of interlinked objects related to zones on the one side, plant loops on the other side. Such objects and their relations are illustrated in Figure 5.10.

TRNSYS control equations. Modeled control schemes are mostly defined by equations. These control equations start with the definition of zone demand, followed by delivery equipment demand and circuit demand, ending with control variables in various components: pumps, diverting valves, generation components. Pumps and diverting valves are controlled differently according to circuit type and control level. For a hydronic system, control equations define the following variables:

1. Zone temperature set points, as constants, or reading hourly values from an external file.
2. Zone control signals, based on zone temperature values and set points, typically using a control unit, for instance an on/off differential controller with hysteresis (type 2b).
3. Delivery component control signals, determined for instance as the zone control signal multiplied by the proportion of delivery heat rate of the component in the zone, or otherwise if a delivery component is to have priority.
4. Diverting valve flow proportions in distribution groups, according to Equation 5.1.

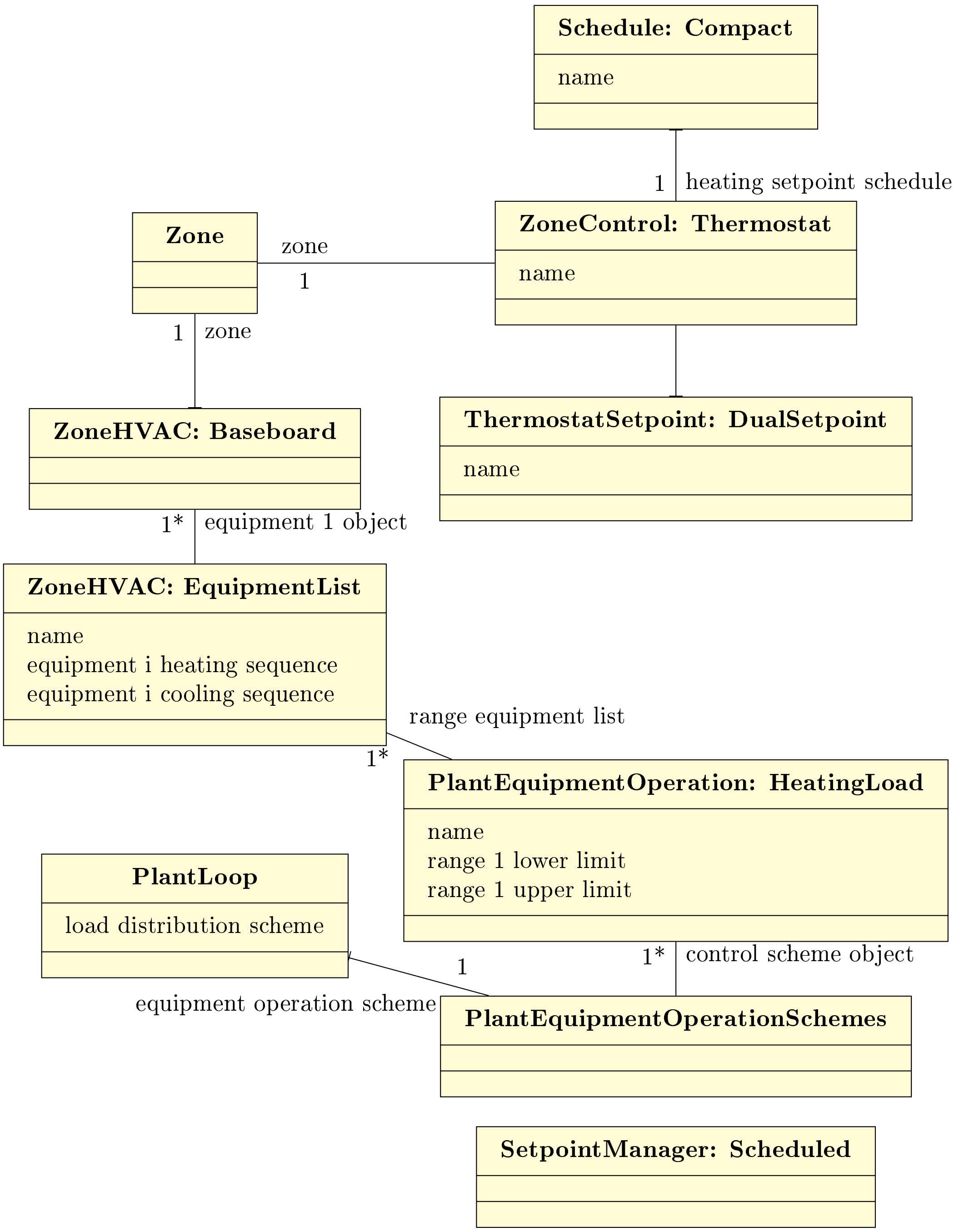


Figure 5.10: Objects involved in HVAC system control simulation in EnergyPlus for a hydronic heating system. Control objects as such are on the right side, while the corresponding physical objects are on the left. This figure uses the UML class diagram even though the EnergyPlus input definition is not strictly object-oriented. The colon-separated “class” names are the names of EnergyPlus objects as defined in the input data dictionary. Also, the links of several of these objects to schedule objects are not reflected in the figure.

5. Diverting valve flow proportions for diverting, mixing and injection systems.
6. Dynamic heat rate demand for each circuit, equal to the sum of delivery component heat rate demands (component signal multiplied by capacity proportion).
7. Volume flow rate required in main distribution for each circuit, depending on circuit type and heat rate demand for each circuit.
8. Main pump control signal, sum of the previous volume flow rates.

Noteworthy is that, even in cases where a mixing valve controls flow distribution (e.g. in a mixing circuit), flow control is modelled in diverting valves. This is due to the TRNSYS principle of identifying inputs to inlets and outputs to outlets.

The outlet flow proportion $x_{i,j}$ of output j of a valve v in a distribution group is

$$x_{v,j} = \frac{\sum_{d \in dc(o_{v,j})} x_{dem,d}}{\sum_{d \in dc(v)} x_{dem,d}} \tag{5.1}$$

where $x_{dem,d}$ is the flow demanded by component d, $dc(c)$ is the set of demand components downstream of component c, as defined in Equation 4.5, and $o_{v,j}$ is the component corresponding to the output j of valve v.

Each type of hydronic circuit is controlled in a different way. Let us illustrate this with the control of a mixing circuit. Water flow rate in the demand group is constant, and supplied energy is controlled by mixing return water at temperature $\theta_{circ,out}$ with water supplied by the generation subsystem at temperature θ_s, in order to reach the required temperature $\theta_{dem,circ,in}$.

We consider that $\theta_{circ,out}$ remains constant, and we determine the not-remixed fraction x_{nr} of water from main distribution according to Equation 5.2.

$$x_{nr} = \frac{\theta_{dem,circ,in} - \theta_{circ,out}}{\theta_s - \theta_{circ,out}} \tag{5.2}$$

The required temperature $\theta_{dem,circ,in}$ depends on $\dot{Q}_{dem,circ}$, the power to be delivered to the group of demand components. Assuming the delivered power to be proportional to $((\theta_{circ,in} + \theta_{circ,out})/2 - \theta_a)^n$ according to [189, p.247], with θ_a the zone air temperature and n a radiator exponent, $\theta_{dem,circ,in}$ can be expressed as a function of $x_{dem} = (\dot{Q}_{dem,circ}/\dot{Q}_{design,circ})^{-n}$, as in Equation 5.3.

$$\theta_{dem,circ,in} = x_{dem}\theta_{design,circ,in} + (x_{dem} - 1)\ \theta_{circ,out} + 2\ \theta_a\ (1 - x_{dem}) \tag{5.3}$$

Simulation control. Apart from the model of a building and the corresponding HVAC systems, and the HVAC control information added in the last step, simulation tools require additional data controlling the actual flow of simulation. Examples of such data for EnergyPlus are listed in Table 5.5.

Main simulation control parameters are simulation start and end time (relative to the weather data) and time step. The time step can be chosen between one minute and one hour, and is expressed as a fraction of an hour (EnergyPlus) or in number of seconds (TRNSYS). An adequate time step is particularly important to avoid numerical errors in co-simulation.

Also related to simulation control is the choice of simulation outputs. The two simulation tools deal with large amounts of data, the main part of which is not output at the end of calculations, unless this is required by the user.

Table 5.5: Simulation control objects and parameters in EnergyPlus.

Object	Example value	Description
Version	8.5	version to use
RunPeriod	Begin Month:1 Begin Day of Month:1 End Month:12 End Day of Month:31	date range
TimeStep	10	number per hour
SurfaceConvectionAlgorithm:Inside	AdaptiveConvection	choice of algorithm
HeatBalanceAlgorithm	ConductionTransferFunction	choice of algorithm

5.4 System implementation

This section describes a proof-of-concept implementation of the proposed system. An overview of this implementation is presented first. Next, the different implemented methods of acquiring zoned building models are explained. Finally, the integration of the system with simulation tools is described for the two cases of mono-simulation and co-simulation.

5.4.1 Overview

The implementation is characterized by the choice of EnergyPlus and TRNSYS as target simulation engines, and MATLAB as the main programming environment for the system. This is illustrated in Figure 5.11. When the Space Modeler is used to provide the original building model, it also assumes zoning functions.

The implementation evolved from an existing tool already developed at the Austrian Institute of Technology and presented in several papers [190] [191] [192] [92]. The prototypical automated building modeling tool used simplified models, derived from instance from basic template shapes, for detailed simulation in EnergyPlus [192]. Among others, the existing tool was used for simulation of groups of neighbouring buildings, for which manual input preparation would have been prohibitive [193].

In these precursor versions, model entities (buildings, zones, surfaces etc.) were coded as records (called struct in MATLAB). To implement the data model presented in the second section, an object-oriented approach is chosen, as is also supported by MATLAB. This results in more coherence than the original implementation based on records. Further advantages of an object-oriented approach

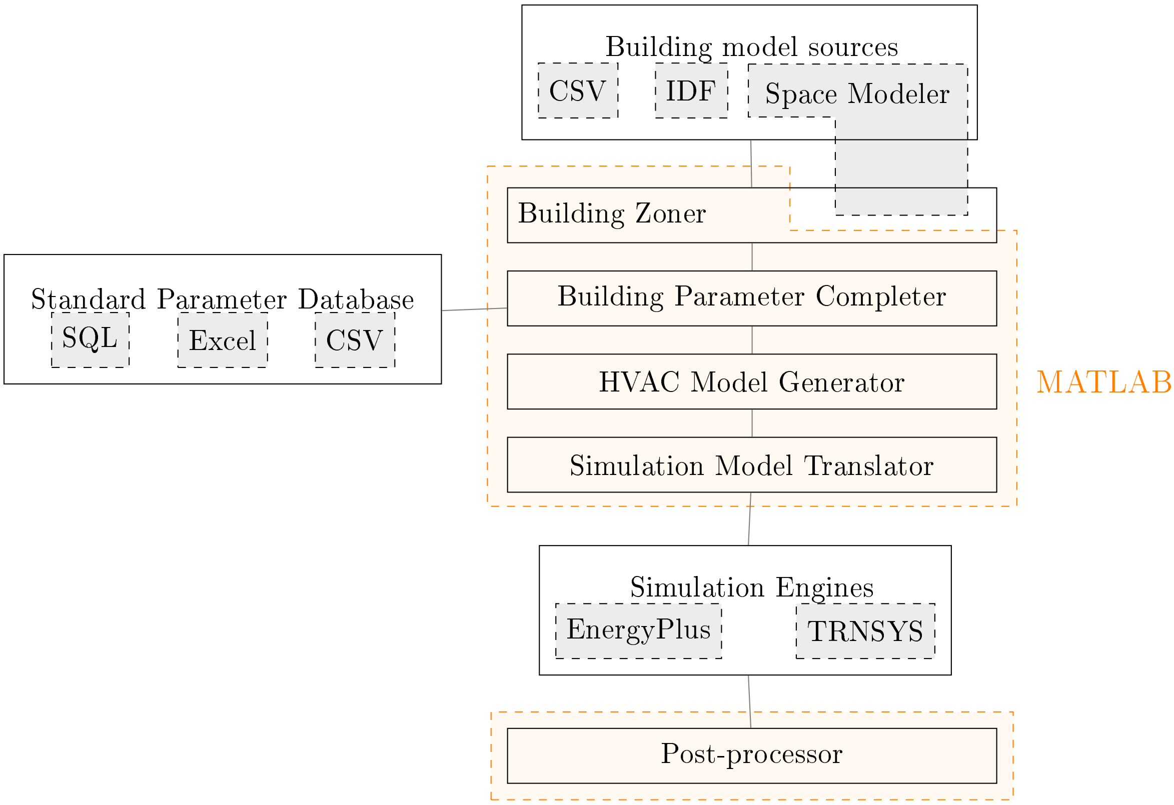


Figure 5.11: System implementation diagram, with implementing systems in dotted frames superimposed to the conceptual architecture.

include self documentation of the code inside of class definitions, value checks thanks to *set* functions, and the use of inheritance.

5.4.2 Building Zoner implementation

This section describes three implemented ways of loading zoned building models in the proposed systems. By no means do they exhaust all possibilities. On the contrary, more standardized import of building models should be preferred. However, these three possibilities serve the purpose of providing building models to the system in a complementary manner. While the import from a space modeling system yields rather detailed models, simplified (2.5D) building geometry can be used more quickly in the absence of available plans. The reuse of existing simulation models is also enabled.

Import from space modeling system. Building information modeling data is imported from the *Space Modeler* system implementing a schema for network-based space layouts [194]. In this schema, geometric networks embedded in three-dimensional space are formed by layout elements (such as *whole spaces* or *space elements*) and spatial relations. The schema supports multiple space views of buildings, with consistent operations that can transform a space layout corresponding to a view into another one corresponding to another view [184]. A plugin for the design and documentation software AutoCAD Architecture [195] makes it possible to draw layouts and export them as input for the *Space Modeler*.

Several characteristics of the *Space Modeler* speak in favor of its use for our purpose. Its space-based representation is consistent with building energy simulation. It supports spatial consistency checking, with constraints on layout elements and spatial relations. The automated derivation of relations, networks and layouts from architectural layouts fits well with the approach of automated simulation. In our case, in particular, operations can be defined for zoning by aggregation of whole spaces according to different criteria defined above. Its interface with AutoCAD Architecture allows building geometry to be modeled intuitively and efficiently. The use of a state-of-the-art geometric modeling engine (ACIS) by the Space Modeler makes robust geometric operations easy.

One instance of space layout can be exported to other tools through two types of files output by the *Space Modeler*: a network file and geometry files. The network file (.sla) is an XML file containing descriptions of layout elements and spatial relations. Geometry files are encoded in the SAT (Standard ACIS Text) format, which is the ASCII text file format used by ACIS for saving information. There is one such file for each type of object in the model. Among these, we are interested in the geometry of internal whole spaces, external whole spaces and window elements. From AutoCAD Architecture, geometry could potentially be exported in other formats.

Layout elements belong to the following categories [194]:

- Whole spaces (*whole_space*) are spaces that may contain subspaces.
- Subspaces (*subspace*) are spaces that are contained in a whole space.

- Space elements (*subspace*), which are physical elements that may be contained in a whole space (such as furnishing elements) or partially enclose whole spaces (such as windows or doors) [194].
- Space boundary elements are "immaterial surfaces that partially bound exactly one whole space".

The following spatial relations are also available [194] in the .sla file: (i) Adjacency between whole spaces (a_ws). (ii) Adjacency between subspaces(a_ss) (iii) "is near" relation between subspaces and space elements (n_ss_se) (iv) "partially enclose" relation between space elements and whole spaces(pe_se_ws)

Geometry is imported through parsing of the SAT files in MATLAB. The level of geometric complexity supported by ACIS is much higher than that required by thermal simulation. However, translation is possible for polygonal geometry. The geometry definition is based on a manifold solid boundary representation (B-rep), including shells, faces, loops, coedges, edges, vertices and points. The geometry of a space corresponds to a manifold solid B-rep, and a space boundary corresponds to a face.

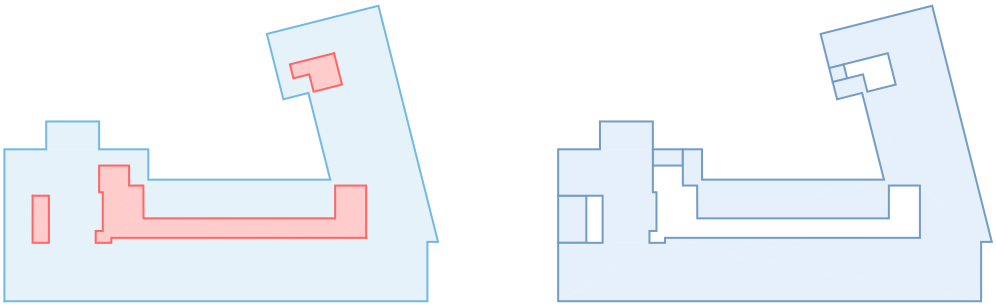
Issues with geometry import. Issues with geometry import can derive from the differences in requirements for the SpaceModeler and for BPS engines. They include the following:

- Polygons with holes have to be divided in several polygons, to conform to the EnergyPlus vertex-list-based geometry definition. Figure 5.12 illustrates the way this is done in the current implementation. For each hole, the internal edge closest to the external contour is found and projected perpendicularly onto the external contour.

- Very short edges may lead to problems, since EnergyPlus considers vertices distant less than 1 cm to be coincident [196], and automatically collapses them. This can lead to degenerate surfaces, with less than 3 vertices. To avoid this, we check that imported surfaces are not too thin, by looking at the ratio of surface area to surface perimeter, which corresponds to a thickness. We discard surfaces for which this ratio is below a certain threshold. Such problematic surfaces are illustrated in Figure 5.13. Given the small area of these surfaces, this can be assumed to have a negligible impact of thermal simulation.

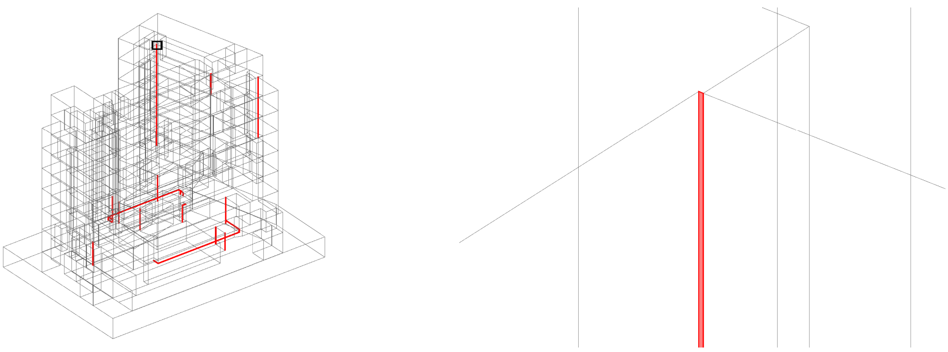
- Vertex order should correspond to the global geometry rules defined in the EnergyPlus model, in order for the surface to be correctly oriented. Although EnergyPlus can accept other sets of rules, we use the rule that vertices are specified in counterclockwise order, as viewed from outside of the corresponding zone.

- A fenestration surface in EnergyPlus should lie on the same plane as its base surface. Therefore, in order to avoid warnings and errors, imported window geometries are projected on the corresponding base surface planes.



(a) Input: polygon with three holes. (b) Output: 4 polygons without holes.

Figure 5.12: Decomposition of polygon with holes into polygon without holes, on the example of a floor surface in a perimeter/core view.



(a) Overview (degenerate surfaces in red). (b) Zoom on a degenerate surface.

Figure 5.13: Example of degenerate surfaces with area/perimeter ratio less than 1 cm.

Matching of geometry with layout elements can be done with the help of the *position* attribute of layout elements.

Space boundary level is an important issue. The space boundary elements of the Space Modeler are "similar to first level space boundaries in IFC" [194], whereas dynamic thermal simulation requires space boundaries of level two. Space boundaries of level one thus have to be decomposed to obtain space boundaries of level 2a according to the IFC classification. The fact that the tool operates with space boundary representations without thickness ("paper thin") makes this operation easier. Space boundaries of level 2b do not occur.

This transformation of space boundaries from level one to level 2a has been implemented on the MATLAB side of the system. It could be dealt with by ACIS within the Space Modeler, which would probably be preferable in terms of robustness and accuracy. The transformation is done with the following steps:

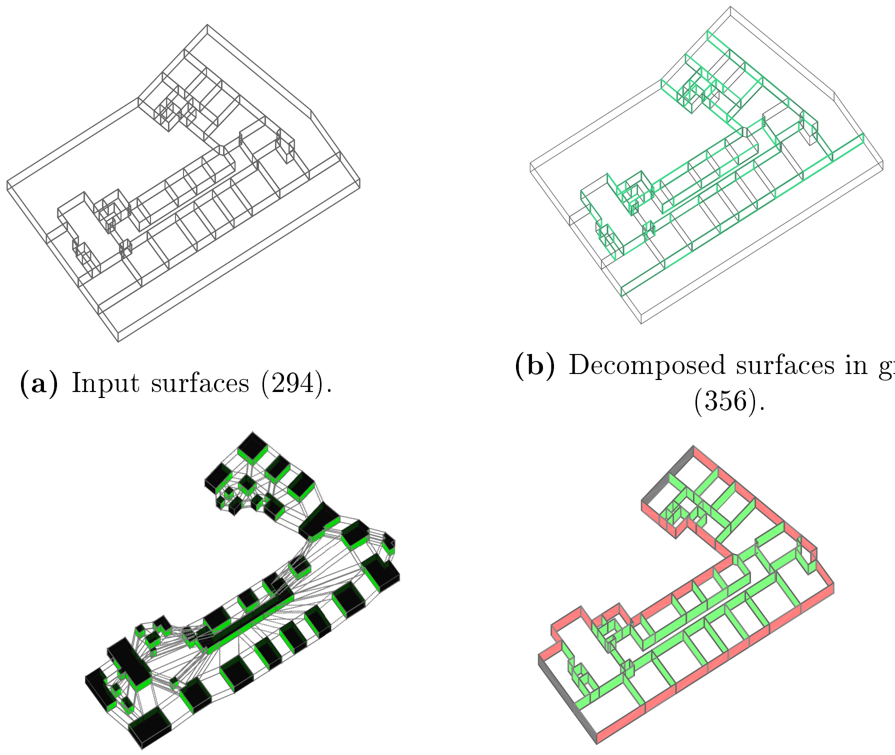
- Pairs of surfaces needing to be decomposed (touch relation) are identified. Here too, this ready information could be retrieved from the Space Modeler. Instead, only space adjacency is retrieved. For each pair of adjacent spaces $\{WS_1, WS_2\}$, pairs of space boundaries $\{S_1, S_2\}$ such that S_1 partially bounds WS_1 and S_2 partially bounds WS_2 are examined for the need to be cut. Only surface pairs sharing the same plane are filtered.

- If two coplanar surfaces S_1 and S_2 have an intersection with non-null area, the resulting decomposed surfaces consist in this intersection $S_1 \cap S_2$, as well as the connected components, if not empty, of $S_1 \setminus S_2$ and $S_2 \setminus S_1$. These operations are carried out with a MATLAB library for boolean operations in two-dimensions. Thus, S_1 and S_2 need to be projected on the 2D plane, and the results projected back onto the original 3D plane.

Surface decomposition and matching is illustrated in Figure 5.14 for a one-floor model.

Reuse of existing simulation models. An existing simulation model (IDF) may also be parsed, and parts of it reused to generate a new simulation model. At least the space boundaries are reused. Fenestration and shading objects may be retrieved or not, as well as non-geometrical data, such as constructions, internal loads and schedules. Cluster information of each zone may be retrieved from its name, as we name zone in a standard way, e.g. Z003_F01_Office. In terms of run time, this is the fastest way of getting a zoned building model in the system. As the focus of this work lies on HVAC systems, model variations with the same geometry are frequent, which often makes this partial reuse of simulation models useful.

Simplified building geometry. In this scenario, the building geometry is limited to two-and-a-half-dimensional solids. It is given as a planar polygon, and a specified building height and number of floors. Automated zoning based on a straight skeleton algorithm is used, as illustrated in Figure 5.15. Usage may be defined for each floor separately, but not room-wise. One case of this is implemented



(a) Input surfaces (294).

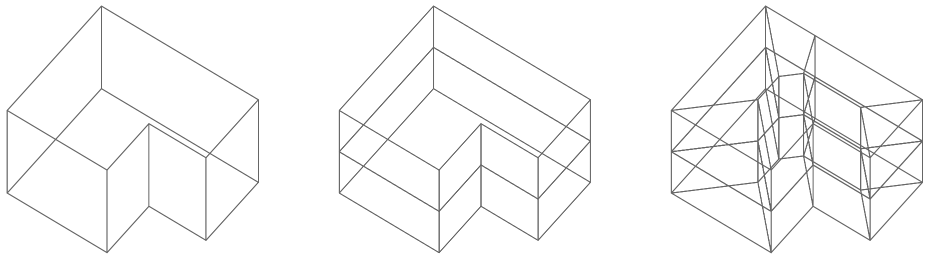
(b) Decomposed surfaces in green (356).

(c) Exploded view of surface matching (matched surfaces in green).

(d) Resulting walls: interior in green, exterior in red, adiabatic in dark grey.

Figure 5.14: Surface decomposition and matching for a one-floor model.

as a web-based application, where all the necessary information for a simulation is transmitted to the tool at once. In contrast to the other considered possibilities, no call to databases or additional data is necessary.



(a) Envelope. **(b)** Floors. **(c)** Zones.

Figure 5.15: Simplified geometry based on 2D L-shape, with successive decomposition of the envelope (5.15a) into floor (5.15b) and zone boundaries (5.15c).

5.4.3 Simulation implementation

Once all the input files are generated, simulation can be carried out using the chosen tools. Input model requirements for the two tools EnergyPlus and TRNSYS are presented in Section 3.3. The way simulations are executed and the files required for simulation vary according to whether co-simulation or mono-simulation is used.

Mono-simulation. In the mono-simulation case, simulation is carried out with EnergyPlus as a single tool. The execution of EnergyPlus is started directly from MATLAB, by calling a batch file with two arguments, giving the locations of the input model (IDF) and of the weather file.

Co-simulation. Co-simulation approaches for integrated simulation of building physics and HVAC systems have been reviewed in Section 2.2.6. We make use of a co-simulation environment based on Ptolemy II and the FMI++ library, developed at the Austrian Institute of Technology (AIT). The FMI++ library [197] provides high-level functionalities, making the use of different tools within the FMI specification easier. Like the Building Controls Virtual Test Bed, it is based on Ptolemy II [198], a software framework for heterogeneous systems.

In the co-simulation case, inputs correspond to a building model in EnergyPlus and a model of the HVAC system in TRNSYS. Each of these models is encapsulated in a *Functional Mock-up Unit (FMU)* containing auxiliary files and metadata, as illustrated in Figure 5.16. Finally, the co-simulation can be executed in the software environment Ptolemy II [198] using a statement of the co-simulation problem in XML form.

Thus, the files generated in the co-simulation case are as follow: (i) An EnergyPlus input file (IDF) containing, instead of HVAC-describing objects, external interface objects dealing with the exchange of temperature and heat transfer rate

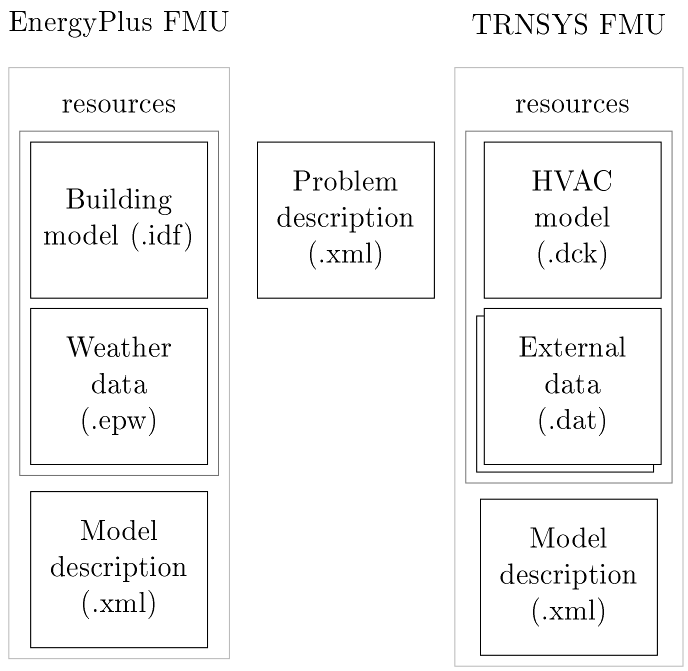


Figure 5.16: Files required for co-simulation and their encapsulation in two Functional Mock-up Units.

values; (ii) A Functional Mock-up Unit (FMU) containing the IDF, weather file and auxiliary files in given cases, produced with *EnergyPlusToFMU*, an FMU interface for EnergyPlus [199], which may be called through a batch file. (iii) A TRNSYS (.dck) file containing the model of the HVAC system; (iv) A corresponding FMU containing the .dck file and external data, created using the FMI++ TRNSYS export utility [188]; (v) An XML-based description of the co-simulation configuration using the previous files, for use in Ptolemy II [198]; (vi) A batch file allowing the co-simulation problem to be actually executed, once both FMUs are created.

Summary

This chapter has presented the architecture, design and implementation of a system for automated simulation model creation. The system architecture is composed of modules allowing an integrated building and HVAC model to be progressively created, before being translated into an input for specific simulation engines. This implies the use of a data structure allowing general building and HVAC models to be expressed.

In particular, this chapter has also explained how a simulation input can be derived from such a general model. This step is dependent on the requirements of the specific tools. It requires not only to map objects, but also to transform the structure of the model, and to complete it with additional information. This additional information includes a description of the system control, which is not contained in the physical HVAC model but depends on it, and simulation control parameters.

The presented system implementation offers several possibilities for the import of zoned building models. The import of building layouts from the *Space Modeler* shows the possibility of loading data from a CAD system, thereby using associated design and verification functions. However, it was found out that the desirable and accessible level of geometric detail was higher in the original layouts than in BPS tools, which could cause difficulties. Beyond ad-hoc corrections, robust simplification procedures would be desirable, but do not fall within the scope of this work. Two possibilities are implemented for simulation: mono-simulation with EnergyPlus and co-simulation of an EnergyPlus building model with a TRNSYS HVAC model.

The application of the proposed system to design support is demonstrated in the next chapter.

Chapter 6

Decision support for conceptual design

6.1 Overview

This chapter aims at demonstrating the application of the proposed system to design support in the concept phase. Design is meant both as building design and HVAC design.

In the absence of opportunities for case studies embedded in real planning processes, we opt for the use of fictitious scenarios illustrating each use case. The chapter is organized around the three use cases introduced in Chapter 3. For each use case, a general overview is followed by the presentation of a specific example. In the context of these use cases, the proposed system can be applied in many ways, to various buildings and various system types. The examples presented in the following are illustrative. Their results should not be extrapolated to other cases.

Common steps to all three use cases are the definition of HVAC systems for comparison, the simulation of alternatives, and the post-processing and display of results, which involves the calculation of performance metrics for each alternative.

Definition of HVAC system types. One of the tasks common to all use cases is to compare the performance of HVAC systems. An important step is thus the definition of these systems. As argued before, modeling each system manually is not plausible. Rather, each HVAC system model is created automatically based on a model of the building to serve and on a set of input parameters. These input parameters used to define each HVAC system, summarized in more detail in Appendix B, are numerous. More than 50 such parameters are used in defining a hydronic heating system. Thus, the user of the proposed system cannot be expected to set all these parameters for each simulation run. Some parameters will have the same values in all compared variants. This may be the case of parameters having been determined to be non-influential after sensitivity analysis, and of general parameters having no reason to differ between variants, for which a single best guess value is chosen. For the rest, sets of parameter values are assumed for each system type selected by the end user for comparison. All parameters are thus reduced to a single nominal macro-parameter representing a type of system. These system types can be seen as points to be chosen strategically in a high-dimensional parameter space. Firstly, they should be chosen inside of the subset of realistic systems. This not sharply defined subset could be characterized by physical and logical possibility, as well as technical and economic feasibility. Secondly, the subset of realistic systems should be discretized in some way. The number of resulting types should be low enough for the examination of results by an expert to be viable, and preferably high enough for promising solutions to be identified.

Performance metrics. In the same way as multiple input parameters are reduced to comprehensible "system types", simulation results ought to be condensed into performance metrics in order to facilitate their interpretation. This corresponds to functional requirement R5.

Since energy efficiency is the focus of this work, building performance metrics are bound to involve some measure of energy consumption. Given the variety of energy sources for HVAC systems, ways to compare energy quantities from different sources are required. Primary energy, which includes all losses from the extraction or production process, provides such a way of defining the cost of consumed energy. Primary energy use can be estimated from primary energy factors, as summarized in Table 6.1, keeping in mind that such factors depend on the corresponding energy supply infrastructure and are subject to variations. A distinction between the renewable and non-renewable parts of energy should be observed. Similar conversion factors can also be defined for carbon dioxide emissions, which stand for some of the environmental impacts of energy consumption.

Table 6.1: Conversion factors for primary energy and carbon dioxide emissions according to OIB Richtlinie 6. Primary energy f_{PE} and non-renewable primary energy $f_{PE,nr}$.

Conversion factor Unit	f_{PE}	$f_{PE,nr}$	f_{CO_2} g/kWh
Natural gas	1.17	1.16	236
Biomass	1.08	0.06	4
Electricity	1.91	1.32	276
District heat (renewable)	1.60	0.28	51
District heat (non-renewable)	1.52	1.38	291

Table 6.2 summarizes performance metrics used in this chapter. These metrics have in common that lower values indicate better performance, which makes comparisons easier. One may refer to Chapter 3 for a more general discussion of performance metrics.

The derivation of performance metrics from simulation results usually requires several operations. Let us illustrate this with the discomfort metric TD, which indicates the degree to which a heating systems fails to maintain sufficiently high temperature. One starts from simulated temperatures $\theta_i(t)$ for each (conditioned) zone and the respective heating set points $\theta_{min,i}(t)$. The temperature deficit at

Table 6.2: Performance metrics.

Metric	Unit	Description
TD	K	Temperature deficit relative to set point
UT		Proportion of temperature under set point
FE	kWh	Final energy
PE_{tot}	kWh	Primary energy
PE_{nr}	kWh	Primary non renewable energy
SL	%	System losses from primary to delivered energy
PA	m^2	Total pipe lateral area

time t in zone i is $d_i(t) = \begin{cases} \theta_{min,i}(t) - \theta_i(t) & \text{if } \theta_{min,i}(t) > \theta_i(t) \\ 0 & \text{otherwise} \end{cases}$. Averaging these numbers on the simulation period leads one value for each zone i: $\bar{d}_i = \sum_{t=0}^{T} d_i(t)$. Finally, a single metric for the whole building can be obtained by computing an area-weighted average of these n_z zone values: $TD = \frac{\sum_{i=1}^{n_z} a_i \bar{d}_i}{\sum_{i=1}^{n_z} a_i}$, with zone floor areas a_i. Note that other metrics representing for instance worst performance may be formed by using the maximum instead of averaging.

System losses (SL) are calculated as the relative difference of final energy use to delivered energy. As ambient energy is not taken into account in final energy use, these losses may be negative, for instance for heat pump systems. They do not include control inefficiencies related to occasional excessive delivery. An alternative way of calculating system losses would be to compare final energy to the results of ideal load simulation.

Result visualization. These metrics are eventually meant to be examined by users to inform design decisions. This is where visualization comes into play, to present these metrics and other more or less aggregated simulation results. Typical plots which may allow experts to evaluate the performance of HVAC systems are summarized in Table 6.3. Some plots (e.g. bar plots) may allow results for several

Table 6.3: Types of plots for the visualization of building and HVAC performance.

Plot type	Used to assess
temperature histograms	comfort
Sankey diagrams	subsystem efficiencies
stacked bar plots	energy use by component energy use by source
bar plots	primary energy use CO2 emissions
group bar plots	monthly energy use
time series plots	temperature dynamics energy rates

variants to be superimposed and directly compared, while others are preferably used for the detailed inspection of a single simulation run. Additionally, each of the use cases presented below may call for different types of graphical representation.

Simulations. Simulations for the following use cases are carried out as mono-simulation with EnergyPlus. Simulations are whole-year simulations with weather data corresponding to Vienna, Austria. Pipe losses are neglected, as a bug in the simulation tool prevents floor heating and detailed pipe models from being used simultaneously. The already presented simple 8-zone building model illustrated in Figure 6.1 is used.

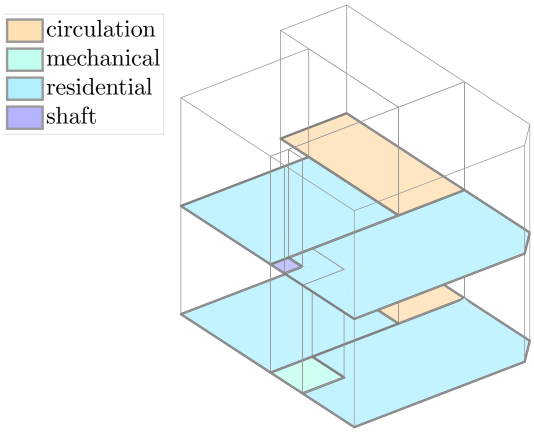


Figure 6.1: Example 8-zone model.

6.2 Use case 1

6.2.1 Overview

The first use case, defined in Section 3.1.2.1, is about comparing the performance of various HVAC systems for a given building with fixed properties.

In this case, the main steps of using the proposed system are as following: (i) A zoned building model is prepared. (ii) Sets of parameters corresponding to several system types are prepared. (iii) For each of these system types, a model is created and a simulation is run. (iv) The results are post-processed and displayed for verification and interpretation.

6.2.2 Example

This section describes an example application of use case 1. A heating system is to be selected for an existing building (construction year 1990).

Six system types are considered. Some significant properties of these systems are summarized in Table 6.4. As revealed by the choice of identifiers, the choice of a type of generation component is a major determinant of each system type. This goes along with the choice of a supply temperature.

A system like B-HT is not really a candidate, as a high-temperature boiler is expected to perform poorly in comparison to other generation components, if only gas boilers of a more recent and efficient type. However, it behaves as a baseline, and may represent an earlier system.

Table 6.4: Compared systems. The generation subsystems for the respective systems consist in district heating, high-temperature, mid-temperature and condensing gas boilers, an air-source heat pump (bivalent with a gas boiler) and a brine/water heat pump with ground heat exchanger (HeatPumpGX) in the form of a surface collector (SC).

System	**DH**	**B-HT**	**B-MT**
emissionComponent	floorHeating	radiator	radiator
generationComponent	DistrictHeating	BoilerHighTemp	BoilerMidTemp
generationTemperature	55	80	60
designLoopTempDiff	15	20	12
System	**B-C**	**HP-A**	**HP-SC**
emissionComponent	floorHeating	floorHeating	floorHeating
generationComponent	BoilerCondensing	HeatPumpAirSource*	HeatPumpGX
generationTemperature	45	40	40
designLoopTempDiff	12	10	10

6.2.3 Results

Multiple results have to be considered, including the use of different sources of energy and zone temperatures.

Table 6.5: Results for compared systems in use case one.

	TD	UT	FE	PE_{tot}	PE_{nr}	SL	PA
Unit	10^{-3} K	10^{-3}	MWh	MWh	MWh	%	m^2
DH	0.21	1.95	9.5	14.4	13.1	1	1.26
B-HT	0.13	1.91	11.1	13.0	12.9	29	1.27
B-MT	0.21	2.61	10.3	12.1	12.0	20	1.61
B-C	0.03	0.77	9.2	10.7	10.6	3	1.39
HP-A	1.55	8.73	6.8	10.9	8.5	−24	1.60
HP-SC	2.47	10.5	2.5	4.7	3.2	−73	1.60

Table 6.5 shows metrics calculated from simulation results for each simulated variant. Hourly values as displayed in Figure 6.2 are not very helpful for the comparison of energy use, because the simulated systems have different dynamics. It can be seen that the air-source heat pump switches on and off, with the smoothing of distributed energy relying on a small storage tank. A different appearance of the corresponding curve, as it can be observed from 04/01 to 06/01, reveals the

periods in which the gas boiler takes over heat generation. The total final energy used by each of the simulated systems is shown in Figure 6.3, with colors indicating the corresponding energy carriers. The surface collector heat pump system is characterized by a distinctly lower final energy use. Corresponding primary energy values obtained with primary energy factors are also displayed in Figure 6.3. The back-up boiler used with the air-source heat pump system represents a significant share of final energy use for this system.

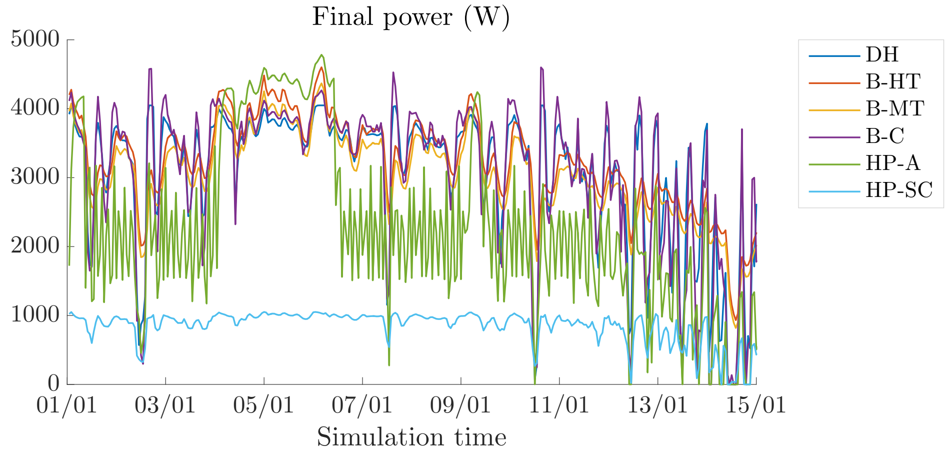


Figure 6.2: Final energy rate (W) for the first two weeks of the simulation period.

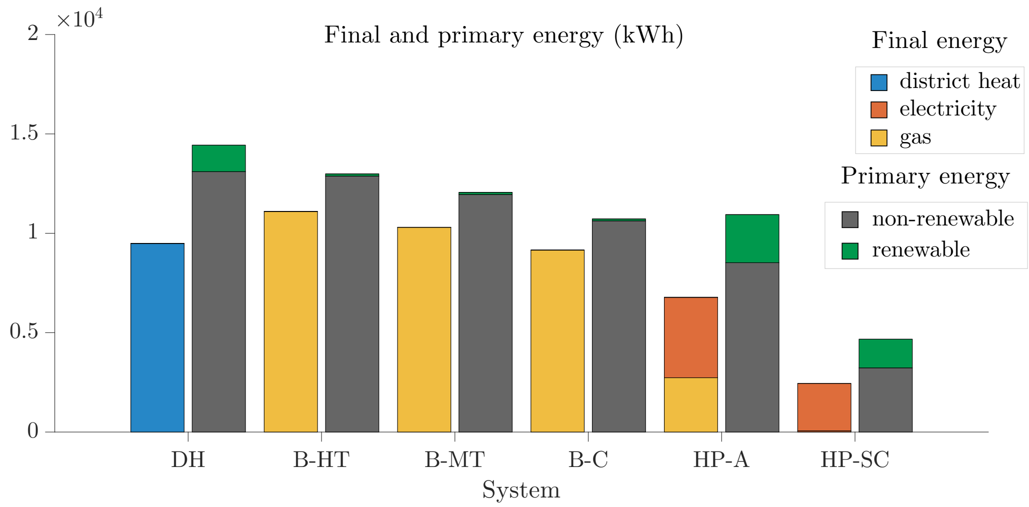


Figure 6.3: Final energy and primary energy consumption for each variant, for the one-year simulation period. Final energy is broken down by energy carriers, and primary energy is subdivided in renewable and non-renewable.

Figure 6.4 shows the distribution of zone temperatures with the six simulated systems. In this case, differences are hardly distinguishable, and all system types succeed in maintaining set point temperatures for almost the whole year, with very limited shortfalls. A slight overheating problem can be seen, for all systems. However, summer behavior is not addressed here.

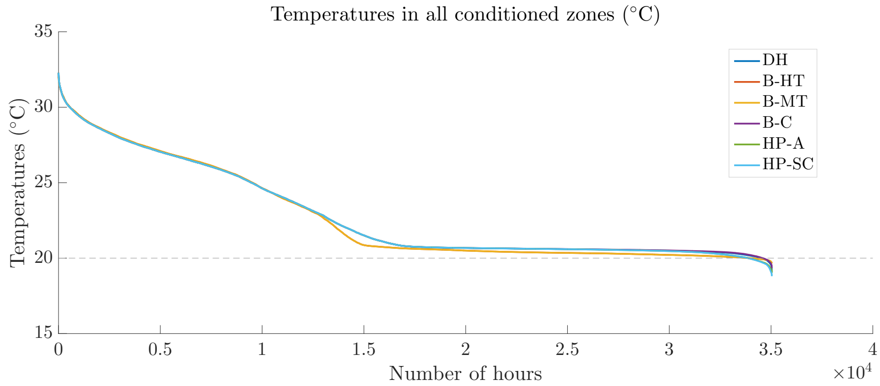


Figure 6.4: Distribution of hours with given temperatures.

The surface collector heat pump system clearly appears to be the best system in terms of energy use. It would probably also require the highest first costs.

Several aspects affecting the fairness of comparisons can be discussed. Primary energy factors have a significant influence. The primary energy factor for electricity used here (1.91) corresponds to Austrian guidelines. Compared to values of 2.8 in the German standard [148] and 3.07 in the UK standard assessment procedure for energy rating of dwellings [200, p.225], this is a relatively low value, which contributes to the favorable assessment of heat pump systems. The assumption that district heating uses energy from a heat plant operating with non-renewable sources is decisive in making the corresponding system the worst in terms of non-renewable primary energy use. The primary energy factor used for district heating (1.52) is high in comparison to values proposed in other European states [201]. One may argue that floor heating is at a disadvantage compared to radiator heating in terms of control modeling. While radiator heat delivery is ideally controlled to meet zone temperature set points, a proportional control scheme with a throttling range around set point is used for floor heating. To some extent, this difference in modeling can be justified by the higher inertia of floor heating systems.

6.3 Use case 2

6.3.1 Overview

Use case 2 was described in Section 3.1.2.2. It differs from use case 1 in that some degree of freedom in building design is added, so that not the alternatives to investigate differ not only by the installed HVAC system, but also by properties of the building envelope.

This use case tackles the interplay of passive and active measures, which is recognized to play an important role in energy-efficient building design [202]. There is a broad consensus that the optimization of passive features should have priority. One could start by determining those, for instance with the help of ideal load simulation, and then decide on the best HVAC system to serve the building, which corresponds to use case 1. However, the importance of interactions between building and HVAC system could invite designers to consider several HVAC alternatives before finalizing the envelope design, as here.

This use case is characterized by a higher number of design variables. Variations in envelope and HVAC parameters could be made in many ways. For simplicity, we use a factorial design, considering all combinations of a number of envelope variants and HVAC variants. One obtains a matrix of alternatives with the two dimensions of envelope and HVAC system.

6.3.2 Example

This section describes an example application of use case 2. HVAC selection and adjustment of envelope properties are considered concurrently.

This example assumes the construction of a new building. Envelope variations are formed by increasing quality step-wise, starting from a base case corresponding to current minimum requirements, and improving it one component (building element) at a time, as summarized in Table 6.6.

Table 6.6: Compared envelope qualities. U-values in W/(m^{2}K).

Id	**1**	**2**	**3**	**4**	**5**	**6**
Improvement	Base	Wall	Roof	Ground	Window	Airtight
main infiltrationRate	0.11	0.11	0.11	0.11	0.11	0.04
groundUValue	0.4	0.4	0.4	0.2	0.2	0.2
wallUValue	0.35	0.2	0.2	0.2	0.2	0.2
roofUValue	0.2	0.2	0.12	0.12	0.12	0.12
windowUValue	1.4	1.4	1.4	1.4	1.0	1.0

The same six types of HVAC systems are considered as in the first use case example. This results in 36 combinations to simulate.

6.3.3 Results

Figure 6.5 shows the results of the use case example in terms of primary non-renewable energy use. Improvements in envelope quality result in lower primary energy use. The corresponding drops in energy use are largest for the first and third steps (better wall and ground insulation). Improving on the already well-insulated roof appears less effective. The relative scores of the considered systems remain similar for each envelope quality, with exception of the district heating system, which becomes better than the high- and medium-temperature boilers for better envelopes. The ground-source heat pump system consumes considerably less energy than all other systems, even for the base envelope quality. As a consequence, the absolute values of savings realized with improved envelope quality are lower than for other systems. The primary energy demand of the most energy-intensive system (high-temperature boiler) with the best envelope alternative is less than that of the air-source heat pump with the base envelope. In order to

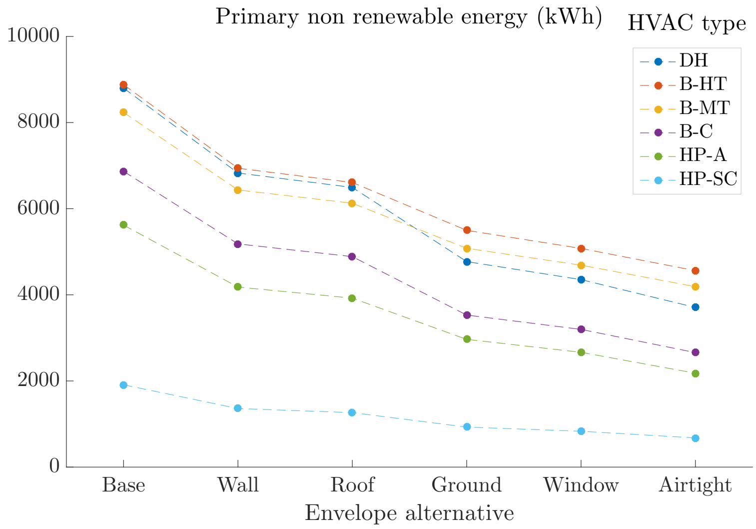


Figure 6.5: Primary (non-renewable) energy for the 36 simulated alternatives in use case 2 example.

find the right tradeoff between improving envelope and choosing a more efficient HVAC system, installation and operation costs should also be considered. In this respect, envelope improvements can also reduce initial costs by allowing smaller HVAC systems to be used.

6.4 Use case 3

6.4.1 Overview

Use case 3 was described in Section 3.1.2.3. It specifically deals with retrofit situations, and differs from the first two use cases in that only part of the HVAC system is to be modified. Such partial replacement of an HVAC system may be motivated by the unequal service lives of components. As summarized in Table 6.7, delivery components and pipes in heating systems are typically more durable than generation components and pumps.

Also, the refurbishment of the building envelope may lead to situations where the installed HVAC system is not appropriate any more. Refurbishment may aggravate an already present oversizing of the installed system. There is indeed evidence that a significant proportion of existing HVAC systems are oversized [204]. This usually derives from the use of safety factors, which have been seen as a way of reducing uncertainty [205, p.2], but often impair performance [206]. Also, the impact of refurbishment on loads to be met may vary for each zone, potentially compromising the balance of the installed HVAC system.

It is assumed that the distribution and delivery subsystems are preserved, with the exception of pumps. In order to optimize the performance of the new subsystem, the replacement of the generation subsystem can be associated to a lowering of supply temperatures. However, this is constrained by the conservation

Table 6.7: Average service life of heating system components according to VDI 2067 guideline [203].

Component	**Service life** (in years)
cast iron radiator	40
panel radiator	30
floor heating	50
steel pipes	40
circulating pump	10
gas boiler	18-20
wood pellet boiler	15
heat pump (air/water)	18
heat pump (water/water)	20

of the delivery components, as their capacity depends on water temperatures.

The procedures described in this thesis can be combined in such a way as to answer the questions asked. In a first step, a simulation model corresponding to the original heating system is created. Parameters corresponding to this original system are used, including an assumed safety sizing factor, and the calculation of design loads is carried out with envelope properties before refurbishment.

In a second step, a simulation model for a new heating system can be created, using new system parameters and refurbished envelope properties. In order to model the maintained delivery components, their capacity is retrieved from the original model and, if applicable, modified to account for temperature changes. It can then be verified that the capacity of these existing components is sufficient for the actual new conditions.

6.4.2 Example

We test the use case on a refurbishment scenario described in the following. The building envelope of a house is to be refurbished. The existing central heating system uses a high-temperature gas boiler for generation, and radiators for heat delivery. Standard default values are assumed for the original envelope, according to construction year 1960, and for the refurbished one, according to current standards. A global oversizing of 25% is assumed for the existing system.

$$\dot{Q}_{op} = \dot{Q}_n \left[\frac{\frac{\theta_{s,op}-\theta_{r,op}}{\ln\left(\frac{\theta_{s,op}-\theta_{a,op}}{\theta_{r,op}-\theta_{a,op}}\right)}}{\frac{\theta_{s,ref}-\theta_{r,ref}}{\ln\left(\frac{\theta_{s,ref}-\theta_{a,ref}}{\theta_{r,ref}-\theta_{a,ref}}\right)}} \right]^n \tag{6.1}$$

Radiator capacity is modified according to Equation 6.1 [165, p.787] with θ_s supply temperature, return temperature θ_r and air temperature θ_a in both operational op and reference (or standard) ref conditions. For the heat output exponent n describing the non-linear relation between heat output and temperature difference, a typical value of 1.3 is assumed [165, p.1296].

We would like to investigate three types of generation equipment, and several levels of supply temperature for each of them, as summarized in Table 6.8.

Table 6.8: Parameters of the compared systems. Considered generation components are high-temperature gas boilers (B-HT), condensing gas boiler (B-C) and air-source heat pumps (HP-A).

Parameter	**BHT80**	**BHT60**	**BC60**	**BC50**	**BC40**	**HP50**	**HP40**
deliverySizingFactor	1.2	1	1	1	1	1	1
generationComponent	B-HT	B-HT	B-C	B-C	B-C	HP-A	HP-A
generationTemp.	80	60	60	50	40	50	40
designLoopTempDiff	20	20	20	15	10	15	10

6.4.3 Results

Table 6.9: Minimal ratios of available capacity to required capacity for the simulated system alternatives. A value under 1 signifies a lack of capacity.

System	**Delivery capacity**	**Mass flow rate**
BHT80	2.28	2.28
BHT60	1.14	2.28
BC60	1.14	2.28
BC50	0.78	1.72
BC40	0.46	1.14
HPAS50	0.78	1.72
HPAS40	0.46	1.14

The ratios summarized in Table 6.9 indicate the proportion of required capacity which is available with the different alternatives, both in terms of the heating capacity of delivery components (following Equation 6.1), and in terms of the mass flow rate which pipes are to accommodate. The latter is proportional to the design heat load and to the inverse of the temperature difference between supply and return. The capacity ratio for the existing system (BHT80) means that the envelope refurbishment and the abandonment of a safety factor for sizing result in a halving of the design heat load. For all other considered systems, the delivery capacity ratio is lower than the mass flow rate ratio. Thus, the capacity of installed delivery components, rather than the diameter of pipes, will determine how much supply temperatures can be lowered.

Simulation results for the considered alternatives are summarized in a radar chart in Figure 6.6. Comfort performance metrics UT and TD give a different interpretation of the static capacity ratios of Table 6.9: indeed a supply temperature of 40 °C does not allow delivery components to provide enough heat to the spaces, but temperatures of 50 °C are sufficient, whereas the static calculations gave a contrary indication.

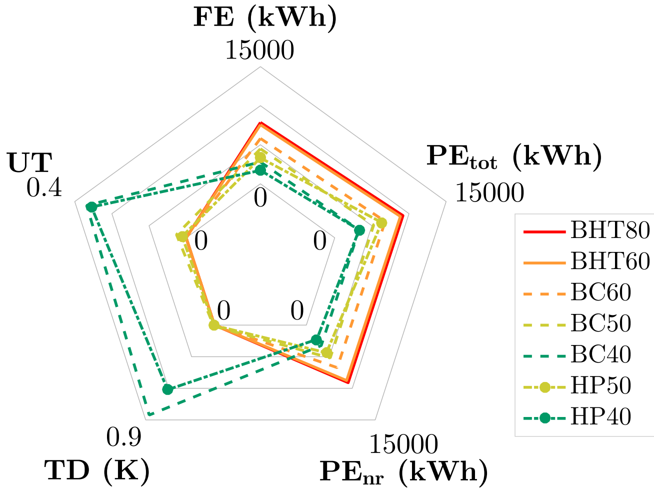


Figure 6.6: Performance metrics for the simulated alternatives for a partial HVAC system renovation.

As expected, the energy use of condensing boilers and heat pumps decreases when their set point temperature is lowered. The choice is thus reduced to the two best-performing alternatives: BC50 and HPAS50.

6.5 Discussion

This section discusses the results obtained with the three use cases. One may start by remarking that the creation of simulation models, on which the bulk of this thesis has focused, is only part of the effort needed for building performance analysis in the context of design support.

Some post-processing of simulation results is necessary, starting with aggregation. Looking at (sub)hourly time plots corresponding to the raw results of simulation is not the most fruitful way of investigating results. The results of several simulated alternatives must be compared, which adds to the challenge of visualization and post-processing. The three use cases call for different ways of analyzing and displaying results. Some pre-processing is also required, consisting in the preparation of sets of parameters corresponding to each alternative. Both pre- and post-processing also pose the risk of errors, which may include trivial errors, such as the omission of values in aggregating energy uses, but also less clear-cut issues related to the understanding users may have of input parameters.

Compared to simpler methods of performance analysis, an additional difficulty is the consideration of cases in which the HVAC systems may fail to provide the required comfort. All comparisons must take into account several objectives. Some of these objectives can be represented by performance metrics. Others are assumed to correspond to stakeholder knowledge. This is the case for everything related to economic performance.

Different performance results for the same system types in different cases prove the value of the proposed approach compared to the simplistic approach of assigning default efficiency coefficients to system types.

Use case 3 represents a first step towards more complex and less linear applications that may come up in real systems which change over time. Variations of these use cases (extensions) alluded to in use case definition have not been addressed here. In real design applications, feedback loops would be possible and probably necessary. The parametric definition of system types may be modified after observing results (e.g. because previous parameters did not yield sufficient comfort), system types found to perform poorly may be removed, or new system types may be added, for instance in the neighborhood of well-performing types. Such iterations could also be guided by other actors in the design process than the simulation user.

In the applications presented in this chapter, performance analysis is carried out in a deterministic way, without taking into account uncertainties. Overcoming this limitation would be challenging in more than one respect. Sensitivity analysis taking into account separately design variables and uncertain variables is indeed acknowledged to be difficult to carry out and interpret [207].

Summary

This chapter investigated the application of the proposed system to three different use cases for which it was developed. A common method used in all three cases is to create simulation models for a number of alternatives, carry out simulation and post-processing.

Use case 1 may be considered as the most straight-forward, since the objective is simply to compare the performance of several types of HVAC systems. Use case 2 is potentially more complex, as design variables related to the building enveloped are also considered. Use case 3, on the other hand, is more constrained than use case 1, as only the generation subsystem is subject to variations. It is also more involved, as it demands the consideration of previous buildings and HVAC systems together with refurbishment measures. As a consequence, the way the procedures developed in this thesis have to be combined differs from the previously considered cases.

By investigating how the proposed system can be applied to the use cases for which it was developed, this chapter represents a first test. The usefulness of the proposed system will depend on the quality of the simulation models it generates. System validation is addressed in the next chapter.

Chapter 7

Comparative testing

Verification and validation of the software system described in the previous chapters are the main objectives of this chapter. One may define verification as determining that the system accurately represents the specifications and concepts underlying its development, and validation as determining the degree to which the system provides an accurate representation of the real world from the perspective of its intended use [208]. After introducing these objectives, this chapter shows how the proposed system can be tested by comparing its results with each other and with reference values. By testing the system, we mean submitting it to a critical evaluation, using procedures that will either lead to the discovery of errors or to gaining confidence in the system. Testing the system in multiple conditions is expected to bring a first answer to the question of how sensible the results are, and how sensitive to various parameters. In this chapter, this is done by comparing: (i) obtained model parameters with standards; (ii) simulation results obtained with varying input parameters; (iii) simulation results obtained with different simulation implementations. Moreover, some of the comparative testing may also highlight the benefits of detailed HVAC simulation based on the HVAC system generation method. This is a first step towards validation of the system.

7.1 System accuracy and validation

Defining what it means to validate the proposed system for automated generation of building and HVAC simulation models is not straightforward. Difficulties include the facts that the system may be expected to operate on a wide variety of inputs, and that it relies on other tools (simulation engines) for which validation is a challenging endeavor. This section starts with a review of approaches to the validation of building performance simulation. After this, validation objectives for the proposed system are presented, and the use of sensitivity analysis for validation is discussed.

7.1.1 Validation of building performance simulation

A prerequisite for the validation of the proposed system is the validation of the simulation programs for which it creates inputs. Judkoff [209] distinguishes between three main techniques of evaluating the accuracy of a building energy simulation program, each of which presents disadvantages limiting its claim to absolute validity:

- *Empirical validation* is based on the comparison of simulation results with monitored data. It is limited by experimental uncertainties and the cost of each experiment.
- *Analytical verification* is based on the comparison of simulation results with known analytical solutions. These are only available for very schematic configurations, and the validity of the actual model is not tested.
- *Comparative testing* is based on the comparison of simulation results produced by different programs or the same program. It provides only relative results.

The designations for these three techniques reveal that they pertain to three different kinds of processes: validation, verification and testing are not synonymous. Considering simulation models in general, Sargent [210] defines model verification as “ensuring that the computer program of the computerized model and its implementation are correct” and model validation as ensuring “that a model within its domain of applicability possesses a satisfactory range of accuracy consistent with the intended application of the model”. Validation is determined with respect to a specific purpose. Given the empirical nature of buildings, building simulation validation can only be empirical. Parameter adjustments in order to improve the goodness-of-fit of simulation results to measured references are referred to as calibration and addressed in Chapter 9. Calibration should not be mistaken for validation, or used to increase confidence in a model. Next to empirical validation, analytical verification and comparative testing play an important role in the assessment of simulation software and models. Comparative testing makes it possible to extrapolate from the individual cases for which empirical validation can be done to a wide range of input parameters [209]. In particular, discrepancies identified thanks to intermodel comparisons can help to locate areas requiring further investigation.

The BESTEST (Building Energy Simulation Test and Diagnostic) method [211] combines the three techniques, starting with analytical verification, followed by empirical validation, while comparative testing makes extrapolation possible and can pinpoint areas for further investigation. These tests are partly incorporated in ANSI/ASHRAE Standard 140 (Standard Method of Test for the Evaluation of Building Energy Analysis Computer Programs).

EnergyPlus was subjected to formal independent testing [212], using collections of analytical tests (usually for simple configurations, e.g. cube with the same construction on all six sides, ASHRAE 1052RP), comparative testing (ASHRAE Standard 140P), empirical testing and sensitivity testing. TRNSYS was also subjected to validation efforts. The calculation of heating and cooling loads was validated according to ASHRAE Standard 140 [213]. Validation is generally carried out and presented for each new component model (type).

Table 7.1: Error types in simulation according to Judkoff and Neymark [209]. The distinction between internal and external error types is relative to the simulation engine.

External error types
Differences between weather input and actual microclimate
Differences between assumed and actual occupant behavior
User error in deriving building input files
Differences between input and actual building or HVAC properties
Internal error types
Differences between actual physical processes and simplified models
Inaccuracies in the mathematical solution of the models
Coding errors

Table 7.2: Error types for the developed system. Different from Table 7.1, the distinction between internal and external error types is relative to the developed system.

External error types
Use of the system for cases where it is not applicable
User input error
Errors in input data and external databases
Internal error types
Inaccuracies in creation of HVAC system model
Errors and inaccuracies in translation to tool-specific model
Coding errors

In the context of simulation engine validation, one has distinguished internal and external errors types, as summarized in Table 7.1. Only internal sources of errors can be ruled out by validation. External sources of errors may be resolved by the training of users, better interfaces or the use of reliable input repositories. A similar distinction can be proposed for our proposed system, as in Table 7.2. The reference being different, some errors internal to our system can be external with regard to the simulation engine. These are the errors which we can hope to minimize by testing our system.

Finally, one should distinguish errors from uncertainties. Defining uncertainty as “any deviation from the unachievable ideal of completely deterministic knowledge of the relevant system”, Walker et al. [214] distinguished three relevant dimensions of uncertainty: location, level and nature. Sources of uncertainties in model outputs can be grouped in several categories, as in Table 7.3. Which sources of uncertainties can and should be taken into account depends on the tools used and on the problem at hand. For instance, in a study on the thermal performance of buildings under climate change [215], de Wilde and Tian considered specification and scenario uncertainties, and not modeling and numerical uncertainties.

Table 7.3: Sources of uncertainty. The classes are taken from two pieces of research dealing with computerized models in general [216] and with building performance simulation [205]. Examples are related to the present work. Distinctions correspond to both location and nature of uncertainties [214].

General ([216])	**BPS** ([205])	**Example**
Parameter uncertainty	Input parameters	Parameters of boiler efficiency curve.
Model inadequacy	Model realism	Adequacy of quadratic curve for boiler efficiency.
Residual variability	Stochastic processes	Future weather, occupancy.
Code uncertainty	Simulation program	Choice of algorithm.
Parametric variability	Design variations	Choice of boiler.
Observation error		In calibration cases.

7.1.2 Validation objectives

Given their history of validation and verification, simulation tools like EnergyPlus deserve a high degree of confidence. However, this confidence cannot be transferred to the proposed system without more ado.

Reasons not to trust the proposed system include the impossibility of validating individually the infinite number of models that could potentially be generated by the system, the length of the chain that leads from available data to performance feedback and the size of the system implementation, considering that “an error in even one character of one line of code can lead to seriously flawed results” [209]. The number of parameters in each model is also an issue (e.g. more than sixty parameters for a single ground heat exchanger model component in TRNSYS, depending on the number of pipes).

Hence the necessity of a significant effort for building confidence in the system. Confidence in the system may be increased gradually if the system fulfills expectations for a number of cases.

The system may fail at various points, and one may distinguish several levels of expectations. The following expectations are listed by order of difficulty: (i) The execution of the system with valid inputs should lead to the creation of a simulation input file. In contrast, errors should be raised for invalid combinations. (ii) The created input file should be executable without error and yield the desired results for the whole specified simulation period. (iii) The executed simulation should correspond to the system behavior assumed by the user: temperatures should remain near set point or control dead band, energy should be supplied by the generation system and delivered by delivery components when needed etc. (iv) Resulting performance indicators should roughly correspond to known rules of thumb and experience values. (v) Resulting performance indicators should feature meaningful variations as expected when changing the values of input parameters; (vi) Given appropriate inputs corresponding to a real case, results should comply with measurable reality. (vii) The system should be useful in supporting conceptual building and HVAC design.

The ultimate goal would be to validate the system in terms of its ability to support building and HVAC design. This would require user studies and is not pursued in the present work. A necessary but not sufficient condition would be that all preceding expectations be fulfilled, and in particular that created simulation models yield reasonable results. The system would also have to be usable, and allow alternatives considered by planners to be modeled and compared satisfactorily. Also, gains resulting from the presumably higher modeling accuracy obtained with the proposed system should outweigh the effort spent on using the system.

7.2 Comparison with existing HVAC systems

Static characteristics of HVAC systems may allow for results of the proposed system to be compared to actual systems planned by professionals. Such comparisons make all the more sense since the HVAC model creation method is inspired by common workflows for system sizing.

7.2.1 Case study: hydronic heating distribution

Introduction. This case study overlaps with the case study presented in [217] to illustrate the creation of distribution subsystem models. There are minor differences in input parameters and consequently in results between the two.

In this case study, the model creation procedures are applied to an existing academic building in Vienna, Austria. The building, first constructed in 1930, is equipped with a recently refurbished central hydraulic heating system, with radiators as delivery components. This case study focuses on the six uppermost floors, which include offices and are served by the heating system. Plans of the heating system are available in 2d line drawings, except for the last floor, so comparisons of pipe lengths are based on five floors.

Default values corresponding to construction year 1930 were assumed, except for windows, which have been recently changed and for which a U-value of 1.2 $W/(m^2K)$ was assumed.

Concerning the delivery subsystem, a radiator is placed under each window. This heuristic rule does not exactly correspond to the actual system, as radiators are indeed located under windows, but not for all windows.

The HVAC model creation procedure is applied to this building with three sets of parameters summarized in Table 7.5.

Table 7.5: Parameter sets for comparison of system characteristics with real heating system in an academic building in Vienna, Austria. NPDC intermediate nodes are either centroids of non-conditioned zones ('few') or offset space boundary vertices ('many'). The tree finding algorithm is either minimum spanning tree (MST) or shortest path (SP).

Parameter	**Parameter set**		
	A	**B**	**C**
NPDC z-weighting	1	1	1
NPDC intermediate nodes	few	many	many
Tree finding algorithm	MST	MST	SP

Table 7.6: Comparison of system characteristics in the existing system and in the created models. Pipe lengths are compared for floors 1 to 5. For pump hydraulic power P_h and electric power P_{el}, the first value corresponds to the product's maximum capacity, whereas the value in brackets corresponds to the design point indicated in the system documentation.

Characteristic	**Unit**	**Existing**	**Created models**		
			A	**B**	**C**
Number of radiators		165	265	265	265
Pipe length	10^3 m	1.42	1.34	1.64	2.70
$\dot{V}_{max}$	m^3/h	21.4	20.0	20.0	20.0
Main pipe size	mm	100	86	86	86
Pump head	m	13 (7.5)	5.5	5.3	3.4
P_h	W	980 (440)	297	290	185
P_{el}	W	1550 (800)	743	723	462

Results. Table 7.6 presents a comparison of real and generated system characteristics. As expected, the pipe layout obtained with parameter set A is simpler and more direct than the one obtained with many intermediate nodes (B). This is reflected in the corresponding sums of pipe lengths, which are below the real values for A and above for B. The shortest path algorithm (C) yields a star-like structure which is found to largely overestimate total pipe lengths, while yielding a low estimate of pump head.

In reality, nominal pipe sizes have discrete values (DN 80, DN 100, DN 115), and the obtained internal diameter of 86 mm would probably be rounded up to a pipe of diameter DN 100.

Considering the properties of the circulating pump, one ought to distinguish the maximum capacity of the installed product from the design values. The heating system documentation mentions a pump head of 7.5 m, less than the maximum head of 13 m allowed by the pump. Together with the volume flow rate of 21 m^3/h, this means a design hydraulic power of 440 W, considerably less than the pump maximum (980 W).

The installed pump has a good efficiency rating (energy efficiency index EEI $\leq$ 0.20). According to the characteristic curves, the power consumption at the design point (7.5 m and 21 m^3/h) is around 800 W, which corresponds to an efficiency P_{el}/P_h of 0.55. The proximity of design electric power for the real pump and created models A and B partly results from a compensation effect due to the underestimation of both pump head and pump efficiency.

7.2.2 Discussion

Comparing characteristics of real HVAC systems to those of models created with the proposed system, one can assess the reliability of the latter, and the value of some assumptions it uses. A comparison of pipe lengths in the previous case study can lead to a conclusion concerning the use of different algorithms for distribution tree finding: the minimum spanning tree should be preferred to the shortest path algorithm, which yields distribution layouts with an implausibly high total pipe length. However, one cannot treat every manually sized system as an absolute reference or optimum. Solutions realized in practice in response to the same design problem may vary. The question of whether existing systems are oversized, and to what extent, should also be asked. As a consequence, more real buildings would need to be modeled to test the plausibility of generated models. Presently, the evaluation of real system characteristics (e.g. total pipe lengths) can be cumbersome, involving manual selection of elements or even redrawing. With the uptake of BIM, objects to compare and their properties may be systematically extracted and make such comparisons much easier. In the meantime, comparisons with default values from standards may allow the developed system to be tested in more cases.

7.3 Comparison with standards

Candidates for a comparison with default values from standards and guidelines are both static characteristics of the generated models and metrics calculated from simulation results. In the following, we focus on the former.

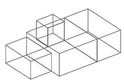
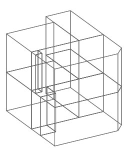
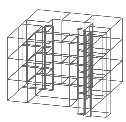
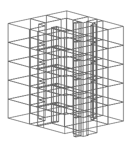
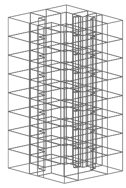
Given the parametric character of the proposed HVAC model creation methods, a one-to-one comparison between system characteristics obtained with them and default values from standards is not possible. Rather, several sets of parameters for HVAC model generation are considered, and several standards are considered.

Default values in standards are generally based on a very limited number of variables, typically starting from building size, whereas the proposed system tries to reflect the impact of a higher number of variables on HVAC systems. For instance, pipe lengths obtained with our system depend on envelope quality (through sizing), zone uses and the locations of delivery components therein, in addition to layout creation parameters. Conversely, European standards for hydronic systems often only distinguish between radiators and floor heating.

7.3.1 Comparison of pipe lengths

Formulas for default pipe lengths are obtained from the following standards: (i) The Austrian Standard *ÖNORM H 5056* [167] on the energy use of heating systems; (ii) The German version of the preliminary European Standard *EN 15316-3* on space distribution systems [218]; (iii) The German Standard *DIN V 18599-5* on the final energy demand of heating systems [219].

Table 7.7: Example buildings for comparison of system characteristics, with n_f number of floors and n_z number of zones. More information on these buildings is presented in Appendix C.

Building	**1f4zR**	**2f8zR**	**3f35zR**	**5f57zR**	**8f80zR**
n_f	1	2	3	5	8
n_z	4	8	35	57	80
Floor area (m^2)	100	84	530	880	$1.4 \cdot 10^3$
Outline					

The comparison is made for four example buildings whose characteristics are summarized in Table 7.7. Models are created with four distinct sets of parameters summarized in Table 7.8.

Figure 7.1 shows the total pipe lengths obtained with our system (round markers) and with standard equations (square markers), for the four buildings. For

Table 7.8: Parameter sets for experiments to compare pipe lengths and pump power. NPDC intermediate nodes are either centroids of non-conditioned zones (few) or offset space boundary vertices (many). A z-coordinate weight of 1.5 in the NPDC favors layouts with more horizontal (H) segments, whereas vertical (V) segments are favored by a weight of 0.5.

Parameter	**Parameter set**			
	Simple H	**Simple V**	**Detailed H**	**Detailed V**
NPDC z-weighting	1.5	0.5	1.5	1.5
NPDC intermediate nodes	few	few	many	many
Tree finding algorithm	MST	MST	MST	MST
pump overall efficiency	0.4	0.4	0.4	0.4

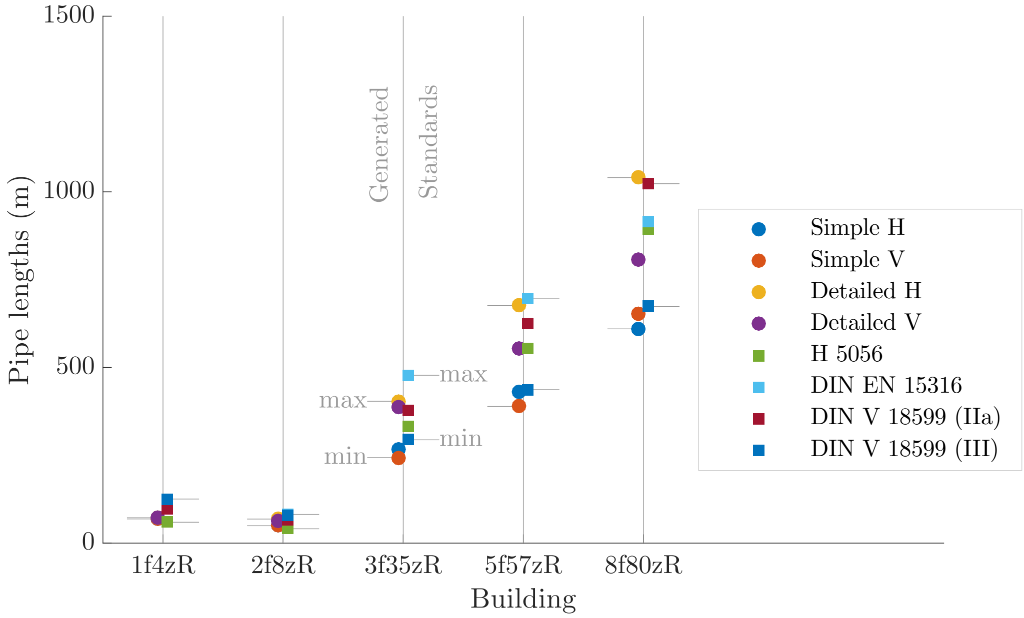


Figure 7.1: Comparison of pipe lengths obtained with model generation (with the 4 parameter sets of Table 7.8, round markers) and according to 3 standards (square markers).

every building, there is an overlap between the min/max interval of generated values and that of values from standards. The former values are generally lower that the latter. Pipe lengths obtained with simpler networks (Simple H and Simple V) are consistently near the bottom range of standard values. Pipe lengths obtained with detailed networks are higher, especially for the larger buildings.

Further, one may try to compare lengths for different pipe types. In the standards, three types of pipes are distinguished according to their location: (i) connection pipes, which are horizontal and connect delivery components and riser pipes; (ii) riser pipes, which are vertical; (iii) main distribution pipes (from generation to risers). In the generated models, we may distinguish: (i) horizontal pipes part of distribution groups; (ii) vertical pipes part of distribution groups; (iii) primary pipes not part of distribution groups, but added later between generation components and distribution groups, including circuit pipes. There is no exact one-to-one mapping between the two classifications: most horizontal pipes in group distributions would be connection pipes, but some of them would be classified as main distribution pipes.

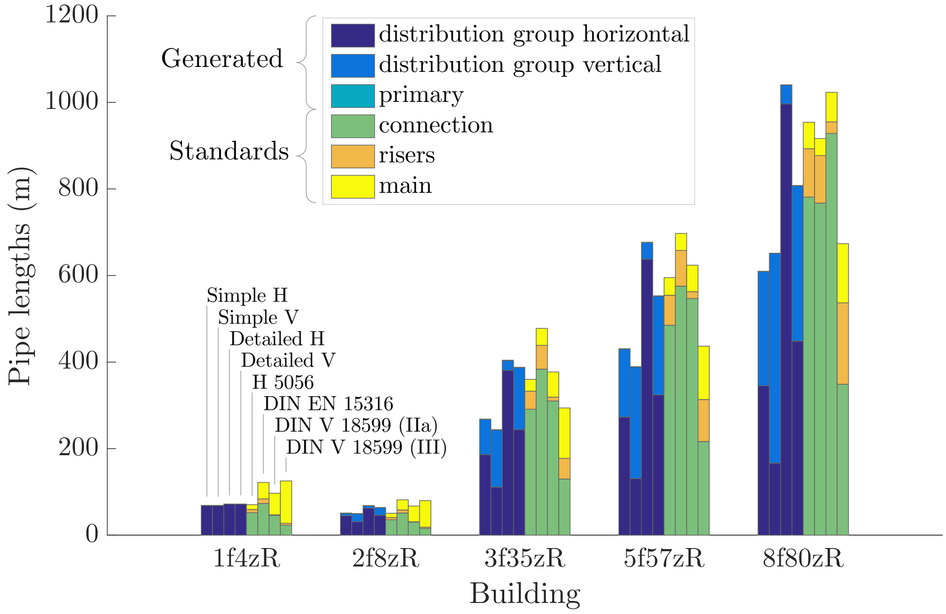


Figure 7.2: Comparison of pipe lengths obtained for 4 buildings, with model generation (with the 4 parameter sets of Table 7.8) and according to standards (H5056), disaggregated by type of pipe.

Figure 7.2 shows total pipe length and the respective proportions of these pipe types in the investigated cases. Default riser lengths are similar to the lengths of vertical pipes in the models created with the horizontal-promoting parameter sets (H), but significantly exceeded with the other parameter sets (V). The default lengths of main distribution pipes are significantly higher than the (very low) lengths of primary pipes in the created models. However, as already mentioned, some of the group pipes running in primary equipment rooms should be considered as main distribution pipes. Besides, our model creation procedures are limited in that they do not yield detailed pipe layouts in primary equipment rooms.

7.3.2 Comparison of pump power

In the following, the compared system characteristic is pump power at design conditions. Pump electric power P_{el} depends on pump hydraulic power P_h and pump efficiency. The overall efficiency of a pump can be seen as the product of its hydraulic efficiency and of the efficiency of its motor. Pump hydraulic power is the product of water flow rate and pressure difference, which in turn can be seen as depending on the most unfavorable (longest) distribution path. As a consequence, there may be a balancing or a multiplication of successive errors and uncertainties.

Comparisons are made with default values from two standards. ÖNORM H 5056 [167] gives default values for the electrical power consumption P_{el} of pumps for several system temperatures and types of delivery subsystems. For instance, $P_{el} = 45\,\mathrm{W} + 0.11\,\mathrm{W/m^2}\ BF$ for a heating circuit serving a space of gross floor area BF (in m^2) with 55 °C / 45 °C supply and return temperatures. DIN V 18599-5 [219] also allows default values to be determined for the electrical power consumption of pumps. However, these values are not calculated directly, but through intermediate default values for maximal pipe path length and pressure drop. The assumed maximal pipe length depends on the characteristic length and width of each building.

Models are created with the parameter sets in Table 7.8, for the five building models summarized in Table 7.7. It is desirable to carry out the comparisons for various building sizes, as the increase of pump power is not linear.

Results for longest pipe lengths, pump head, pump hydraulic power and pump electric power are shown in Figure 7.3.

Our systems rather leads to slightly lower maximum path lengths than standard 18599-5 for smaller buildings, and higher lengths than standard for larger buildings. As assumed flow rates are the same, relative differences in hydraulic power are the same as relative differences in total pressure drops. These differences are rather limited.

Standard DIN V 18599-5 considers the fact that large circulating pumps are generally more efficient than smaller ones:

$$f_e = \left(1.25 + \left(\frac{200\,\mathrm{W}}{P_h}\right)^{0.5}\right)\ b \tag{7.1}$$

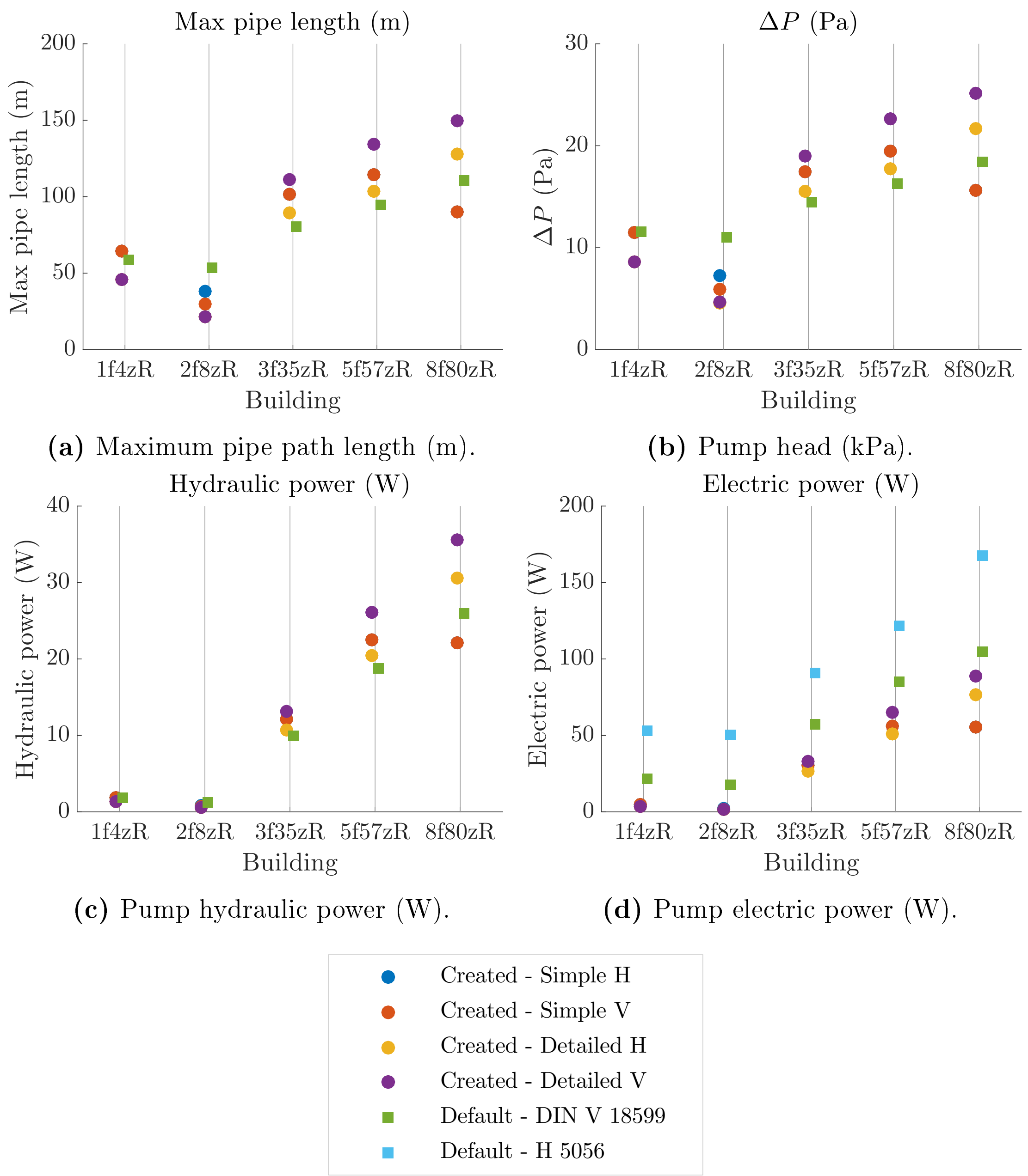
where $f_e = P_{el}/P_h$ is the inverse of pump efficiency and b is an oversizing factor.

As illustrated in Figure 7.4, this yields very low pump efficiency factors for smaller buildings, significantly smaller than our default factor 0.4. EU regulation 547/2012 [220] imposes lower limits on an efficiency index depending on pump type and characteristics, such that hydraulic efficiencies of new pumps should be superior to 0.6 in most conditions. As for motor efficiencies, they are required to be higher than 0.75 by EU regulation 640/2009 [221]. Thus, the default factor used in our system seems to be more realistic, at least for recent systems. Size-dependent efficiency values corresponding to existing regulations could also be integrated in the model-creation system.

Standard H 5056 seems to overestimate pump power significantly and for all test buildings, even in comparison to standard DIN V 18599.

7.3.3 Discussion

Characteristic values for pipe lengths and pump characteristics obtained with different standards vary significantly. When comparing values obtained from our method with those from standards, one cannot take any of these as a ground truth. One should also keep in mind the fact that some default values are deliberately pessimistic, if only to encourage users to research actual values or carry out



(a) Maximum pipe path length (m).

(b) Pump head (kPa).

(c) Pump hydraulic power (W).

(d) Pump electric power (W).

Figure 7.3: Comparison of pump characteristics.

more detailed analyses. Also, our calculations are often more detailed and depend on more inputs and parameters. Ideally, the parameters used in HVAC model creation could represent the variability of possible systems for a given building.

On the other hand, it should not be forgotten that our system also makes uses of default values, for instance for the additional pressure drops due to valves and fittings. Thus, the proposed comparisons can assess the compatibility of both sets of assumptions more than they can validate the proposed system. Still, large deviations represent a good indication that something may not be right. Accordingly, comparing pipe lengths and pump capacity with standard values during model creation may allow issues to be caught. The presented comparison

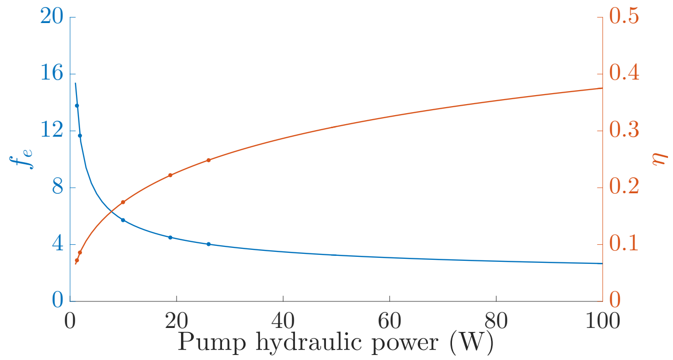


Figure 7.4: Pump efficiency η and inverse factor f_e according to Equation 7.1 with $b = 1$, following DIN V 18599-5.

does not show such large deviations for pipe lengths. It would if the shortest path algorithm was used for tree finding, as in Section 7.2.1. The comparison of pump characteristics shows that large discrepancies can result from the value assumed for pump efficiency, and suggests that a correlation of default efficiency with system size may be used.

Considering the number of parameters in the proposed methods, only a few parameter sets were considered. Many more could be used, and a detailed sensitivity analysis could be attempted. Other standard values could also be compared with simulation results. Values of control losses listed in ÖNORM 5056 [167] would be an example of this.

7.4 Comparisons between simulation options

This section tests the system by comparing results obtained with the co-simulation implementation and with the EnergyPlus "mono-simulation" implementation (with detailed HVAC model), as well as with ideal loads. Comparing results with different simulation options is a way of checking that the transformation of internal models into simulation inputs is carried out in an acceptable way.

7.4.1 Comparison approach

Table 7.9 summarizes the three simulation options compared in the following.

Table 7.9: Three simulation options: ideal load simulation, integrated simulation of building and HVAC in EnergyPlus, co-simulation between building EnergyPlus model and TRNSYS HVAC model.

Option	Simulation tools	HVAC system model
Ideal	EnergyPlus	conceptual
MonoSim	EnergyPlus	component-based (EnergyPlus)
CoSim	EnergyPlus + TRNSYS	component-based (TRNSYS)

The design of comparison experiments should consider the fact that input parameters are not the same with the three options. There are many additional inputs for detailed HVAC models as compared to ideal load simulation. Co-simulation with TRNSYS uses parameters for HVAC control which are not used in mono-simulation, as control modeling is more idealized in EnergyPlus.

Table 7.10: Outputs for the three compared simulations. Some control losses may be present with MonoSim, but they cannot be considered realistic. The outputs of green cells are compared (row-wise) with each other in the following.

Output	**Ideal**	**MonoSim**	**CoSim**
zone temperatures	✓	✓	✓
delivered energy	✓	✓	✓
end energy		✓	✓
generation losses		✓	✓
distribution losses		✓	✓
control losses			✓

Neither can all outputs be compared between the three options, as indicated in Table 7.10. Only zone temperatures and delivered energy rates are compared between the three simulation modes. End energy use are compared between MonoSim and CoSim.

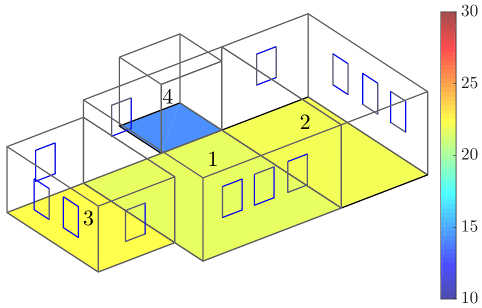
The amount of delivered energy should remain close to that calculated with ideal load simulation. Simulation of distribution segments in EnergyPlus relies on simplification procedures described in Section 4.3.7 and tested in the next chapter.

Simulations are carried out on the eight-zone example building already used in Chapter 4. Default values corresponding to a residential construction in 2015 are used for building parameters. As the radiant fraction of heat delivery was found to play a significant role, two systems differing in radiant fraction (0 and 0.3) were considered. A radiant fraction of 0 corresponds to convector heating, or to conceptual HVAC modeling, as ideal loads are injected directly in zone air. A radiant fraction of 0.3 would be typical of radiator heating [222, p.199].

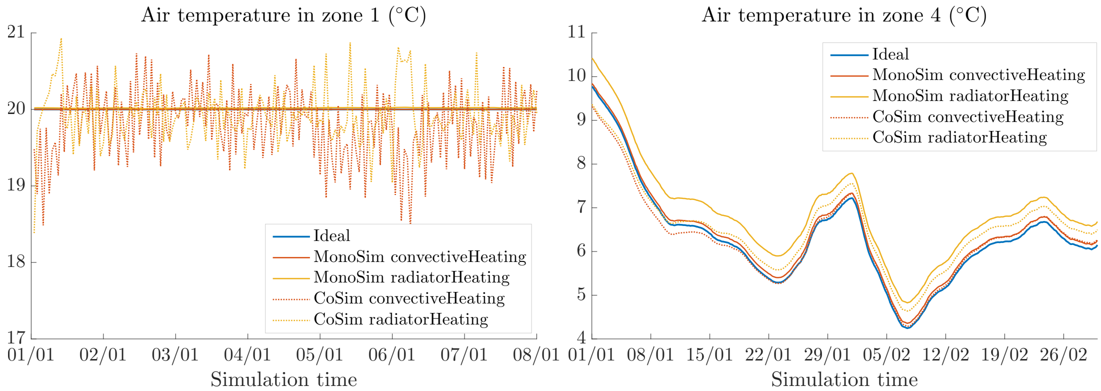
7.4.2 Results

Zone air temperatures are rather straight-forward quantities to compare. Figure 7.5 shows simulated air temperatures resulting from the three simulation options, for a conditioned and a non-conditioned zone.

Results in mono-simulation are consistent with ideal load calculations. With purely convective heat delivery, temperatures are very close to those simulated with ideal loads. For conditioned zones, the difference to set point - and thus to temperatures simulated with ideal loads - lies within 10^{-4} K, and can be seen as a numerical residue. When raising the radiant fraction, temperatures in conditioned zones feature small oscillations (under 0.1 K), mostly above set point. More significantly, temperatures in non-conditioned zones become significantly higher than in ideal load simulation. This can be explained by the increased heat transfer



(a) Zone identifier numbers and yearly mean air temperatures (°C) with ideal loads.

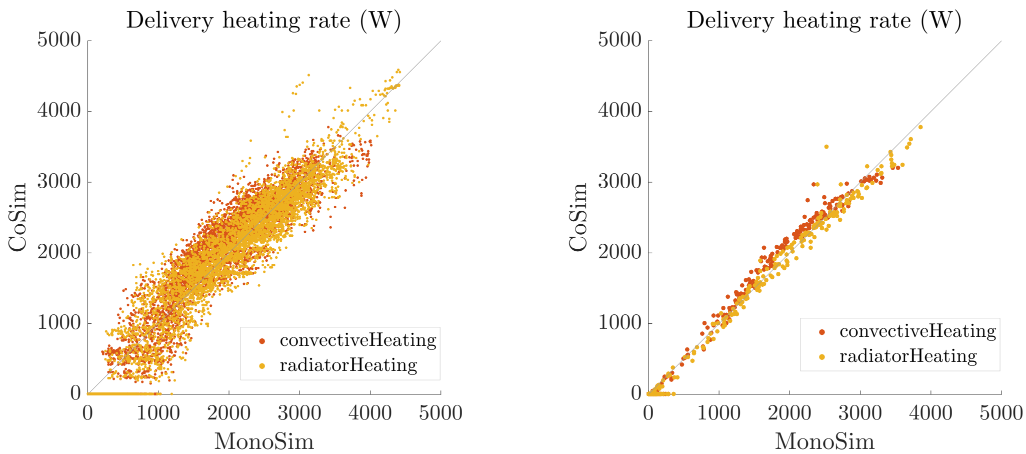


(b) Conditioned zone (1) for the first week of January.

(c) Non-conditioned zone (4) for January and February.

Figure 7.5: Hourly simulated air temperature with three simulation options (ideal, mono- and co-simulation) and two types of heating systems. A constant set point of 20 °C is assumed for conditioned zones.

to building elements between conditioned and non-conditioned zones with radiant heating (the air temperature on the conditioned side being the same). Lower temperatures in the first co-simulation days can be discerned in Figure 7.5c. They are due to the fact that EnergyPlus does not import co-simulation heat rates during warm-up: an appropriate initial value has to be provided, which in this case was slightly lower than needed.



(a) Hourly averaged.

(b) Daily averaged.

Figure 7.6: Comparison of simulated delivered energy rates summed over the three conditioned zones for a whole-year simulation. CoSim versus MonoSim for two types of heating with different radiant fractions: convective (0) and radiator (0.3). Each data point corresponds to the delivered energy rate averaged for one hour (left) or one day (right).

Results for delivered energy rates can also be compared between the different options. As seen in Figure 7.6, daily averaged heat rates are much closer in both implementations than hourly heat rates. In the lower range, almost discrete levels can be distinguished for hourly delivered heat rates in co-simulation. This derives from the on/off control scheme, with hourly (and spatial) averaging. Because of the dead band, there are hours during which co-simulation yields null heating rates whereas mono-simulation yields low but positive heating rates.

Results for boiler final energy rates, shown in Figure 7.7, are similar to those for total delivered energy rates.

7.4.3 Discussion

The frequency at which one inspects results plays an important role. Hourly results of both implementations are sometimes hardly comparable, because of different control schemes. Ideal loads smoothly follow zone heat losses, whereas the steps of on/off control implemented with the co-simulation approach have an almost stochastic aspect. Co-simulation results are more difficult to compare to ideal loads.

Averaging on days makes common trends in the different simulation options recognizable. However, one should not forget the raw values. A look at results

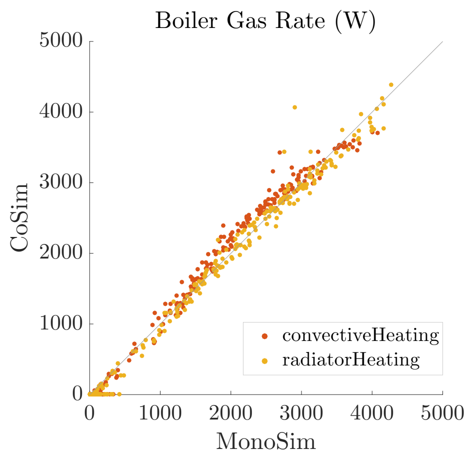


Figure 7.7: Comparison of simulated boiler energy rates summed over the three conditioned zones for a whole-year simulation. CoSim versus Monosim for two types of heating with different radiant fractions: convective (0) and radiator (0.3). Each data point corresponds to the delivered energy rate averaged for one day.

for the subhourly simulation time steps can be needed to check the behavior of controls, and may reveal undesired oscillations.

The radiant fraction of heat delivery plays a significant role. The accuracy of co-simulation with the present setup is limited by the exchanged variables.

Comparisons are made difficult by limitations and assumptions pertaining to the respective simulation programs and their built-in components. The idealized control of radiator heat delivery in EnergyPlus cannot be replicated with co-simulation, and especially not with the on/off control with hysteresis used here. With radiant floor heating, one could model the same proportional control strategy in the two simulation tools, but co-simulation does not make a detailed modeling of the radiant slab possible. What is more, results not shown here indicate that assuming an isothermal slab, as done in the TRNSYS type originally selected for this kind of heat delivery component, is not acceptable.

These simulation comparisons contributed to the detection of errors. Actually finding errors should be the main intention of software testing [223]. Table 7.11 summarizes a selection of errors which were detected by testing the system, as explained in this section and in the previous ones.

Table 7.11: Examples of errors detected in past system implementations and/or applications.

Error	Revealed by
Internal space boundaries not matched.	plotting space boundaries
Wrong input value for physical parameter.	domain checking
Ventilation not present in ideal load calculations	result checking: high temperatures
For sizing runs, internal gains not set to zero in all space uses	local sensitivity analysis
Wrong depth of floor heating pipes.	result checking: set point temperatures not reached
Control temperature radiant fraction parameter not applied for floor heating.	local sensitivity analysis
Incorrect area of floor heating component in zones with several floor surfaces.	result checking: set point temperatures not reached
OAT reset not implemented for EnergyPlus.	local sensitivity analysis
Inconsistency in ventilation scheduling	comparison between simulation options
Wrong extrapolation of pipe diameter for high flow rates	warning thrown by very high pipe diameter for larger building

Summary

This chapter has introduced the issue of how to validate the proposed system. There is no single absolutely sufficient validation method, neither for BPS tools, nor for this system. Rather, the best results are probably achieved with an appropriate combination of methods.

This chapter has reported on different ways of testing the system and increasing confidence in its outputs, focusing on comparative testing methods.

Characteristics of HVAC system models created by the system can be compared with existing HVAC systems, which have been manually designed and sized, as well as with default values mentioned in several standards. This is illustrated in the case of hydronic heating systems with the sums of pipe lengths and the sizing of circulating pumps.

The proposed tests supplement each other. They differ in the parts of the system which they contribute to checking. By comparing HVAC system characteristics in generated models and in real buildings, one may validate the model creation procedures. However, this validation approach is dependent on how well the existing systems have been planned, and may require considerable effort for each comparison. Comparisons with standard values can be carried out with a much higher number of buildings. Comparisons between mono-simulation and co-simulation implementations, as well as with ideal load simulation, allow the transformation of models into simulation inputs to be verified. These comparisons between simulation options also make it possible to verify some assumptions, e.g. that the simulated HVAC system does meet its requirements in terms of providing comfort.

The next chapters can also be seen as contributing to testing and validation. Model simplifications and parameter screening (Chapter 8) make additional tests possible and may raise confidence in the system, and Chapter 9 deals with empirical validation and calibration.

Chapter 8

Impact of model and parameter simplifications

This chapter aims at investigating the impact of various simplifications on simulation results. This is expected to help in building confidence in the proposed system and in determining the appropriate level of detail in different cases. A method for this purpose is to start from a model with the highest level of detail and study the impact of various model simplifications on simulation results.

The level of detail of building and HVAC performance simulation can vary in various respects, as summarized in Table 8.1. These different aspects are interlinked. The choice of a simulation tool naturally determines the structure of a model and the possible choices of component submodels. A simulation parameter like time step should be defined with regards to the model, as detailed HVAC models may require a shorter time step for numerical convergence and to capture the dynamics on the modeled system.

This chapter investigates three aspects in particular: simulation zoning, HVAC model granularity and parameter screening.

Table 8.1: Aspects of level of detail for building and HVAC performance simulation in the proposed system.

Aspect	**Example**
Simulation tool	EnergyPlus or TRNSYS
Spatial resolution	zoning
Simulation parameters	time step
HVAC model approach	conceptual, system-based, component-based or equation-based
HVAC model granularity	heat pump modeled as single component or with separate components
Building parameters	single-layer or multilayer wall constructions
HVAC simulation parameters	number of nodes in storage tank model

8.1 Zoning studies

8.1.1 Overview

The issue of spatial resolution and zoning was identified in Chapter 2 as one important aspect of simulation. However, in our context, a clear distinction should be made between two concepts related to "zoning", which we will refer to as *simulation zoning* and *HVAC zoning*. Indeed, simulation zoning is a property of the simulation model, and may offer a potential for model simplification, whereas HVAC zoning corresponds to characteristics of HVAC systems and controls independent of simulation. The two concepts are further contrasted in Table 8.3.

Table 8.3: Comparison of the concepts of simulation zone and HVAC zone.

	Simulation zone	**HVAC zone**
Context	BPS	HVAC design and control
Characteristics	Assumption of perfectly mixed air in a zone. Discretization element for heat and mass balance Inputs and outputs defined at zone level	Desired conditions maintained using a single sensor Similar heating and cooling requirements
Spatially	Room, part of room or collection of rooms with common thermal characteristics	Room, part of room or collection of rooms with common thermal characteristics

An alternative definition of an HVAC zone is that it corresponds to spaces served by a common device, e.g. same air handling unit [224]. We prefer the ASHRAE definition of "a space or group of spaces within a building with heating and cooling requirements that are sufficiently similar so that desired conditions [...] can be maintained throughout using a single sensor" [225], as it is less dependent of the type of HVAC system.

Objectives. In this section, we propose to apply a systematic zoning method to simulation zoning. The following questions are asked, which are to be answered with the help of this method:

- For a variety of building models and parameters, what is the influence of different simulation zoning schemes on simulation results?
- How can HVAC zoning impact the performance of HVAC systems?
- In the case where HVAC zoning is determined, how should it be taken into account for simulation zoning? In particular, how fine should the simulation zoning be in order to observe the impact of HVAC zoning on system performance?

Zoning method. The already introduced space modeling system [194] is used for systematic zoning based on space properties, according to the method presented in Section 5.1.2. The zoning schemes used in the following zoning studies are summarized in Table 8.5. PZ only distinguishes between perimeter zones, which are in contact with external spaces, and core zones, which are not. OZ lumps spaces together according to their orientation, also defined in relation to external spaces. FZ lumps together spaces with similar functions. OFZ is a combination of OZ and FZ, where connected spaces with similar functions and the same orientation are merged.

Table 8.5: Zoning schemes.

Scheme Id	Description
PZ	perimeter/core
FZ	functional zones
OZ	orientation zones
OFZ	orientation and functional zones

8.1.2 Simulation experiments

The four zoning schemes summarized in Table 8.5 are used and compared to the architectural view, which can also be seen as room zoning (RZ).

The zoning method is applied to multiple building floors, chosen to represent a variety of floor plan types in apartment buildings and summarized in Table 8.6. K2010 corresponds to a restoration of M1951. The two buildings have the same enclosure but different floor plans. J1972A2 and J1972A5 correspond to two parts of the same residential complex.

Table 8.6: Building floors for zoning experiments.

Id	D1989	M1951	K2010	J1972A2	J1972A5
Location	Amsterdam, NL	Chicago, US	Chicago, US	Stuttgart, DE	Stuttgart, DE
Building year	1989	1951	2010	1972	1972
Floor	regular	regular	regular	roof	regular
Floor area (m^2)	321	650	650	340	398
Number of rooms	36	38	35	27	32

Two experiments are presented. The first experiment only deals with simulation zoning, whereas the second experiment considers both simulation zoning and HVAC zoning.

Experiment with unknown HVAC zoning. The first experiment considers HVAC zoning to be unknown. Therefore, HVAC zoning is not considered, and only the impact of simulation zoning is investigated. The experiment is carried out with ideal load simulation. As rooms aggregated into one zone can have different functions and internal loads, the experiment also deals with the way internal loads can be modeled in such cases, looking at three possibilities: (i) *uniform*: all zones are assumed to have the same space use and internal loads; (ii) *majority*: internal loads for a zone correspond to the space use with the largest area among the aggregated rooms. (iii) *interpolated*: internal loads for a zone are interpolated (area-weighted) from those in the aggregated rooms.

Experiment with known HVAC zoning. With this experiment, HVAC zoning is assumed to be known, and it is attempted to question the relation between simulation zoning and HVAC zoning. On the one hand, the impact of model simplifications resulting from simulation zoning is investigated, as in the previous experiment. On the other hand, HVAC zoning is assumed to follow different schemes, and for each of these its impact on HVAC performance and thermal conditions is observed. The main question, in this case, is whether simulation zoning should follow HVAC zoning. This experiment is carried out using co-simulation, as this is the only way to dissociate simulation zoning and HVAC zoning. In EnergyPlus mono-simulation, the calculation of air temperature and the determination of heat demand takes place at the same zone level.

Table 8.8: Simulated variations in thermal zoning and HVAC zoning. Column-wise comparison to RZ simulation zoning allows simulation zoning error to be assessed, as in previous experiments. Inefficiencies due to HVAC zoning are revealed by row-wise comparison to RZ HVAC zoning. Cell colors indicate the relation between simulation and HVAC zoning: green for identical zoning, yellow where simulation zoning is finer than HVAC zoning; where simulation zoning is coarser than HVAC zoning, blue if allowed by ASHRAE, otherwise orange.

Simulation zoning / HVAC zoning	**RZ**	**OFZ**	**FZ**
RZ	RZ-RZ	RZ-OFZ	RZ-FZ
OFZ	OFZ-RZ	OFZ-OFZ	OFZ-FZ
FZ	FZ-RZ	FZ-OFZ	FZ-FZ

The simulated variations are summarized in Table 8.8. Three zoning schemes are used for HVAC zoning as well as for simulation zoning. In these three zoning schemes, only rooms with the same function - and thus the same set point temperatures - are grouped together. Also, the advantage of choosing these three schemes is that the resulting models can be ordered in terms of their level of detail: RZ is finer than (or equal to) OFZ, which is finer than (or equal to) FZ. Several cases can be distinguished in terms of the relative level of detail of HVAC and simulation zoning, which are highlighted with different colors in Table 8.8.

If simulation zoning is finer than HVAC zoning (yellow cells), we model the HVAC zoning by changing the control equations in TRNSYS. Let $(z_i)_{i=1:n_z}$ be the n_z simulation zones corresponding to the same HVAC zone, and z_l the largest of them. For $i = 1 : n_z$, the temperature in zone z_i is replaced by the temperature in zone z_l for the heat demand calculation of zone z_i. This substitution corresponds to having a single thermometer (in zone z_l) for the whole HVAC zone, as illustrated in Figure 8.1. Note that we model HVAC zoning only in terms of control, and do not change the distribution subsystem model according to HVAC zoning. This corresponds to the ASHRAE definition, which mentions only “a single sensor” and not the distribution subsystem. In reality, an HVAC zone may also correspond to a distinct heating circuit, and the distribution subsystem should be generated based on HVAC zoning.

We also consider cases where simulation zoning is coarser than HVAC zoning. According to ASHRAE [225], the grouping of HVAC zones for simulation is acceptable in cases where the grouped zones have the same space use and orientation (blue cell in Table 8.8). Otherwise (red cells), it is not acceptable. The simulation experiment should confirm these recommendations. Note that in these last cases the simulation itself is not modified by the HVAC zoning assumption: simulation OFZ-FZ is the same as simulation FZ-FZ. Only the assumed reference changes: the “truth” for OFZ-FZ is OFZ-RZ, while for FZ-FZ it is FZ-RZ.

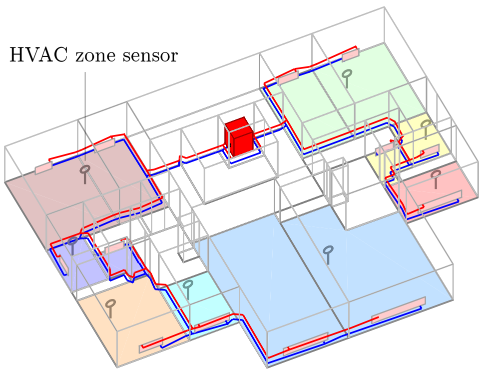


Figure 8.1: Illustration of the FZ-RZ case: functional zoning scheme for HVAC zoning and room zoning for simulation. Measurement point symbols (⚲) indicate what simulation zone is used for temperature control. Floor colors correspond to HVAC zoning, with non-conditioned zones transparent.

8.1.3 Results of zoning experiments

Zone properties. The layouts obtained with the application of five zoning schemes on five floor plans are presented in Figure 8.2.

For each zone layout, we define the zoning factor as the number of rooms in the architectural layout divided by the number of zones in the considered layout. The zoning factor indicates how many rooms in average are aggregated into one zone.

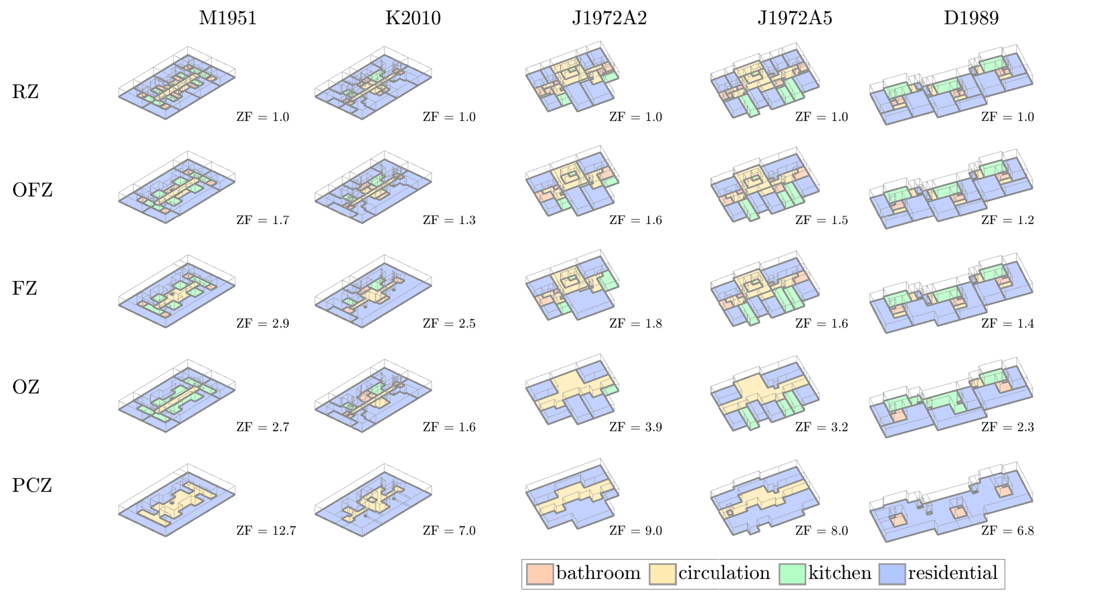


Figure 8.2: Resulting layouts for the selected floor models and zoning schemes, with the corresponding zoning factors (ZF). Floors are colored according to zone use profile.

The corresponding values are highest for the PZ zoning scheme and, apart from the architectural layout, lowest for the combined OFZ scheme. Zoning factors are alternately higher with the orientation and functional zoning schemes, according to the original layout.

As appears from Figure 8.2, the functional groups used for OFZ and FZ schemes do not exactly correspond to zone use definition for simulation. The latter distinguishes between kitchen and bathroom spaces, whereas the Space Modeler sees them as belonging to the same functional group of serving spaces, and thus merges them in the FZ view of the J1972A2 model. As a consequence, the error indicators calculated in the following for OFZ and FZ are probably slightly higher than they would be if there was an exact correspondence between functional groups and simulation space uses.

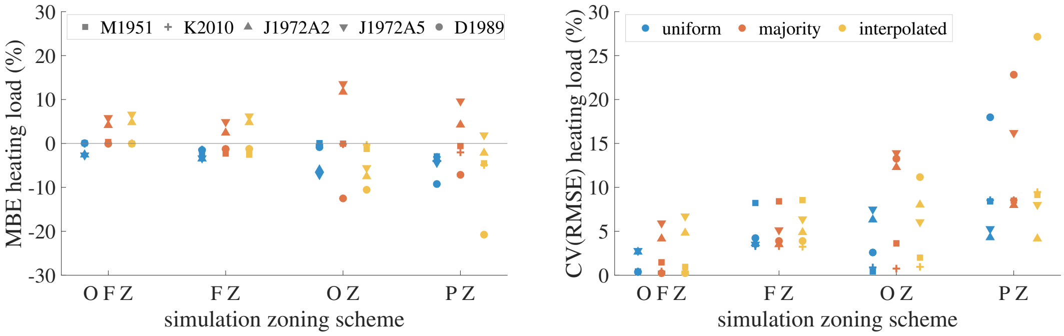
Deviation measures. We resort to mean bias error (MBE) and coefficient of variation of the root-mean-square error (CV(RMSE)) in order to quantify how much the results (vector **s**) obtained with a simplified model deviate from those (vector **r**) obtained with a reference model, which in the following we take to be the corresponding one-zone-per-room model. MBE, defined in Equation 8.1, corresponds to the relative change of averaged results. MBE alone is not a sufficient indicator, because of the possibility of compensation effects, positive bias over a period canceling out negative bias over another period.

$$MBE = \frac{\sum(r_i - s_i)}{\sum r_i} \tag{8.1}$$

$$RMSE = \sqrt{\frac{\sum_{i=1..n}(r_i - s_i)^2}{n}} \tag{8.2}$$

$$CV(RMSE)(\%) = \frac{\sqrt{\frac{\sum_{i=1..n}(r_i - s_i)^2}{n}}}{\bar{m}} \qquad (8.3)$$

Results with unknown HVAC zoning. Figure 8.3 shows the values of the MBE and CV(RMSE) indicators for the first zoning experiment, with unknown HVAC zoning.



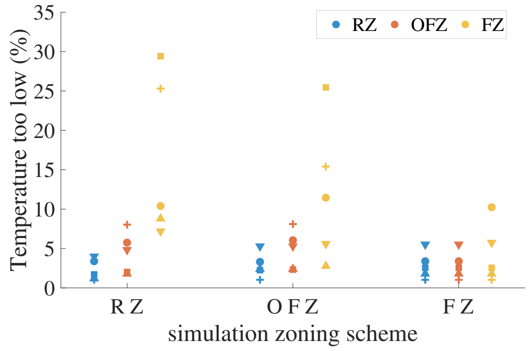
(a) MBE **(b)** CV(RMSE)

Figure 8.3: Error in total building heating load for buildings floors, zoning schemes and internal load variations relative to room-based zoning (RZ). Marker shapes represent building floors, and colors stand for internal load variations.

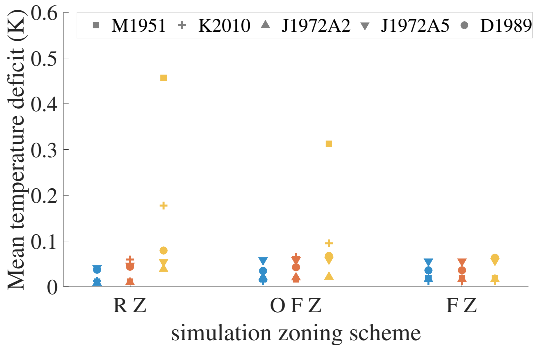
The impact of each zoning scheme on heat load results can vary significantly for different floor plans. It is clear from Figure 8.3 that the way internal loads are treated cannot be neglected. It has a significant impact, especially for the orientation-based zoning schemes OFZ and OZ, and also for the coarser PZ scheme.

Uniform internal loads yield lower discrepancies. This is logical, as these only correspond to discrepancies in the response to external conditions, to which differences in internal loads are added in the other two cases. The mean bias error with respect to the reference architectural view is generally negative with uniform internal loads, which agrees with the idea that aggregating several rooms in a simulation zone can lead to a compensation in the simulated loads, and consequently to an overall underestimation. This is not the case with non-uniform internal loads, where the mean bias error takes both signs, according to the floor plan. Different types of errors (load offsetting and change in internal loads) can compensate each other. This could be the reason why interpolating internal loads sometimes leads to larger error values than the majority space use approach. The highest values of CV(RMSE) are reached by building D1989 with the perimeter/-core zoning scheme. The corresponding layout stands out by the large size of its unique perimeter zone. Like J1972A5, which has the second highest CV(RMSE) values, D1989 is also characterized by rather large kitchen spaces, which disappear in the PZ layout.

The different definitions of space uses in the Space Modeler and in simulation may play a role in the amount of discrepancies. Also, there is no satisfactory way of setting set point values for zones aggregating spaces with unequal set points or, worse, conditioned and non-conditioned spaces.



(a) Average time below heating set point.



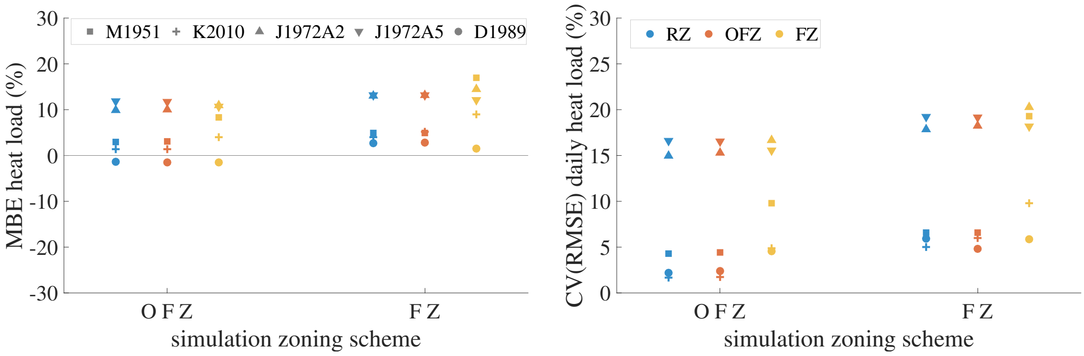
(b) Average temperature deficit relative to set point.

Figure 8.4: Comfort indicators based on simulated temperatures with various HVAC zonings (indicated by marker color) and simulation zonings. These indicators correspond to UT and TD, introduced in Chapter 6 (Table 6.2). They are averaged on all zones.

Results with known HVAC zoning. Results of the second zoning experiment are shown in Figures 8.4 and 8.5. It can be observed from Figure 8.4 that thermal discomfort increases with coarser HVAC zonings. The amplitude of this discomfort varies strongly with the individual floor plans, but also with the simulation zoning. While large discomfort values are revealed with the more detailed RZ and OFZ simulation zonings, they fail to appear when the coarser FZ scheme is used for simulation zoning. It can be surmised that the relative position of the temperature sensor plays an important role in the observed variations. For instance, a temperature sensor placed in a south-oriented space may lead to underheating in other spaces with less solar gains. Conversely, placing the HVAC zone sensor in a space with little solar gains may lead to overheating in other spaces. The high discomfort values with functional HVAC zoning (yellow markers) of buildings M1951 and (to a lesser degree) K2010 stand out. This can be ascribed to the presence in FZ layouts for both buildings of a large residential zone surrounding the whole perimeter in all orientation. For M1951, this also resulted in the highest CV(RMSE) values with the FZ scheme in the first experiment (Figure 8.3b).

Figure 8.5 shows the discrepancies caused by simulation zoning in terms of heating energy results. OFZ simulation zoning generally does a better job than FZ, but the difference is often unremarkable. This may be because temperatures play a confounding role. Interestingly, these errors also tend to be higher when the HVAC zoning is coarser. This contradicts the view that a simulation zoning following HVAC zoning would be appropriate. In cases where HVAC zoning is too coarse, a fine-grained simulation zoning is advisable, as it allows control inefficiencies to be simulated.

Discussion. The effects of zoning schemes on simulation results may vary widely. Having calculated error indicators quantifying the deviation in results between one-zone-per-room simulation zoning and a coarser simulation zoning, a major source of error seems to be the aggregation of rooms with different uses. This is



(a) MBE **(b)** CV(RMSE) of daily heat load

Figure 8.5: Error indicator values with various HVAC zoning and simulation zoning schemes, with marker color by HVAC zoning scheme.

particularly problematic in cases of differing set points, or when grouping conditioned and non-conditioned zones. Of the four investigated zoning schemes, only OFZ (combined orientation and functional zoning) seems to be a relatively safe bet.

A simulation zoning finer than the HVAC zoning may allow load differences due to coarse HVAC zoning to be evaluated. This was only shown for one type of HVAC system, and using simplifications which may not be generally applicable. Modern radiator systems are usually equipped with thermostatic valves which allow them to regulate the flow of hot water based on the surrounding air temperature. Applying the definition of an HVAC zone in such cases is not straight-forward. These limitations of the presented experiments do not invalidate the idea that: (i) HVAC zoning can lead to inefficiencies; and (ii) only a simulation zoning finer than the HVAC zoning may make a quantification of these inefficiencies possible. A motivation for this discussion of HVAC zoning was the need to avoid confusion in the context of zoning and HVAC modeling. However, at the conceptual stage targeted by the present work, one may assume HVAC zoning to be yet undetermined, and thus leave it out of consideration.

Simulation zoning also comes into play in the proposed HVAC model creation method. Thus, simplifications of simulation zoning can indirectly simplify the resulting HVAC models. However, there are other better possibilities to simplify HVAC models independently of simulation zoning, as shown in the following.

8.2 HVAC model simplifications

8.2.1 Overview

An HVAC system model resulting from the method described in Chapter 4 may be very complex. Simplification procedures may be helpful in reducing the number of components and in producing simpler structures. A reduced number of components lowers the simulation run time, and may be crucial when the model size gets close to the limits imposed by simulation tools (see TRNSYS limitations).

Simpler structures are easier for users to inspect, and may be required for certain computations. In particular, a simplification of the distribution subsystem model is necessary in order to fit it into the EnergyPlus plant loop structure. Simplification procedures for distribution subsystems have been presented in Section 4.3.7. They can perform (i) merging of consecutive distribution segments, or (ii) merging of distribution segments per zone.

In addition to those, we consider the possibility of merging delivery components. In this case, all delivery components belonging to the same type and located in the same zone are merged into an equivalent component. The value of additive characteristics - heating or cooling capacity, maximum flow rate, rated flow rate - of this equivalent component is the sum of their values in the original components. Design supply and return temperatures remain unchanged.

An attempt is made at evaluating the impact of these HVAC model simplification procedures. In particular, it is attempted to determine whether the distribution subsystem model simplifications are acceptable.

8.2.2 Experiment

The experiment introduced in this section compares simulation results obtained with several HVAC model simplifications. The reference for comparison corresponds to a non-simplified HVAC model, whose structure does not match the EnergyPlus loop structure. As a consequence, the experiment uses co-simulation. The three simplification procedures mentioned above cannot be combined arbitrarily. We consider the five simplification options listed in Table 8.9. The merging of delivery components must lead to a modified distribution subsystem, so that it is necessarily combined with zone segment merging. Another possibility would be to merge delivery components before the determination of the distribution subsystem, but this would result in an underestimation of required distribution paths, as observed in [226].

Table 8.9: Simplification options, from the highest level of detail (no simplification) to the lowest level of detail, which is that of traditional autosizing methods.

Option	Distribution	Delivery
S0	no simplification	no simplification
S1	consecutive segment merging	no simplification
S2	zone segment merging	no simplification
S3	zone segment merging	zone component merging
S4	subsystem deleting	zone component merging

The experiment is made with three example hydronic systems summarized in Table 8.10. The building models are rather small, as with larger ones the number of components in the most detailed model would exceed the limits imposed by TRNSYS. Table 8.11 exemplifies the decrease in the number of components achieved with the four simplification levels.

Table 8.10: Systems used for HVAC model simplification experiment. A building standard corresponding to construction year 1975 and hydronic heating with gas boiler and radiators is assumed for all cases.

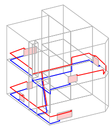
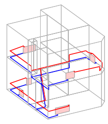
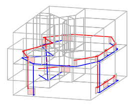
System	**A**	**B**	**C**
Outline			
Building	2f8zR	2f8zR	2f14zR
Original distribution	detailed	detailed	simple
Insulation factor	0.1	0.2	0.2

Table 8.11: Number of elements at the various simplification levels for example heating system A (8-zone example building).

Simplification level	**Pipe segments**	**TRNSYS units**
S0	71	99
S1	33	63
S2	16	36
S3	12	30
S4	0	18

8.2.3 Results

The metric we use to investigate the impact of simplifications is the distribution loss, calculated as the difference between the energy rate supplied by the generation subsystem to the distribution subsystem and the delivered energy rate.

Simulation results obtained with the four simplification levels are compared to the results obtained with the original model S0. Figure 8.6 shows the mean bias error in simulated distribution losses with the four simplification levels, as compared to the original model. The merging of consecutive flow segments (S1) has a very limited impact on results. So does the merging of delivery components, realized from S2 to S3. The merging of distribution components per zone, realized from S1 to S2, has more influence, but the mean bias error does not exceed 10%.

In Figure 8.7, daily-averaged distribution losses simulated with the original model and with simplified models (S1 and S2) are compared. Results obtained with S2 deviate more from S0 than those obtained with S1, as already expected. It can be seen in 8.7b that distribution losses with the original and with the simplified models tend to be closer when they are near their minimum (0) and maximum values. This corresponds to days in which no zone is heated, or all zones are heated. Conversely, differences in results are larger in partial load days, during which heat is presumably delivered only to certain zones. These differences are much larger for hourly values, as illustrated in Figure 8.8. This can be explained by the fact that, with the simulated on/off control, even small differences in distribution losses between models can cause heating to be activated at different times.

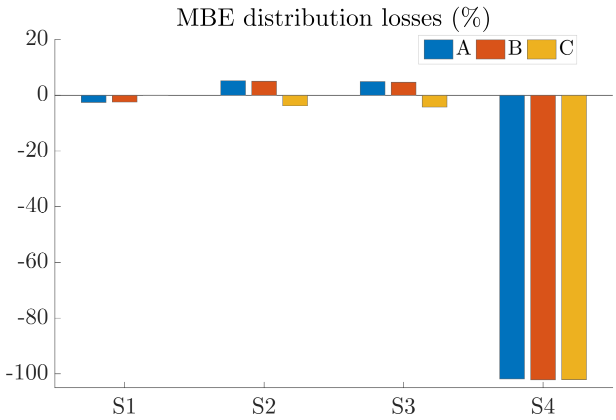
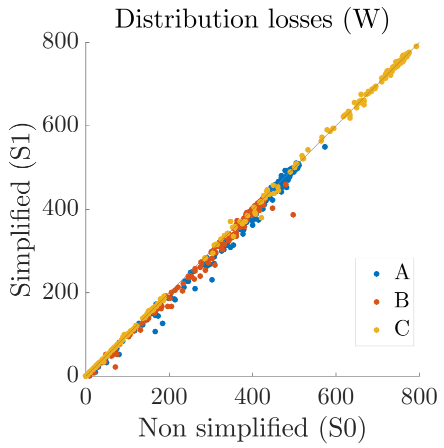
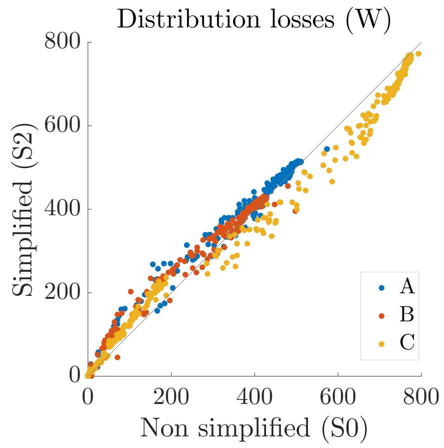


Figure 8.6: Mean bias error in distribution losses with four simplification levels as compared to S0, for 3 systems (A,B,C).

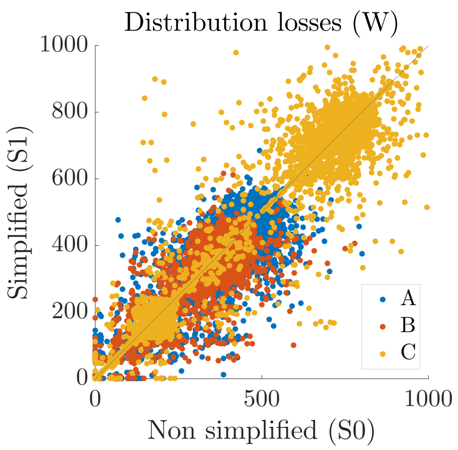


(a) S0 vs S1.

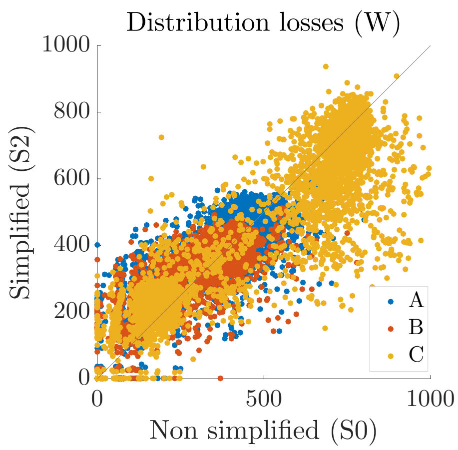


(b) S0 vs S2.

Figure 8.7: Scatter plot of daily-averaged simulated distribution losses before and after simplification. Results are shown for three different systems (A,B,C).



(a) S0 vs S1.



(b) S0 vs S2.

Figure 8.8: Scatter plot of hourly-averaged simulated distribution losses before and after simplification. Results are shown for three different systems (A,B,C).

The differences in distribution losses between S0 or S1 and S2 can be ascribed to differences in fluid temperatures in the pipes. In the simplified model (S2), hot water flows in a pipe segment if and only if there is a heat demand in the corresponding zone. In the original model, hot water may also flow in a pipe segment when there is a heat demand in a zone other than the one in which the pipe segment is located.

Discussion. For the investigated examples, the impact on simulation results of simplifications S1 to S3 remains within an arguably acceptable range. In fact, one could argue that even neglecting pipes altogether is acceptable. Indeed, most of the distribution losses are "reused". For the simulated examples, the underestimation of final energy use with S4 is around 1%. However, we have seen that distribution losses do affect the dynamics of heat delivery. What is more, their relative importance can be expected to increase in better-insulated buildings [227] and in larger buildings.

8.3 Sensitivity analysis and parameter screening

In contrast to the previous sections, which dealt with model simplifications, the simplifications investigated in this section relate to input parameters. Sensitivity analysis is used to see how uncertain inputs can affect simulation outputs. We focus on parameter screening, which is an application of sensitivity analysis consisting in the choice of a subset of parameters based on their significance. It is often the case that a few parameters account for most of the uncertainty [27, p.10]. Although parameter screening does not lead to a simplification of the produced simulation model, it may allow the input to our system to be simplified. If it can be shown that a given input parameter exhibits only negligible effects on the results for a wide range of systems, a well-chosen default value may be assumed.

This section introduces the topic of sensitivity analysis for BPS, presents a well-known method of sensitivity analysis for parameter screening, and applies it to simulations with the proposed system in several cases.

8.3.1 Sensitivity analysis in building simulation

Sensitivity analysis can be defined as the "study of how uncertainty in the output of a model can be apportioned to different sources of uncertainty in the model input" [27, p.1]. Some applications of sensitivity analysis are to establish research priorities, to "identify critical regions in the space of the inputs" and to simplify models [27, p.10]. Related but distinct is uncertainty analysis, which aims at quantifying uncertainty in the output of the model. This makes it necessary to quantify expected variations in the input, which is not the case for sensitivity analysis [205].

In our case, considered outputs will be performance metrics of the building derived from simulation. Inputs will be model parameters corresponding to characteristics of the modeled buildings and systems.

One may distinguish internal methods and external methods for sensitivity and uncertainty analysis [205]. Internal methods embed the propagation of uncertainties in the computation. External methods investigate the system as a black box: variations in inputs are made, and the corresponding changes in outputs are examined without following changes inside of the model. As internal methods would only be made possible by reengineering the simulation tools, we focus on external methods. A further distinction within external methods is the one between local and global sensitivity analysis. With local sensitivity analysis, variations in input are carried out from one point, changing only one parameter at a time, so that only a restricted region of the input space is explored and interactions between inputs are ignored. With global sensitivity analysis, a sampling scheme is used to explore the whole input space.

Different indices can be used to interpret the results of sensitivity analysis. For an input x_i and an output y_i, a simple indicator is the incremental ratio $\frac{y_i(x_1,...,x_{i-1},x_i+\Delta x_i,x_{i+1},...,x_k)-y_i(x_1,...,x_i,...,x_k)}{\Delta x_i}$. It may be related to the partial derivative $\frac{\partial y_i}{\partial x_i}$. Scatter plots are considered to be a simple and insightful tool for sensitivity analysis [27].

Local sensitivity analysis may represent a useful start, for it has a low computational cost and is easy to interpret [207]. However, the significance of tests carried out with local sensitivity analysis is limited. A more advanced sensitivity analysis technique for parameter screening is presented in the next section.

8.3.2 Method of elementary effects

The method of elementary effects, also named after Max D. Morris, who introduced it [228], has been shown to be an effective screening method for large models with many input parameters. It has been successfully applied to building performance simulation, for instance [229, p.67-68]. The method uses one-at-a-time variations of input variables, but in such a way that the whole parameter space is sampled.

Each model input x_i for $i = 1..k$ is assumed to vary across p selected levels, so the *region of experimentation* is a k-dimensional p-level grid. The elementary effect of the i^{th} input factor at input point $\mathbf{x} = (x_1, ..., x_k)$ is defined as

$$\mathrm{d}_i(\mathbf{x}) = \frac{y(x_1, ..., x_{i-1}, x_i + \Delta, x_{i+1}, ..., x_k) - y(\mathbf{x})}{\Delta} \tag{8.4}$$

with $\Delta \in \{1/(p-1), ..., 1-1/(p-1)\}$. Typically, one chooses p even and $\Delta = \frac{p}{2(p-1)}$.

The idea of the method, illustrated in Figure 8.9, is to build r trajectories of $k+1$ points in the region of experimentation, in such a way that each trajectory allows one elementary effect to be calculated for each input factor. This yields an estimate of the finite distribution of elementary effects on the region of experimentation. On this basis, the sample mean μ and standard deviation σ of each elementary effect can be calculated as in Equations 8.5 and 8.6.

$$\mu_i = \frac{1}{r}\sum_{j=1}^{r} \mathrm{d}_i(\mathbf{x}^{(j)}) \tag{8.5}$$

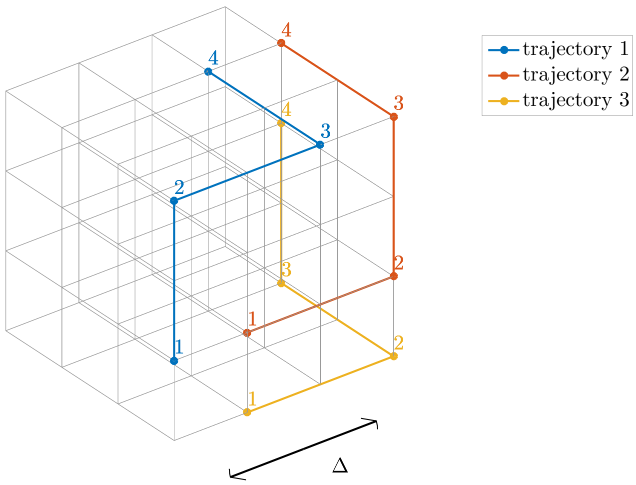


Figure 8.9: Illustration of $r = 3$ trajectories with the method of elementary effects for $k = 3$ and $p = 4$, $\Delta = \frac{p}{2(p-1)} = \frac{2}{3}$.

$$\sigma_i = \sqrt{\frac{1}{r-1}\sum_{j=1}^{r}(\mathrm{d}_i(\mathbf{x}^{(j)}) - \mu_i)^2} \tag{8.6}$$

$$\mu_i^* = \frac{1}{r}\sum_{j=1}^{r}|\,\mathrm{d}_i(\mathbf{x}^{(j)})| \tag{8.7}$$

The observation of these statistical indicators makes it possible to determine, for each input, whether it is: (a) negligible, if both μ and σ are small; (b) significant, linear and additive, if the amplitude of μ is large and σ is small; (c) significant, but either nonlinear or interacting with other inputs, in other cases. This is typically made with the help of a scatter plot with means (x-coordinate) and standard deviations (y-coordinate) of the elementary effects for each input. Figure 8.10 shows how the position on such a plot can be interpreted in terms of input properties.

The measure μ^* (Equation 8.7) proposed by Campolongo et al. [230] can be used for parameter ranking. The number of runs with the method of elementary effects is $k\ (k+1)$. This is typically higher than for a local sensitivity analysis with n levels $(k\ n+1)$, but lower than with global sensitivity analysis techniques. The method can give a reliable indication of which parameters are influential, but no quantitative estimation of the true output variance, so it cannot be used for uncertainty analysis.

8.3.3 Application

The method of elementary elements is applied to several cases, which differ with the considered sets of parameters and are summarized in Table 8.12. The objectives of these experiments are: (i) to show the possibility of applying the chosen

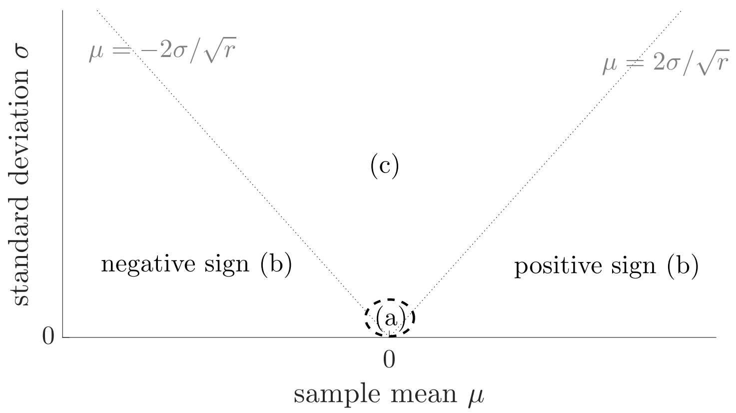


Figure 8.10: Scatter plot for the interpretation of elementary effects. Negligible inputs are those with small values of both μ and σ (a). The lines of equation $\mu = \pm 2\sigma/\sqrt{r}$ can be considered as a boundary between effects of definite sign below the lines (b) and effects of indefinite sign above the lines (c) [228].

screening method to the proposed system; (ii) to determine which parameters are most influential in several situations; (iii) to ensure that simulation results exhibit reasonable variations on a wide region of the input space. Like in the previous sections of this chapter, these experiments represent investigations of the general behavior of the proposed system, without assumption of the underlying use case. In order to limit computation time, a simple building with 4 zones (1f4zR, defined in Appendix C) is used, and single-tool simulation is carried out with EnergyPlus for a one-month (January) simulation period.

Considered parameters have to do with HVAC systems as well as with building properties. Appendix B presents all the parameters which have been defined for use with the proposed system. Each sensitivity analysis carried out here uses only a subset of all these possible parameters. For simplicity, uniform distributions are assumed, in plausible ranges. The lists of parameters and their respective ranges for each experiment can be found in Appendix D, along with the calculated values of the statistical indicators.

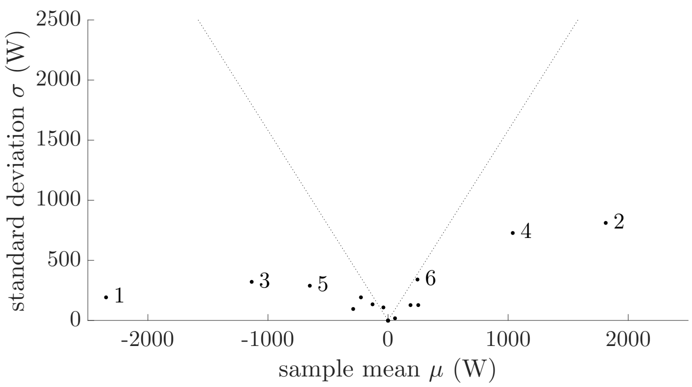
Table 8.12: Screening experiments using the method of elementary elements with HVAC parameters (S), building parameters (B) and mixed building and HVAC parameters (BS). Considered generation components are low-temperature boiler (B-LT), wood pellet boiler (B-P) and ground-source heat pump (GSHP).

Screening experiment	**S1**	**S2**	**B**	**BS**
Number of building parameters	0	0	18	17
Number of HVAC parameters	19	19	0	19
HVAC generation	B-LT	GSHP	-	B-P
Number of trajectories r	10	5	10	5

8.3.4 Results of parameter screening

Even though sensitivity analysis may be applied to investigate a variety of outputs, we focus on final energy rate (W). The corresponding μ/σ plots are presented in Figures 8.11, 8.12, 8.13 and 8.14, along with a summary of the most influential parameters. For each sensitivity analysis, parameters are sorted by decreasing order of μ^*. Only the first 6 parameters are listed in the following tables and identified in the scatter plots. The remaining parameters are only represented by a point in the scatter plots. More on them can be found in Appendix D.

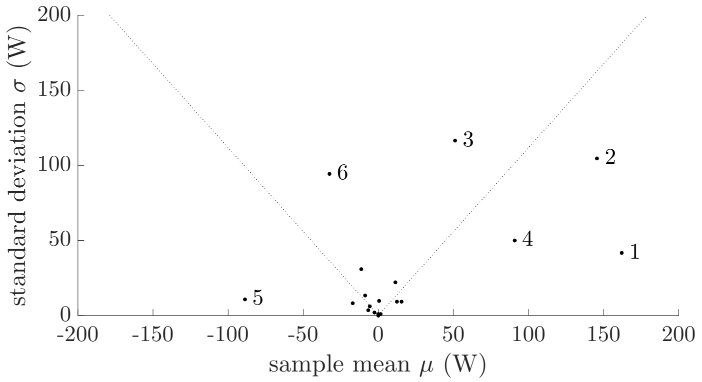
The indicator values obtained depend on the respective input ranges of parameters. Given the degree of arbitrariness in the determination of these ranges, the significance of the exact rankings is limited. Still, it is possible to establish that some parameters are considerably more influential than others. For each experiment, different parameters are found to have the most impact. For the first sensitivity analysis (Figure 8.11), parameters linked to the efficiency of the low-temperature gas boiler are found to be the most influential. For S2 (Figure 8.12), sizing factors and parameters related to system temperatures have the greatest impact.



Id	Input parameter	unit	min	max	μ (W)	σ (W)
1	boilerNominalEfficiency		0.75	0.85	-2.3×10^3	192
2	boilerCubicEffCoeffTwo		-0.1	-0.3	1.8×10^3	812
3	boilerCubicEffCoeffOne		0.1	0.2	-1.1×10^3	319
4	deliverySizingFactor		0.9	1.2	1.0×10^3	729
5	boilerCubicEffCoeffThree		0	0.08	-6.5×10^2	290
6	heatDeliveryRadiantFraction		0.45	0.75	2.5×10^2	339

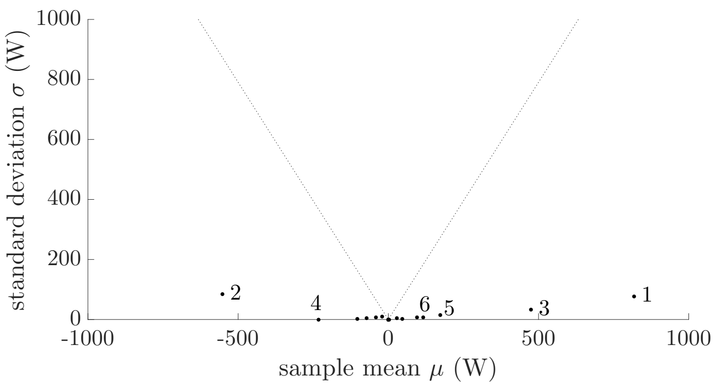
Figure 8.11: Results of parameter screening S1: most influential parameters for the final energy rate with a low-temperature gas boiler, sorted by decreasing order of μ^*. All parameters are below the lines of equation $\mu = \pm 2\sigma/\sqrt{r}$, so their effect can be considered to have a definite sign.

Results for the sensitivity analysis with building parameters (Figure 8.13) show a majority of linear effects, with $|\mu|$ significantly larger than σ. The heating



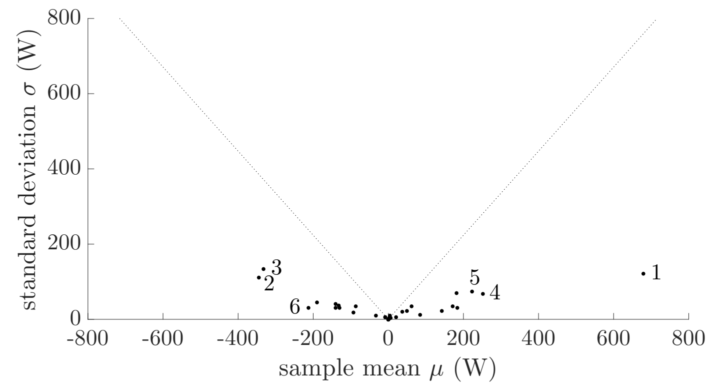
Id	Input parameter	unit	min	max	μ (W)	σ (W)
1	generationTemperature	°C	40	50	162	42
2	generationSizingFactor		0.9	1.2	146	105
3	lowTempDesignOut	°C	26	34	51	116
4	deliverySizingFactor		0.9	1.2	91	50
5	hpNominalCop		4	4.4	−89	11
6	lowTempDesignIn	°C	36	44	−33	95

Figure 8.12: Results of parameter screening S2: most influential parameters for the final energy rate with a ground source heat pump, sorted by decreasing order of μ^*. The effects of parameters 3 and 6, above the lines of equation $\mu = \pm 2\sigma/\sqrt{r}$, are non-linear.



Id	Input parameter	unit	min	max	μ (W)	σ (W)
1	heatingSetPoint	°C	18	22	818	77
2	areaPerPerson	m^2/person	12	20	−552	84
3	infiltrationRate	h^{-1}	0.1	0.3	475	33
4	heatGainElectEqu	W/m^2	8	12	−233	0.6
5	groundUValue	$W/(m^2\,K)$	0.3	0.4	172	15
6	wallUValue	$W/(m^2\,K)$	0.22	0.28	116	6.7

Figure 8.13: Results of parameter screening B: most influential parameters for ideal heat loads, sorted by decreasing order of μ^*.



Id	Input parameter	unit	min	max	μ (W)	σ (W)
1	heatingSetPoint	°C	18	22	679	120
2	boilerNominalEfficiency		0.75	0.85	−344	110
3	areaPerPerson	m^2/person	10	20	−332	134
4	groundUValue	$W/(m^2\,K)$	0.3	0.4	251	68
5	infiltrationRate	h^{-1}	0.1	0.3	222	75
6	groundReflectance		0.2	0.8	−213	30

Figure 8.14: Results of parameter screening BS: most influential (building and HVAC) parameters for final energy rate, sorted by decreasing order of μ^*.

set point is the most influential parameter in the two experiments where non-HVAC parameters are taken into account, along with infiltration rate and occupant density, for which wide input ranges have been used.

Most parameters in these experiments have a rather linear impact on results. This is not the case of parameter *controlTemperatureRadiantFraction*, which determines whether the temperature controlled in each zone corresponds to air temperature (value of 0) or an operative temperature taking radiant temperature into account. Concerning the use of sensitivity analysis for testing, one can start by verifying the sign of μ for each parameter. One can verify that parameters corresponding to an efficiency have negative mean values of elementary effects, meaning that more efficient components lead to a decrease of final energy use. Conversely, parameters like thermal transmittance have clearly positive elementary effects. A surprising result can be observed with the pipe insulation factor, for which μ is positive in experiment BS. This is due to the consideration of the possible pipe heat loss in generation component sizing (with $propDistrLossesForGenerationSizing > 0$), and the fact that, during the simulation period, the simulated boiler tends to perform better when oversized. Thus, the oversizing caused by lesser pipe insulation turns into small energy savings. As pipe heat losses are mostly recycled, $propDistrLossesForGenerationSizing$ should in fact be chosen very small, which would remove this paradox.

Discussion. The previous results show that the method of elementary effects can be used for parameter screening with the proposed system. For each experiment, a number of more influential parameters can be highlighted. The method can point to non-linear effects in the simulated systems, which seem more frequent with HVAC parameters than with building parameters. Applications of parameter screening, as presented here, or of sensitivity analysis in general, can also contribute to revealing different types of errors. Sensitivity analysis can for instance detect errors causing a parameter not to be used by the system (or overwritten), in which case one sees null variations for this parameter. Conversely, errors leading a parameter to have an impact where it should not be the case can also be identified. Sensitivity analysis techniques can also make unstable behavior apparent. More generally, they are useful in checking system behavior on more than one point in the input space.

Summary

This chapter investigates the impact of model simplifications on simulation results obtained with the system, looking successively at zoning, the resolution of component-based HVAC model and parameter screening.

In terms of zoning, a clear distinction is drawn between simulation zoning and HVAC zoning. Different zoning schemes are defined, which systematically aggregate spaces into zones according to various properties. Two series of experiments relative to zoning are carried out. In the first one, only the impact of simulation zoning is considered, and HVAC systems are idealized. In the second one, both

HVAC zoning and simulation zoning are varied. The impact of zoning schemes varies strongly with the building models to which they are applied. In cases where a coarse HVAC zoning would cause control inefficiencies, a finer simulation zoning can allow this issue to be detected.

Several simplification procedures can be applied to models of the delivery and distribution subsystems. The impacts of the proposed simplifications vary in their degree of significance according to the frequency at which results are observed. Mostly, the impact on daily simulation results is very limited, which makes the simplification procedures acceptable.

In order to reduce not only model complexity, but also the number of parameters taken into account, sensitivity analysis techniques can be applied for parameter screening. The method of elementary effects is presented and applied to several cases of simulation with the proposed system. As expected, one can identify sets of parameters considerably more influential than the rest. There appear to be more nonlinearities or interactions between parameters for HVAC-related parameters than for others.

Systematic comparisons as have been presented in this chapter can be carried out with limited user intervention: the presented zoning method and HVAC model simplifications may be automated, and parameter screening only requires parameter ranges to be specified instead of single values. Not only can these comparisons be used for testing purposes and as a way of gaining more confidence in simulation results, which was the main objective of this chapter, but they may also be used on a case-per-case basis to determine significant parameters and suitable simplifications. As the zoning studies showed, the adequacy of certain simplifications may vary strongly depending on the simulated case. Finally, simplifications are very welcome for model calibration, as presented in the next chapter.

Chapter 9

Comparison with measured data and calibration

This chapter deals with empirical validation of the presented system and calibration. By comparing simulation results with real data, the accuracy of the created simulation models can be assessed. Also, they can be made more accurate by adjusting uncertain parameters in such a way that simulation results come closer to measured data. This reconciliation of simulation results and measured data by means of parameter modifications is referred to as calibration. This model calibration is distinct from the calibration of the proposed system for automated model creation, which would refer to the adjustment of assumptions and default parameters in order to produce better results in general. However, model calibration with good-quality monitoring data may also contribute to system calibration.

We start by shortly reviewing calibration methods for building performance simulation. Requirements for calibration in our case are then specified, and a method is proposed. This method is then tested with two kinds of experiments, using successively artificial data and real monitoring data.

9.1 Calibration method

9.1.1 Background

Calibration is traditionally executed manually: the modeler adapts inputs repeatedly until the discrepancy between simulated and measured quantities lies in an acceptable range. These manual iterations may turn out to be very time-consuming, and the determination of modifications to apply is challenging. Practitioners mostly use their experience and intuition of building performance, with the support of graphical representations of simulated and measured data.

Specific tests and procedures have been used to make calibration more consistent. This includes the definition of audit processes, such as the ASHRAE procedures for commercial building energy audits. Specific types of plots, including bin plots, may be more helpful than simple superimposed time-series plots

[231]. Plots of the ratios of changes in output when altering a parameter, known as graphic signatures, may support calibration [232]. In particular, it is interesting to compare parameter signatures and residues (differences between simulated and measured values).

The goodness-of-fit of a simulation model is often described with statistical indices MBE, root-mean-square error (RMSE) and CV(RMSE) [233]. The indicators have already been introduced in earlier chapters for the evaluation of deviations due to model simplifications, and are defined in Equations 8.1, 8.2 and 8.3. This time, measured values (vector $\mathbf{m}$) represent the reference against which deviations are measured. The values of RMSE and CV(RMSE) depend on the time resolution of the used values. The criteria defined in ASHRAE Guideline 14 [234] are among the most widely used to establish that a model is successfully calibrated. They require $MBE < 5\%$ and $CV(RMSE) < 15\%$ for monthly values. One limitation of criteria proposed until now is that they only apply to energy consumption. There is for instance no criterion for calibration based on space temperatures.

Calibration may also be seen as a mathematical optimization problem, consisting in the minimization of an objective function which quantifies the discrepancy between measured and simulated quantities depending on variables representing model parameters. Formulating calibration as an optimization problem makes it possible to develop consistent and automated calibration procedures.

However, this approach involves dealing with several challenges. The objective function is a function of several, possibly many variables. It is not defined explicitly, and its evaluation is computationally expensive, as it requires the execution of a simulation for each input value. Energy consumptions computed by EnergyPlus are nonlinear, non-differentiable and even discontinuous functions of building design parameters [235]. Last but not least, the optimization problem is frequently undetermined [236]: observed data does not allow all the uncertain parameters to be adjusted. This underdetermination or overparametrization is a common property of law-driven models, as opposed to data-driven models [27]. Sensitivity analysis can be used to reduce the number of parameters [237]. The introduction of a penalty term increasing with the difference of each parameter to its preferred value may reduce the number of possible solutions and the underdetermination of the problem [238].

The use of meta-models is considered to be a promising way of dealing with the issue of function evaluation cost for optimization and calibration. After its initial training with a number of simulation runs, performing sensitivity analysis, optimization or calibration on a meta-model only requires a fraction of the time needed when evaluating the initial BPS model.

The preceding discussion has focused on “deterministic calibration”. Some more advanced methods (e.g. Bayesian calibration) can be used to compute likely distributions of input parameters consistent with measured data, acknowledging that these parameters remain uncertain [239].

9.1.2 Calibration requirements

The choice of a calibration method should take into account the context in which it is to be used. Simulation calibration is often used to assess the potential of energy-efficiency measures, or to quantify their gains [234]. In the context of the software system described in the previous chapters, we would like to use calibration in the following cases:

- For an existing building, to adjust the parameters of the building model. The goal could be to enhance the goodness-of-fit of simulations carried out to compare the performance of alternatives for a new HVAC system (use case 1).

- For an existing HVAC system, to adjust the parameters of the building and HVAC model. The goal could be to enhance the quality of simulations carried out to evaluate the performance of partly modified HVAC systems (use case 3). For use case 1, the goal could also be to obtain a better evaluation of the performance of an existing HVAC system to be replaced (baseline).

- In the context of system validation, to determine in which measure a discrepancy between simulation results and monitored data can be attributed to certain parameters and reduced, or rather due to an inappropriate model structure.

One should consider known issues for the calibration of BPS models, which include the underdetermination of the problem (too many simulation model parameters for the available data, many different possibilities to meet calibration criteria), the lack of explicit standards or guidelines and the dependency of methods on available data.

The choice of a calibration method should also reflect a trade-off between the benefits of calibration and the corresponding effort, including time to set up the calibration procedure and computation time. In this regard, our focus on automated procedures and early-stage design decisions is an argument in favor of low-effort approaches.

On the other hand, the calibration method should be general enough to cover a multiplicity of possible cases. In particular, it is desirable to accommodate variations in the choice of measured variables and their resolution.

A characteristic of our system is the use of general variables representing macro-parameters, as opposed to single parameters in simulation program input files. For instance, a single U-value for all external walls of a building is a macro-parameter that corresponds to potentially dozens of material thickness and conductivity values. This logically results in parameter reduction, which may mitigate underdetermination. Even so, the number of parameters used for buildings and HVAC systems is too high for manual tweaking.

9.1.3 Proposed method

If the effort applied to calibration is to be commensurate with other tasks, a calibration method relevant for use with the described system should be extensively automated. As a consequence, we use the optimization approach. Our proposed method, illustrated in Figure 9.1, includes the following general steps: (i) Collection of monitored data. (ii) Definition of a base model. (iii) Definition of variable inputs and their acceptable ranges. (iv) Definition of comparison values m_i and s_i, with respective mappings from monitored data and from simulation outputs. (v) Definition of an objective function, function of comparison values m_i and s_i. (vi) Definition and application of an optimization scheme. (vii) Evaluation of results. These steps are discussed in the next paragraphs.

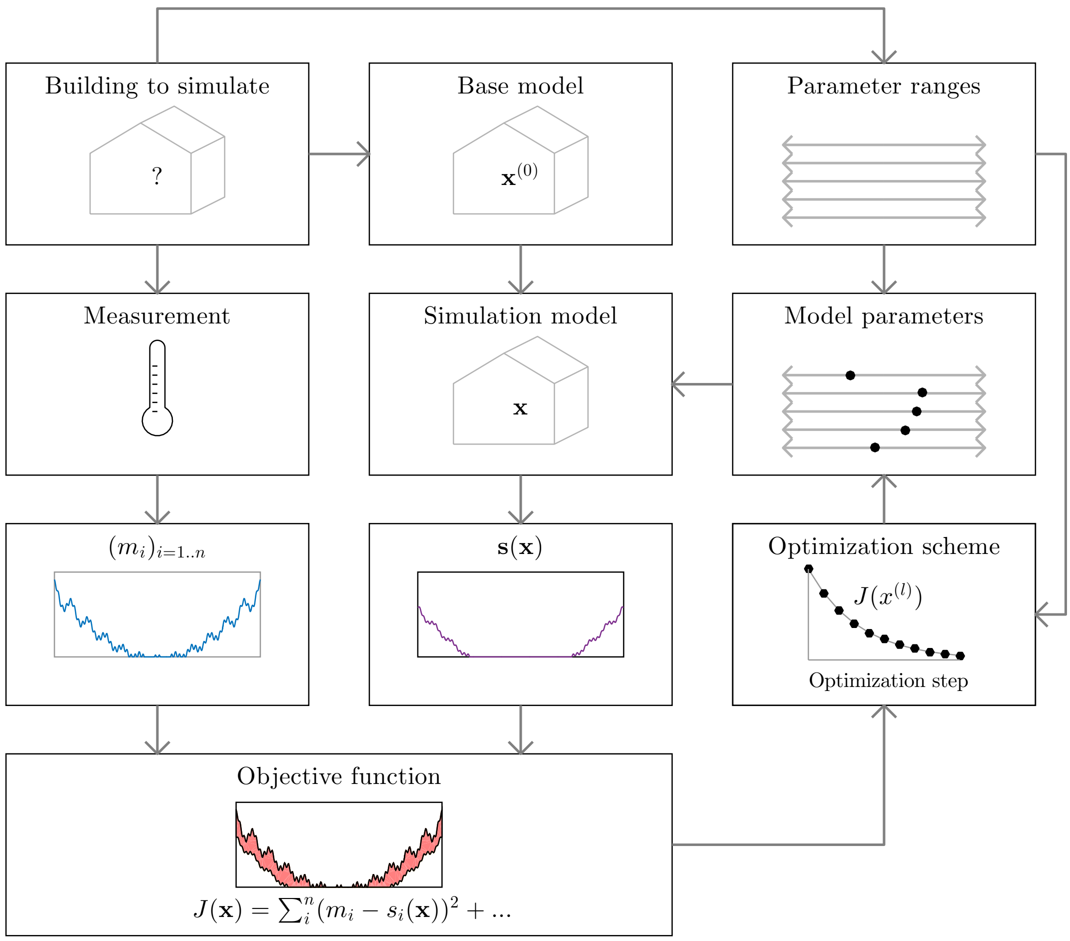


Figure 9.1: General flowchart of the proposed method for automated calibration. $\mathbf{x}$ is the vector of calibration parameters.

Collection of monitored data. Collection of monitored data is essential for calibration, and it is often a limiting step. However, this may be changing with the diffusion of advanced or "smart" metering systems, characterized by communication capabilities and higher measurement resolution [240]. The European Union encourages the use of "individual meters that accurately reflect the final customer's actual energy consumption and that provide information on actual time of use" [241]. Still, privacy concerns make the access to high-resolution data problematic [242].

Determination of a base model. The base building (and HVAC) model can be seen as a best guess. When using the proposed system for deterministic simulation without calibration, it would also remain the only model. It is created using available information on the building and default values. An inspection of the building may increase its reliability. The resolution of the base model should be the result of a well considered decision. Indeed, the model structure remains the same in all model variations for the whole calibration run, and has a significant impact on computation times. The base model differs from later models by the values of certain variable parameters, which should be selected.

Determination of variable inputs and their acceptable ranges. As indicated above, the undetermination issue means that not all simulation parameters can be calibrated simultaneously. Reducing the number of parameters can be advantageous with regard to computation time, especially if the optimization scheme uses numerical differentiation. We limit the discussion to numeric and continuous parameters. The choice of which inputs to vary depends on both the degree of uncertainty of each parameter and its impact on results. Sensitivity analysis and parameter screening are instrumental in determining which inputs should be varied and subjected to calibration.

The acceptable ranges for inputs should be based on available information on the building and its degree of uncertainty, as well as on typical ranges for the most uncertain parameters. Ranges and distribution data can be compiled from different sources. This may require significant expenditure, and even be the most time-consuming part of setting up calibration [239]. As we only carry out deterministic calibration, we do not consider actual parameter distributions but only parameter ranges. Still, the width of a parameter range can be considered to depend on an implicitly assumed distribution. Dealing with range constraints can be an issue with certain optimization schemes, so they may be incorporated in the objective function (see below). In the following, base (starting) values are by default taken in the middle of the corresponding ranges, unless specified otherwise.

Definition of comparison values. Defining comparison values amounts to reducing both monitored data and simulation outputs to two vectors of the same size. These outputs may be time series of any measurable physical quantities. In particular, we look at energy rates and (zone air) temperatures. Outputs are reduced to comparable values by time and spatial aggregation. Typically, the outputs of simulation are much less limited than measured values. Thus, measurements are likely to determine the comparison vector. Depending on the time resolution of measurements, the length n of compared vectors may vary from a dozen (monthly) to several thousands (hourly) values. In cases where values are available for several objects (e.g. temperatures for several zones), a comparison vector can be obtained by concatenating these results for the different objects. Preceded by some normalization, concatenation would also allow calibration to be based on several distinct quantities (e.g. heat rates and temperatures).

Definition of an objective function. The values to be compared are the monitoring values $(m_i)_{i=1..n}$ and the simulation values $(s_i(\mathbf{x}))_{i=1..n}$, with $\mathbf{x}$ the vector of normalized parameters. Parameter values $\mathbf{x}$ are normalized: $x_k = p_k/(p_{max} - p_{min})$, with p_k the original parameter values in their respective physical units. A simple objective function is the sum of squared differences between monitoring and simulation values: $R(\mathbf{x}) = \sum_{i=1}^{n}(m_i - s_i(\mathbf{x}))^2$. Minimizing R is equivalent to minimizing the CV(RMSE) indicator.

A possible modification of the objective function is to add a term penalizing the difference to the best-guess value for each parameter: $J(\mathbf{x}) = \sum_{i=1}^{n}(m_i - s_i(\mathbf{x}))^2 + \lambda|\mathbf{x} - \hat{\mathbf{x}}|^2$ with $\hat{\mathbf{x}}$ the vector of best-guess parameters. This can be seen as a relaxation of the more rigorous approach of explicitly constraining parameter values to stay within the allowed ranges [236]. This relaxation may make the mathematical optimization problem easier to solve.

Definition of an optimization scheme. As the calibration problem has been stated in terms of optimization, a central issue is that of defining an algorithm allowing the objective function to be minimized. There is a significant amount of work on the application of optimization methods to building performance simulation, mainly for design purposes [243]. In all cases, the computational expense associated to each evaluation of the objective function is a determining factor.

A multitude of algorithms can be used. One can distinguish between deterministic and probabilistic optimization algorithms. One can also distinguish gradient-free algorithms from those using gradient calculations. It has been argued that discontinuities in simulation results make gradient-based methods unsuitable [235].

Metaheuristics enjoy popularity in the field of building simulation optimization. The term refers to methods relying on a variety of procedures to search for global optima [244]. This includes, inter alia, population-based methods, like genetic algorithms and particle swarm optimization, and physics-inspired metaheuristics, like simulated annealing. Among others, BPS calibration studies used simulated annealing [118], genetic algorithms [245] and particle swarm optimization [246].

Gradient descent is an iterative method. Starting from a point x^0, steps proportional to the negative of the gradient are taken [247]. The advantage of gradient descent is that it is deterministic and easy to understand. However, only under strong assumptions which do not apply in the proposed cases (function convexity) is it guaranteed to converge towards a global minimum.

Result evaluation. The evaluation of results can be based on statistical and graphical indicators. We look at the values of MBE, CV(RMSE) and of the objective function. These values change at each time step. If the optimization scheme is working, the objective function should decrease. CV(RMSE) should also be mostly decreasing, and MBE should draw nearer 0.

Graphically, one can compare plots of measured and simulated data (before and after calibration). In the case of simple time series plots, one checks that the values from simulation get closer to the values from monitoring. These plots would depend on the size of the compared vector.

9.2 Calibration experiments with artificial data

9.2.1 Design of in silico calibration experiments

Overview. This first series of experiments is performed *in silico*, that is relying exclusively on computer simulation, using simulation results in place of measurement data. The results of a simulation with given parameters (referred to as reference simulation) are used as a surrogate for measurement data. It is attempted to calibrate the model as if the parameters used in the reference simulation were unknown. This strategy, already used by Chaudhary et al. [245] to evaluate a calibration methodology, presents several advantages. Firstly, it makes it possible to test and evaluate a calibration method without relying on any monitoring data. Simulations can be used as a convenient alternative to any kind of monitoring. This allows measurement uncertainty to be ruled out of the calibration process. Within this strategy, reference simulation results represent an absolute truth which is not accessible with real measurements. This also means that reducing the error to zero is possible, whereas in real-world cases the minimal value of discrepancy achievable by varying parameters is unknown. In terms of optimization, this means the global optimum of the objective function is known, whereas in real-world cases there is no certain way of distinguishing local optima from the unknown global optimum.

Experiments. One may design an infinity of calibration experiments, varying according to the structure of building and HVAC models, their reference parameters, the simulation outputs used for calibration, their range and frequency, as well as the applied optimization procedure and its parameters.

We carry out three series of calibration experiments, as summarized in Table 9.1: with building parameters, with HVAC parameters, and with building and HVAC parameters. For each of these, several references (truths) are considered. Sets of n_{rp} reference values representing ground truth are created randomly, according to a normal distribution around the center of the considered parameter ranges. Assumed parameter ranges are similar to those used in the parameter screening experiments (Section 8.3.4), which are also used to determine which parameters to calibrate. Indeed, calibration is only attempted for a number n_p (typically 6) of the n_{rp} uncertain parameters for which a "detuned" reference value has been set. The other parameters remain at their base value, usually different from the reference value.

Table 9.1: Summary of *in silico* calibration experiments. Indicated are the numbers of parameters on which calibration is attempted (typically 6), and the total number of uncertain parameters (in parenthesis). Experiment are named after the type of uncertain parameters (B: building parameters, S: HVAC system parameters) and the output frequency (d: daily, h: hourly). Reference sets of parameter values give the ground truth for each experiment. For each of these reference sets, several attempts at minimizing the objective function are made, with different sets of start values.

Experiment	**B-d**	**S-h**	**BS-h**
Building parameters	6(18)	0	5(10)
HVAC parameters	0	6(19)	5(5)
HVAC simulation	ideal	detailed	detailed
Output frequency	daily	hourly	hourly
Number of reference sets	3	3	2
Number of start sets	3	3	2
Number of simulations	630	630	440

Simulation is carried out for a period of one month (January). A motivation for the separation of building and HVAC parameters is that building parameters may (at least to some degree) be calibrated separately, for instance using temperature data from periods during which a building is neither heated nor cooled. This could make a two-step calibration procedure possible. Reducing the number of variable parameters handled in each step is advantageous. Moreover, the first step with only building parameters can be carried out with ideal load simulation, which is significantly faster.

Method implementation. Calibration is carried out with the method proposed in Section 9.1.3. Comparison values are heating energy rates at different time resolutions. The sum of squared differences between pseudo-measured (reference simulation) values and simulation values is taken as objective function.

Optimization is carried out with a gradient descent method, despite its reported unsuitability for the optimization of non-smooth simulation-based functions [235]. Reasons for this choice are the simplicity, intuitiveness and relative speed of gradient descent. Gradient descent is easy to understand in its principle. A link can be established between the use of signatures for manual calibration and gradient descent optimization on the objective function R. The j^{th} component of the gradient ∇R of the objective function is written in Equation 9.1.

$$\frac{\partial}{\partial x_j}\left(\sum_{i=1}^{t}(s_i(\boldsymbol{x})-m_i)^2\right)=2\sum_{i=1}^{t}\frac{\partial s_i}{\partial x_j}\,(s_i(\boldsymbol{x})-m_i) \tag{9.1}$$

Thus it depends on the correlation between the signature of the j^{th} parameter $\left(\frac{\partial s_i}{\partial x_j}\right)_{i=1..t}$ and the discrepancy vector $(\boldsymbol{s}-\boldsymbol{m})$. In the case illustrated in Figure 9.2, visual inspection would probably lead one to increase the simulated infiltration rate in order to reduce the discrepancy. So will gradient descent. Given n_p parameters,

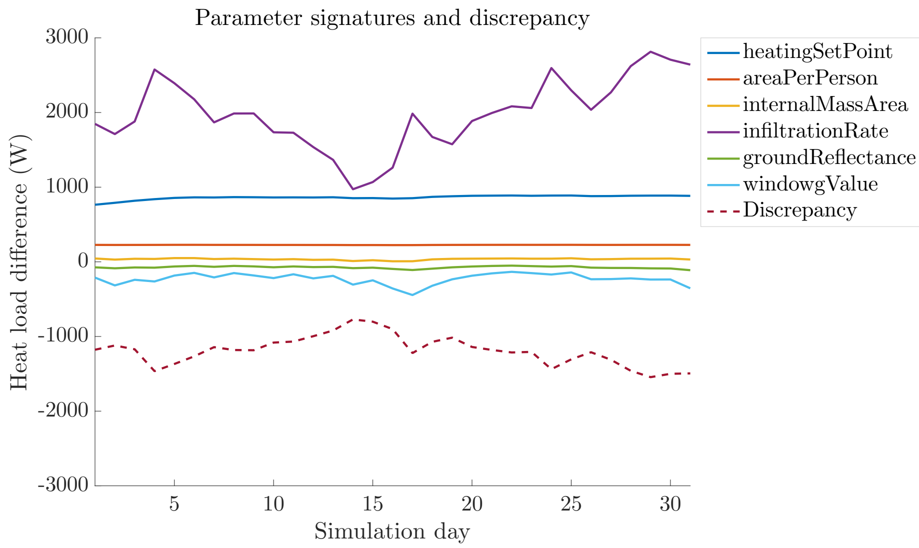


Figure 9.2: Discrepancy vector and parameter signatures for daily averaged heat loads in a calibration experiment for one-month simulation. The signature of a parameter corresponds to the partial derivative of the output with regard to the parameter.

each iteration of gradient descent requires $n_p + 1$ simulations. In the present experiments, we have $n_p = 6$ and perform 10 iterations of gradient descent, so each calibration attempt requires 70 simulations. In comparison, optimization in BPS is often carried out with several hundreds of simulation runs per problem [235]. Also, it is easy to check whether gradient descent works as expected, as the value of the objective function should decrease at each iteration.

9.2.2 Results of in silico calibration experiments

Two interesting questions with regard to the results of these calibration experiments are: (i) How close to the reference results does calibration bring the simulation results? and (ii) To which degree do parameters converge towards their "true" values? We answer the first question by examining values of the statistical indicators MBE and CV(RMSE), and by visual comparison of simulated and measured values. To evaluate the distance between calibrated parameter values $x_k^{(c)}$ and reference parameter values $x_k^{(r)}$, one may use the parameter mean square error (Equation 9.2).

$$PMSE = 1/n_p \sum_{k=1}^{n_p} (x_k^{(c)} - x_k^{(r)})^2 \tag{9.2}$$

Calibration of building parameters. Figures 9.3 and 9.4 refer to the same calibration experiment, for which they show the progression of results and the progression of parameters. While the heat load results converge towards the reference, most calibration parameters do not even seem to get closer to the reference value. Heating set point and infiltration rate, which have been shown to be particularly influential parameters, do come closer. Although very low errors (visually

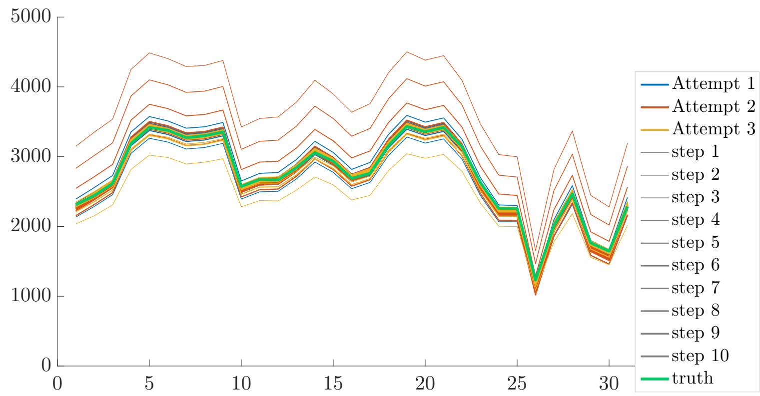


Figure 9.3: Simulated daily heat load curves for successive calibration iterations of three attempts in experiment B-d against reference curve (truth 1). The x-axis represents the 31 days which make up the dimensions of the comparison vector.

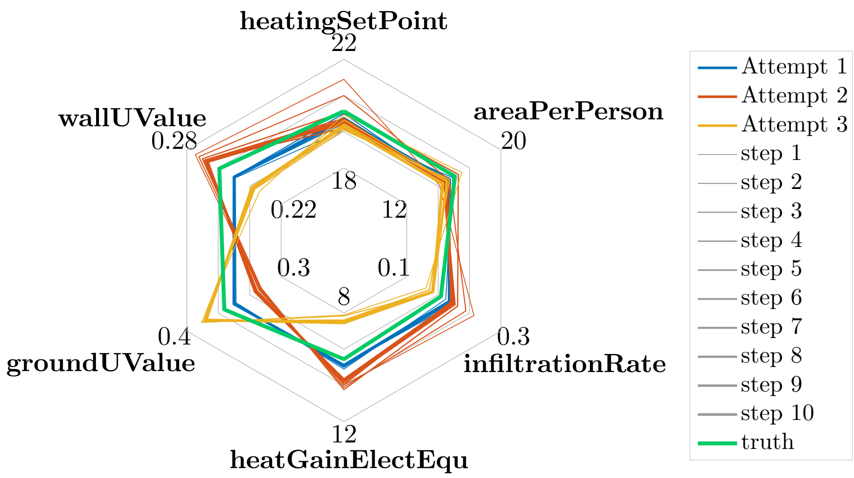


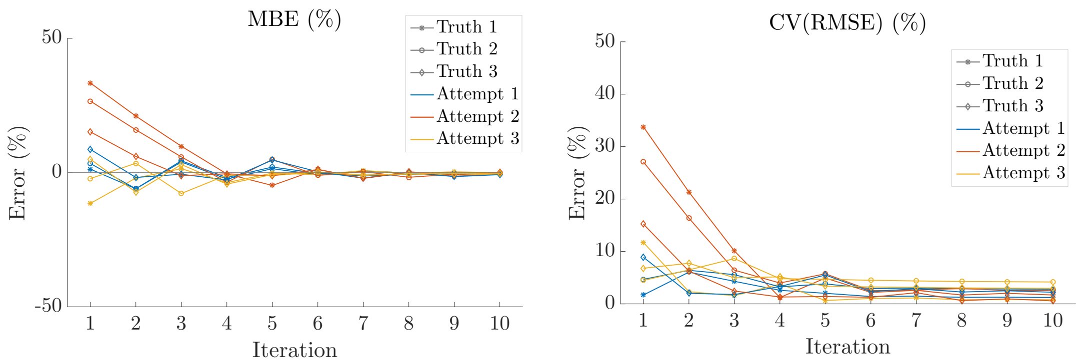
Figure 9.4: Calibration parameters for successive calibration iterations in experiment B-d against reference values (truth 1).

and measured in terms of CV(RMSE)) are achievable, this does not ensure that the true (reference) input parameters are recovered. This confirms the underdetermination of the optimization problem.

Figure 9.5 shows the evolution of error indicators along calibration steps in experiment B-d. A majority of calibration attempts start with already low error values, in which case the benefits of calibration are minor or inexistent. In all cases, optimization seems to converge towards a local minimum characterized by an almost null bias and a low but positive value of mean square error (with $0.5\% < CV(RMSE) < 4.5\%$ for the last iteration).

Calibration of HVAC parameters. In experiment S-h, calibration is carried out only for parameters related to the HVAC system model.

Figure 9.6 shows the progression of the calibrated output (final energy rate),



(a) MBE **(b)** CV(RMSE)

Figure 9.5: Evolution of error indicators along calibration steps in experiment B-d: calibration of building parameters with daily values of ideal heat loads, for 3 sets of reference values (color-coded) and 3 sets of start values each (indicated by marker shapes).

and Figure 9.7 the progression of input parameters for successive calibration iterations. Like in the previous experiment, outputs come very close to the reference, whereas most parameters do not.

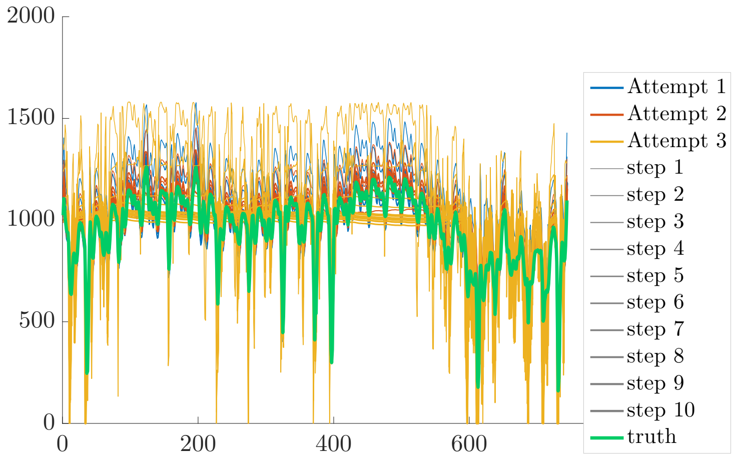


Figure 9.6: Simulated hourly heat pump power consumption curves (W) for successive calibration iterations of three attempts in experiment S-h against reference curve (truth 3). The x-axis represents the 744 hours which make up the dimensions of the comparison vector.

Figure 9.8 shows the results of experiment S-h in terms of error indicators. One attempt can be considered to be failed, with a final $CV(RMSE)$ near 15%. All other attempts reach a $CV(RMSE)$ between 3% and 5%. The calibration problem appears more challenging in this case than with the calibration of building parameters. One may relate this to the fact that some of the corresponding parameter signatures are sharper and more variable across the input space, so that the gradient varies less smoothly. This is even more the case when HVAC control

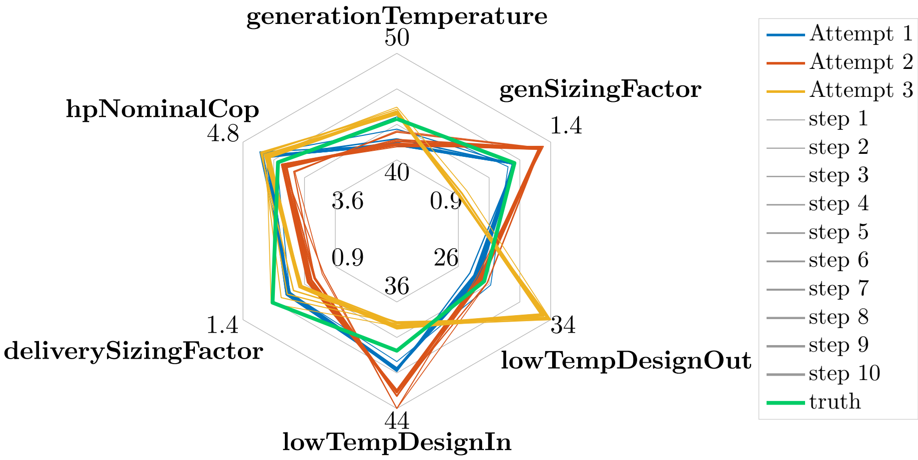
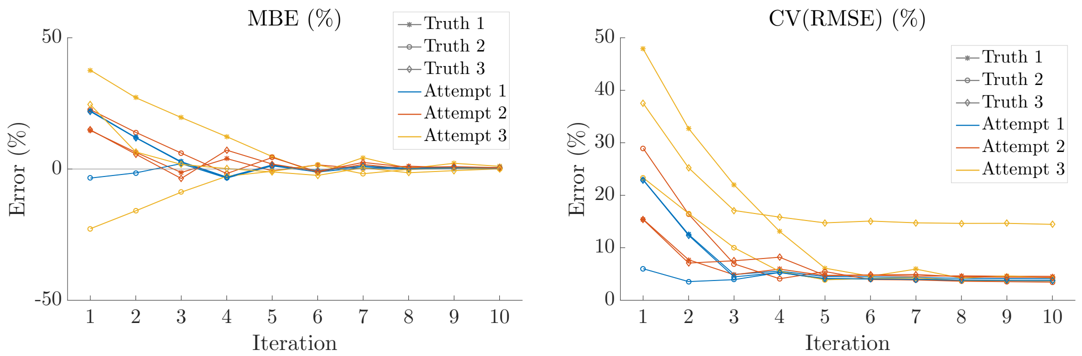


Figure 9.7: Calibration HVAC parameters for successive iterations in experiment S-h against reference values (truth 3).



(a) MBE **(b)** CV(RMSE)

Figure 9.8: Error indicators along calibration steps in experiment S-h: calibration of HVAC parameters with hourly values of the electricity consumption of a ground-source heat pump, for 3 sets of reference values and 3 sets of start values each.

involves discrete states, as illustrated in Figure 9.21.

Calibration of building and HVAC parameters. In experiment BS-h, building and HVAC parameters are calibrated simultaneously, as opposed to a two-step calibration, with building parameters followed by HVAC parameters. The progression of calibrated outputs and the progression of calibration parameters (for truth 2) are illustrated in Figure 9.9 and Figure 9.10, respectively. The progression of error indicators is illustrated in Figure 9.11. The applied method does seem able to deal with the simultaneous calibration of building and HVAC parameters.

Summary of experiments with artificial data. In the cases studied until now, a simple gradient descent approach is generally able to reduce the discrepancy between simulation and (pseudo-)measurements to low levels. It fails to do

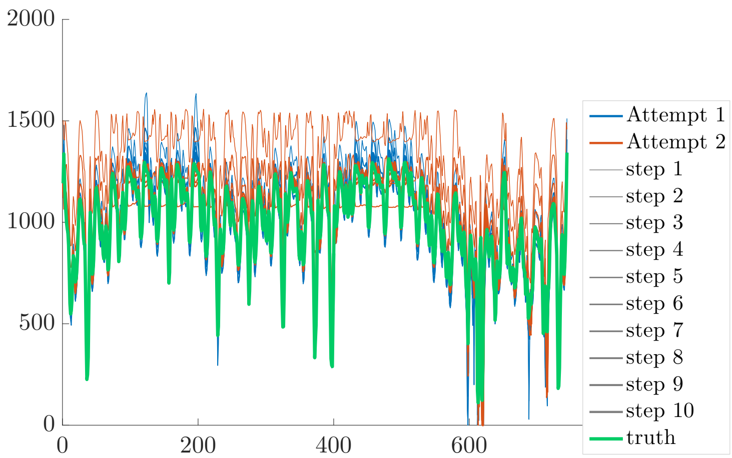


Figure 9.9: Simulated hourly heat pump power consumption curves (W) for successive calibration iterations of three attempts in experiment BS-h against reference curve (truth 2). The x-axis represents the 744 hours which make up the dimensions of the comparison vector.

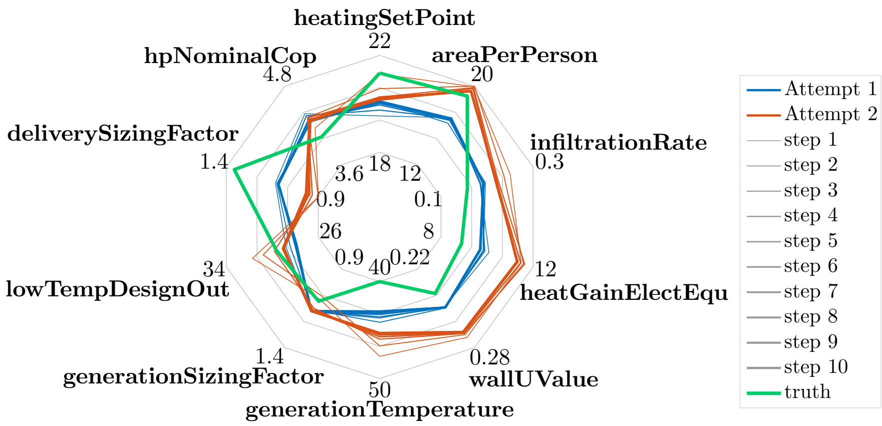
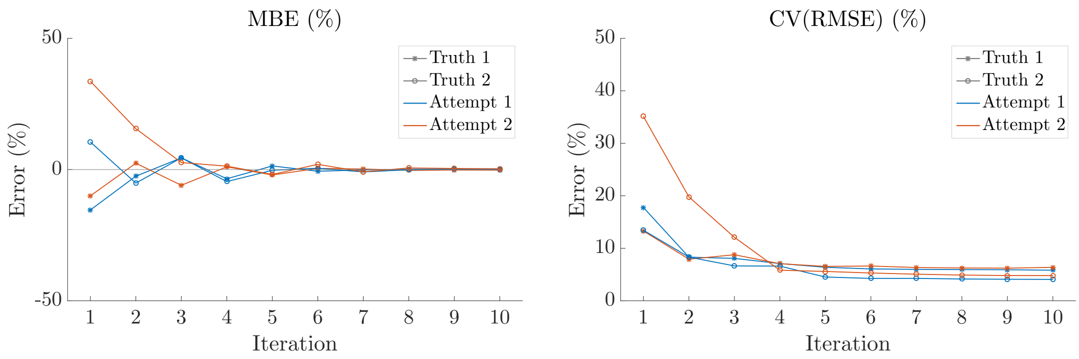


Figure 9.10: Calibration building and HVAC parameters (experiment BS-h) for successive iterations against reference values (truth 2).

so in several cases but, for all sets of reference values, repeating the optimization with 3 sets of start values ensures that at least one attempt succeeds in achieving low values of error indicators: $CV(RMSE) \leq 5\%$ and $MBE \leq 1\%$. Calibrated simulation results are often hardly distinguishable from the respective references. Still, the solutions obtained correspond to local minima of the objective function, and the calibrated parameters mostly do not agree with the reference parameters, especially for the less significant ones. This confirms the already acknowledged issue of underdetermination. As our requirements for calibration focused on the goodness-of-fit of simulations, we can consider them to be met. Simulation time may become a significant limitation: for the 4-zone building used in these experiments, our laptop computer required about 12 minutes for 3 calibration attempts



(a) MBE **(b)** CV(RMSE)

Figure 9.11: Error indicators along calibration steps in experiment BS-h: calibration of HVAC parameters with hourly values of the electricity consumption of a ground-source heat pump, for 2 sets of reference values and 2 sets of start values each.

with 10 iterations and 6 building parameters to calibrate using ideal load simulation (experiments B-d, B-h), but almost two hours for the calibration with HVAC parameters using detailed HVAC simulation. As it is acknowledged that calibration of BPS models, whether manual or automated, is a time-consuming task, such computation times are acceptable, but they require the level of detail of simulation models to be kept rather low.

Of course, some of the difficulties arising in real calibration efforts are not represented in these *in silico* calibration experiments. Only experiments with real data have the potential to uncover these and determine how useful the proposed calibration method can be in practice.

9.3 Calibration experiments with real data

9.3.1 Calibration case one: student residence

Introduction. The first case of calibration with real data deals with a student residence built in the Passivhaus standard in Vienna. The building consists of an 8-floor street-side wing and of a 6-floor courtyard-side wing, as illustrated in Figure 9.13, for a total floor area of 3200 m^2. The building is equipped with a hydronic heating system, a central ventilation system and a photovoltaic system. District heating is used for space heating with floor heating delivery, for domestic hot water, and for air reheating in the ventilation system.

The fact that the building respects the Passivhaus standard reduces the range of possible values for construction parameters. In particular, the U-values of opaque envelope elements should not exceed 0.15 $W/(m^2K)$.

Data has been recorded between October 2010 and June 2012. Meters were read out manually, at irregular intervals. Corresponding measurement values for year 2011 are illustrated in Figure 9.12.

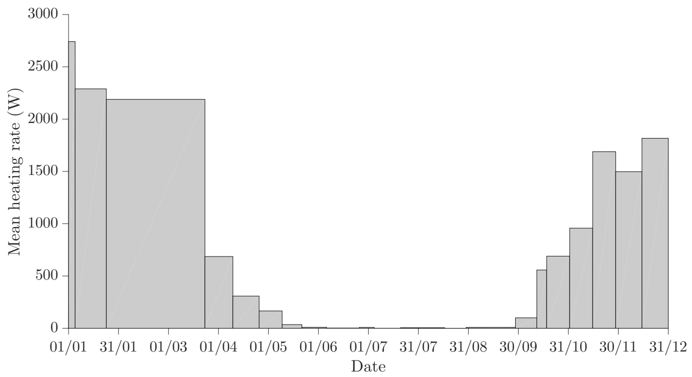
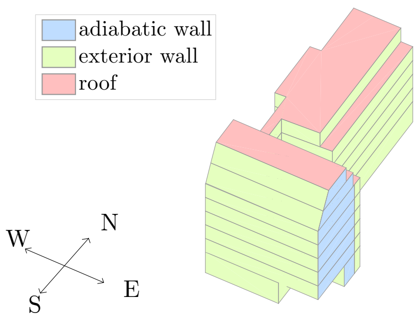
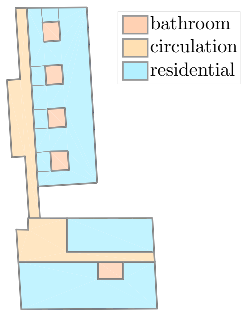


Figure 9.12: Measurement values: total space heating energy rates averaged on intervals between meter readings.

Method. The building is modeled in the Space Modeler. Its geometry is illustrated in Figure 9.13. Exterior walls contiguous to neighboring buildings are modeled as adiabatic. Three distinct space uses are considered: residential (living room and bedroom), bathroom and circulation spaces.



(a) Exterior space boundaries.



(b) Floor zoning.

Figure 9.13: Building model of the student residence.

An appropriate simulation zoning is key to keeping the computation time of calibration within acceptable limits. With this in mind, the following calibration experiments are carried out with a one-floor 10-zone building model corresponding to the second floor (Figure 9.13b). After a comparison of results obtained with this one-floor model and with the full 8-floor model, a multiplier equal to the ratio of simulated heat loads for the full model to those for the one-floor model (equal to 8.8) is chosen. With this multiplier, a CV(RMSE) of 8% for the hourly ideal loads compared to the full model is obtained.

Available weather data for the measurement period is limited. Hourly temperature values measured at the Vienna airport are used, without corrections for the inner-city location of the building. Solar radiation values from a default weather file for Vienna are used, with modifications based on daily reported weather situation, in the absence of better data.

Comparison values are taken to be the average heat rates supplied by district heating to the space heating system, for each of the (irregular) intervals delimited by meter readings in year 2011. The proposed calibration method is applied with gradient descent optimization, starting from 3 sets of base parameters.

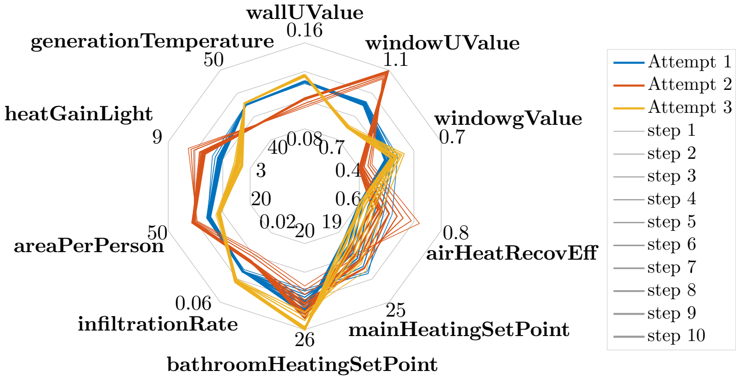


Figure 9.14: Calibration parameters for 3 calibration attempts and successive calibration iterations for student residence.

Results. Figure 9.14 shows that the calibrated parameters are mostly building and zone parameters. With the simulation model used in this experiment, HVAC-related parameters have a limited impact on low-frequency results as are compared here.

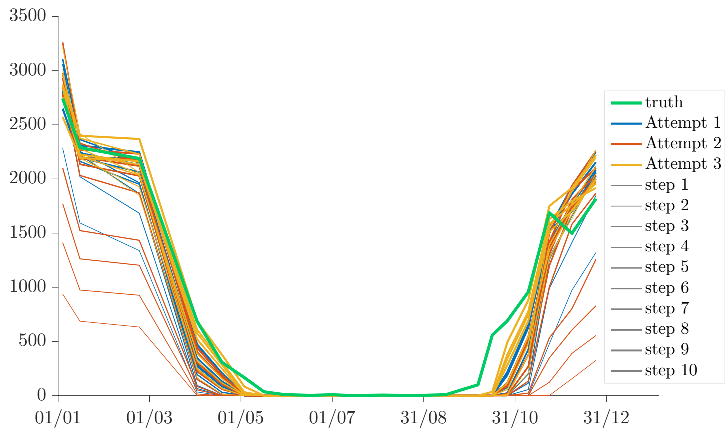
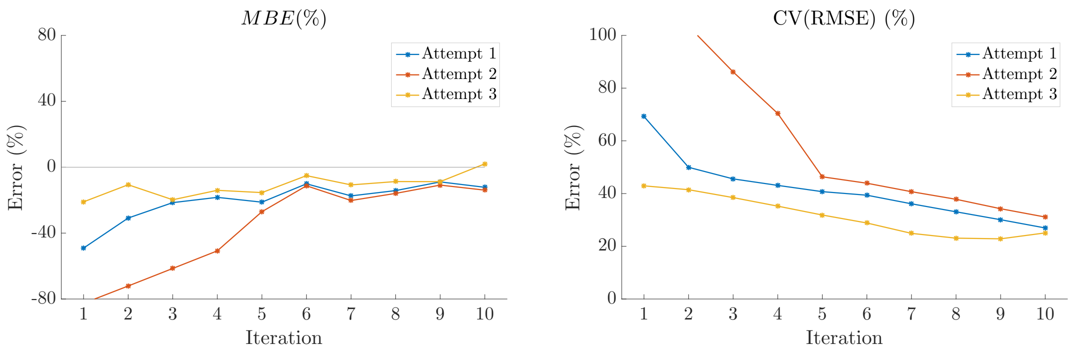


Figure 9.15: Monitored (green) and simulated heating energy rate values (W) for 3 calibration attempts (10 optimization steps each) with student residence model.

Figure 9.15 compares the simulation results for different attempts and optimization steps to the corresponding measured values. Even with calibration, heating energy use mostly remains underestimated, especially in intermediate periods (May, September, October).

Figure 9.16 shows the evolution of error indicators along calibration steps for the three attempts. All initial models significantly underestimate the energy use



(a) MBE. **(b)** CV(RMSE).

Figure 9.16: Error indicators along optimization steps for student residence calibration experiment.

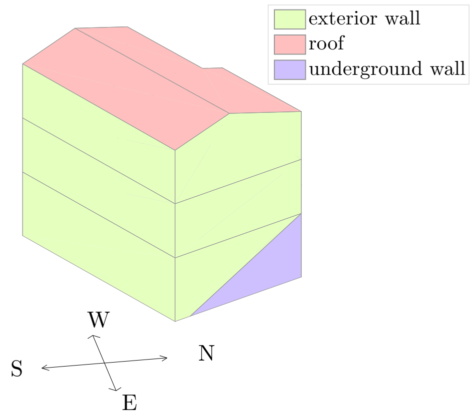
for space heating. The calibration procedure does manage to reduce this bias, but only to a certain degree, and it is not able to improve the goodness-of-fit beyond a certain point. The best agreement achieved is a CV(RMSE) of 23%. This is still more than the 15% CV(RMSE) tolerated by ASHRAE guideline 14 for calibration using monthly data [234].

Discussion. The values of error indicators can be reduced, but the discrepancy in monthly variations between calibrated simulation and measurements can apparently not be reduced below some level. Thus, we come close to falsifying the simulation model structure used for this calibration experiment.

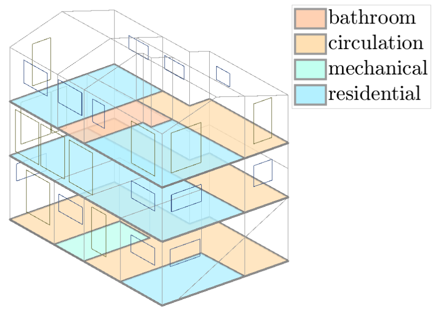
Still, what aspects of the model should be revised is a difficult question. Information about the boundary conditions of the available measurements, which could guide the answer, is lacking. The simplification consisting in using a multiplier to simulate only one floor may bear some blame. One possibility is that the seasonal variations in occupancy of the residence (including holidays) are not modeled satisfactorily. The reduction of the rotary air exchanger to a constant heat recovery rate may not be acceptable. Also, uncertainties do not only affect building parameters, but also weather data and to a lesser degree measured values. This case is a good illustration of difficulties encountered with calibration in practice.

9.3.2 Calibration case two: single-family house

Introduction. This case study deals with a single-family house built in 2015 in the Austrian state of Salzburg. The building has been planned to optimize passive and active solar gains. As appears from Figure 9.17a, the high glazing ratio of the south-east facade stands in contrast to the partially underground north-west side. Solar thermal collectors are to cover a high ratio of domestic hot water (DHW) and space heating needs. Thermal storage for DHW and space heating is ensured by two separate buffer tanks with respective volumes of 1.0 and 0.6 m^3. These buffer tanks are supplied with heat by 15 m^2 of solar collectors and a brine-water heat pump (with a capacity of 4.7 kW) connected to a horizontal ground heat exchanger. The choice of concrete core activation for heat delivery provides more storage potential.



(a) Exterior space boundaries.



(b) Zoning.

Figure 9.17: Building model for the single-family house.

Data from one day of measurements at a frequency of 5 minutes are available. Measured quantities include room temperatures on the two upper floors, exterior temperatures, temperatures in the buffer tanks, supply and return temperatures of the solar thermal system and heating energy rate, as well as energy rate and volume flow for space heating.

Method. The three building floors are divided into nine zones with four different functions (Figure 9.17b). Envelope properties are taken from an energy certificate issued for the house. Weather data is approximated by combining a weather file for Salzburg with the air temperatures recorded on-site. Solar radiation values are not available but assumed to be low. Indeed, the measurement day (November 27) was an overcast day with an average outside air temperature of 4 °C, during which the solar thermal system did not provide any energy. As a consequence, the following simulation experiments neglect the solar system and consider only energy supply through the heat pump.

The variable on which calibration is attempted is the heat transfer rate from the space heating buffer tank to the space heating consumer groups. After initial experiments with high-resolution (5-minute) values, simulated and measured vectors are compared on an hourly basis. The proposed calibration method is applied with gradient descent optimization, starting from 3 sets of base parameters.

Results. Simulation results for different attempts and optimization steps are compared to the corresponding measured values in Figure 9.18. The corresponding values of the input parameters are shown in Figure 9.19, and the evolution of the error indicators can be seen in Figure 9.20. Already with base values, simulation and measurements are in relatively good agreement for the total daily heat rate,

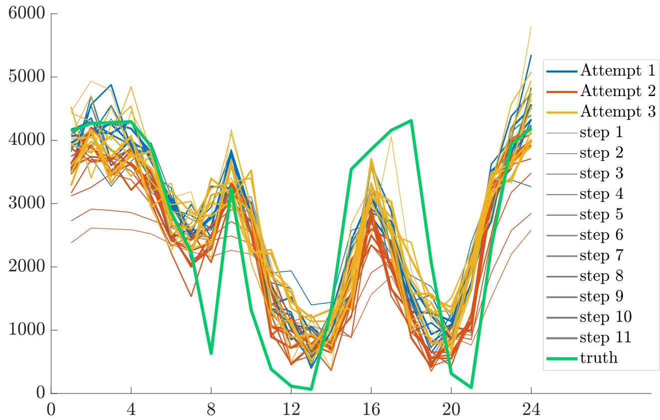


Figure 9.18: Monitored (green) and simulated heat rate values (W) for 3 calibration attempts.

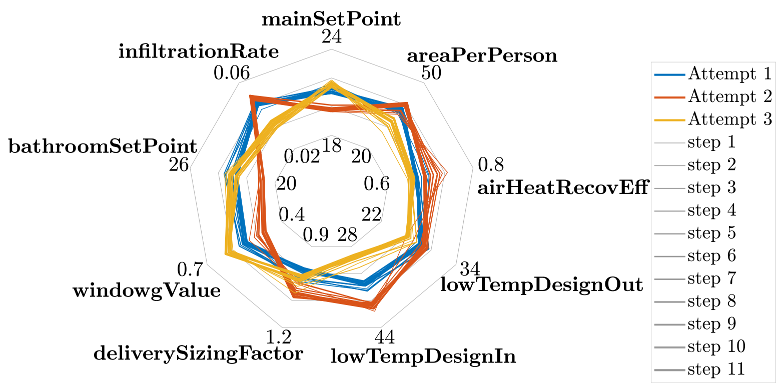
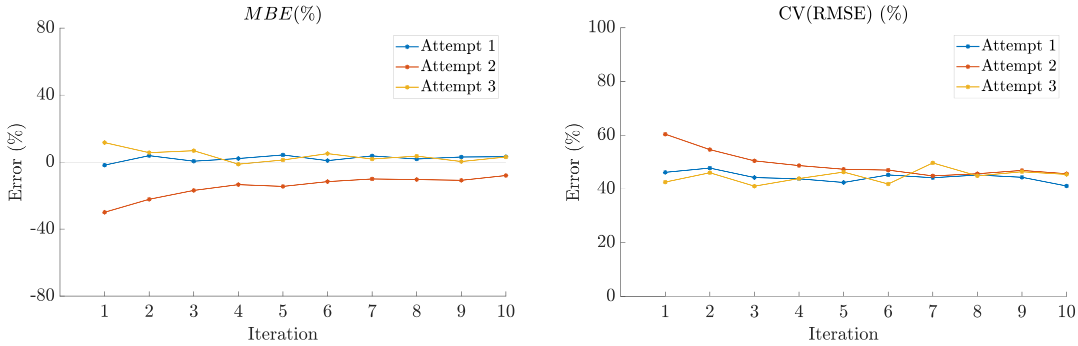


Figure 9.19: Calibration parameters for 3 calibration attempts and successive calibration iterations for single-family house.

but not for its actual course. The calibration procedure fails to improve the goodness-of-fit significantly. The minimum obtained CV(RMSE) is 41%, where ASHRAE guideline 14 requires 30% for hourly calibration.



(a) MBE. **(b)** CV(RMSE).

Figure 9.20: Error indicators along optimization steps for single-family house calibration experiment.

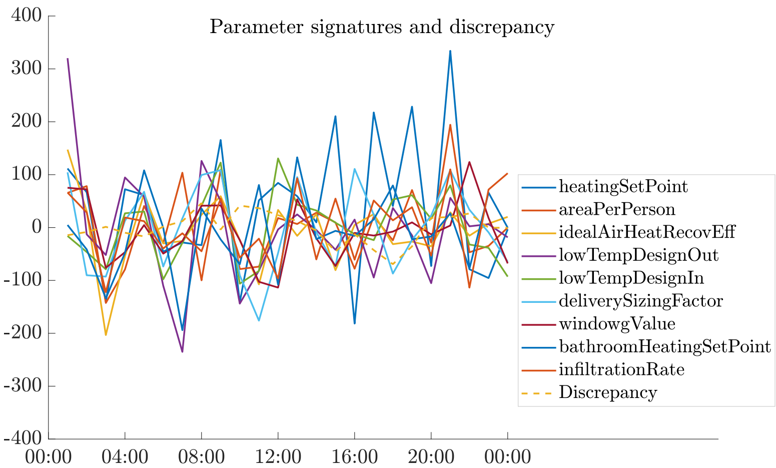


Figure 9.21: Example of parameter signatures and discrepancy for the single-family house calibration experiment, as a percentage of the maximum measured value.

Discussion. Possible reasons for these rather unsatisfying calibration results are multiple. As illustrated in Figure 9.21, the signatures of several parameters exhibit very localized peaks, which correspond to displacements of the heating times. These peaks appear even sharper if one looks at the values with 5 minute intervals. Gradient descent optimization seems ineffective at dealing with the sharply changing curves involved here.

In this case, the measurement frequency is actually too high for a direct comparison with simulation. Some short-term (subhourly) dynamics of the system are not well represented in our simulation models, whether it be heat pump behaviour, control aspects or weather and occupancy boundary conditions. Comparing hourly results probably makes more sense, in addition to smoothing out the signature peaks mentioned above.

Apart from this, model structure is also questionable. It appears from the measurements that the air temperature is maintained at a significantly lower level (4 K less) on the upper floor (bedrooms) than on the ground floor (living room). This difference cannot be represented with the current representation of space uses, which draws no distinction between these two "residential" uses. Controls represent a possibly significant source of discrepancy between the real system and simulation. Like in the first case, some more information about the boundary conditions would be helpful, e.g. how many persons were present during the measurements. Finally, the very short measurement period limits the significance of this experiment.

Summary

This chapter addresses the issue of comparing simulation results obtained by the proposed system to real measured values. A calibration method is proposed, that fits with the automated character of the proposed system. Mathematical optimization techniques are applied to minimize a function of the parameters to calibrate measuring the discrepancy between simulation and measurements.

This calibration method is tested in two series of experiments. First, artificial data derived from simulation results is used instead of measured data. This substitution makes it possible to investigate the behavior of the method on a variety of cases without the costs and uncertainties linked to monitoring. In a second step, the calibration method is applied to real buildings with available monitoring data.

Calibration experiments with artificial data show the ability of the presented method to reduce the discrepancy between simulated values and reference values to very low levels. However, calibrated parameters fail to converge towards their true values, which is in line with the general underdetermination of the calibration problem. In these first experiments, the use of a simple gradient descent algorithm for optimization is usually sufficient: it does occasionally fail to reach a good result, but succeeds at least once when starting from three sets of base values. One issue with gradient descent is when parameters are pushed close to the boundaries, which could be remedied by an appropriate penalty scheme. But other algorithms less susceptible to local optima would probably yield better results.

The results of calibration experiments with real data are less satisfactory. Values obtained for CV(RMSE) fail to go below acceptable thresholds. Several directions may be taken to improve on these results. However, in both cases, one may deplore the lack of information about boundary conditions of the measurements. Respective limitations in the frequency (first case) and the duration (second case) of measurements strengthen the underdetermination of the calibration problems. This underdetermination is such that no calibration procedure can supplant an on-site audit in reducing uncertainties about the building and its operation. Additional, better-documented experiments would be desirable.

In spite of this, the proposed calibration method is able to significantly improve the agreement of simulation with measurements. If it does not bring this agreement to a satisfactory level, it can yield interesting clues regarding the ability of a family of models to simulate the real building.

A drawback is that calibration is computationally expensive. One calibration experiment requires from a few dozens to several hundreds simulation runs. Sensitivity analysis proves to be useful for limiting the number of parameters submitted to calibration. Still, choosing the appropriate model resolution is a critical decision.

To conclude, the significance of this chapter for the rest of this work is twofold. On the one hand, the possibility (or impossibility) of calibrating a model to real data is related to the validation (or falsification) of the model in question and of the software system which created it. On the other hand, it shows how an automated calibration method can be used to improve the accuracy of models produced by the proposed system.

Chapter 10

Conclusions

The present thesis deals with integrated building and HVAC performance assessment. It has been described how automated methods for the creation of simulation models may allow the performance of different alternatives to be compared on a detailed level, where the expense of manual modeling would be prohibitive. This chapter recapitulates the main contributions and indicates directions for future work.

10.1 Contributions

The analysis of existing literature revealed a gap in the completeness of methods proposed until now for automated simulation model creation, in that they did not achieve detailed HVAC modeling. Given the general unavailability of detailed HVAC models at the targeted conceptual design stage, the use of generative procedures to create such models was found to be the most acceptable way to complete data translation in order to reach the aim of automated creation of integrated building and HVAC models. This thesis develops a method which allows integrated simulation models encompassing all HVAC subsystems and their interplay with the building to be created without manual intervention. The contributions can be summarized as follows:

1. At the heart of the proposed method are the procedures used to create component-based models of HVAC systems, based on the sequence of delivery, distribution and generation subsystems. Going beyond autosizing approaches commonly used with simulation tools, the developed procedure allows multiple delivery components to be geometrically located in each zone, based on heuristics derived from HVAC planning practice. Thus creating HVAC simulation models encompassing all subsystems addresses the first gap identified in Section 2.4, that of the completeness of automatically created models.

2. The determination of detailed models of distribution subsystems is a distinctive contribution of the present work. Engineering principles and graph

algorithms are combined to achieve automated generation of these models. Networks of potential distribution components are derived from building geometry and the positions of delivery components. Acyclic subsets of these networks can be determined, according to desirable properties of distribution subsystems, and transformed into networks of distribution and delivery components. Generation components are finally added to these groups of components linked by inlet/outlet relations.

3. Requirements for a software system implementing the proposed approach are defined under consideration of three use cases in which simulation could support decision-making at the concept design stage, by assessing the relative performance of several design alternatives. These alternatives may differ in the type of HVAC system to install, and possibly in the quality of the building envelope, or only in a new generation subsystem. By providing the context for simulation, these use cases address the second gap identified in Section 2.4, that of integration in the design process.

4. A software system design meeting these requirements is described. This involves the determination of a data model able to support the whole model creation process. An essential part of the proposed system is also the transformation of the obtained models into actual inputs for the selected simulation engines, which are two commonly used simulation tools.

5. The application of the proposed system to the defined use cases is illustrated. This implies creating and running simulation models based on several sets of parameters, and post-processing results to derive performance metrics.

6. It is shown how comparative testing can be used to gain confidence in the proposed system. This includes comparing characteristics of generated HVAC models with default values found in standards, and comparing results obtained with different simulation options with each other.

7. Systematic procedures to simplify the resulting simulation models are developed. Zones can be determined by grouping spaces according to their connectivity and shared properties. Detailed HVAC models can be simplified by lumping components together, for instance distribution segments for which similar temperatures can be expected.

8. The impact of model simplifications on simulation results is investigated. This addresses the third gap identified in Section 2.4, concerning the level of detail of simulation models. Zoning experiments using several building floors explore the variable impact of simulation zoning on results. Distinguishing simulation zoning and HVAC zoning, an experiment also shows how a detrimental impact of coarse HVAC zoning on performance can be detected with a fine simulation zoning. It is verified that the HVAC model simplification procedures yield acceptable results. In terms of parameter simplifications, it is shown how a sensitivity analysis technique can be applied to the proposed system for parameter screening.

9. Simulation results are also compared to monitoring data. In this context, an optimization-based approach for automated calibration is proposed to reduce the discrepancy between simulated and measured values with limited user intervention. The method is tested with two sets of calibration experiments. The first experiments use detuned simulations as surrogates for measurements. They show that the calibration method can indeed minimize the discrepancy, but that this does not involve convergence of the calibrated parameters towards their true values. In calibration attempts for two cases with real monitoring data, the discrepancy can also be reduced, but not brought to a satisfactory level.

10.2 Discussion and limitations

The present work shows that component-based HVAC system models encompassing all subsystems can be created automatically on the basis of structured building models, and used for integrated building and HVAC simulation. The research question also referred to the usefulness of such models for the support of energy-efficient planning. In the domain of focus, the models created with the proposed method are more detailed than those which can be created otherwise with similar resources. Still, it would remain to show that these more detailed models are also more accurate, and that the increased accuracy is indeed useful in the intended use cases. The question of accuracy is addressed in the validation part of the present work. As argued there, a combination of techniques can be used to test the proposed system. Additional comparisons with real data should be carried out for further validation. It seems reasonable to assume that more detailed and accurate models would be useful for design support. Still, their added value would be difficult to quantify. It would depend on how practitioners use the more detailed models, which simpler models they are compared to, and what levels of expertise are available to interpret and complete results from both types of models.

One may question the complexity of the generated models, as this complexity might exceed the level needed to answer the questions asked. In particular, the creation of a detailed model of the distribution subsystem, which plays a central role in this work, often yields only minimal differences in simulated energy consumption. The intended generality of the method and the goal of comparing several terms partly justify this complexity. Comparing several systems, one expects the same level of detail to be used for all models, and this should be determined by the system requiring the highest level of detail. As pump power may be negligible in some cases but not in others, it is advantageous for a general method to account for it as accurately as possible. Also, model complexity may be brought down to the desirable level with systematic simplifications such as those proposed in this work. Finally, one may find the models created in this work "unbalanced": modeling HVAC distribution subsystems in detail may not be worthwhile in conjunction with simplistic modeling approaches for occupant behavior, lighting and glazing components. In this respect, the contributions of the present work can only take their full meaning as part of the much wider effort to advance building performance simulation for decision support.

10.3 Future work

Several directions are open in which the work presented here could be extended. Directions for future work are implied by the limitations evoked in the previous section, and by challenges to expect from real-life application of the presented method.

Revision of assumptions. Adjusting certain assumptions would be necessary to treat some cases not considered until now. For instance, the assumption that humidity effects are not important would have to be rejected in order to treat different climates and system types. A far-reaching assumption in this thesis work is that HVAC systems work as planned. In real HVAC systems, dealing with system faults is a substantial challenge.

As some simplifications have been studied in Chapter 8, simplifications part of the actual implementation could be assessed systematically when the possibility for more detail is implemented. For instance, one could assess the impact of assuming a steady-state curve for generation component performance against a higher level of detail including subcomponent modeling, transient behavior and explicit control. Another untouched issue in terms of simplifications is the common use of multipliers to simplify the modeling of, for instance, multi-storey buildings with similar floors. However justified and efficient multipliers are with ideal load simulation, isolating some of the zones served by a central system is quite problematic.

Interfaces and interactions. The standpoint of total automation of the model generation was conducive to the delimitation of this thesis, but real world applications will require interactions. Human interaction could be used to select variants at different steps. The possibility of introducing loops in performance evaluation has been evoked in Chapter 6. However, virtually every automated step could potentially be overwritten manually, or propose the user with a choice between options. An adequate interface should support users in preparing good-quality simulation models, making sure input parameters and assumptions are understood and bringing attention to possible sources of error. Along with the simulation models, it could be beneficial to produce a documentation of the assumptions and processes used for model creation.

Integration with BIM. The use of building information modeling for HVAC systems was avoided, as it has been argued that the translation from BIM to simulation tools remained an unresolved challenge. However, as detailed BIM models of HVAC systems become more available, it may be practical to compare them with some automatically generated models. A partial translation could make interesting comparisons possible, even if it does not result in simulation-ready models. Hybrid approaches could be developed combining translation from

BIM and automated procedures for model completion. In the other direction, the translation of generated models into BIM could be considered.

Use across design and operation phases. Additional use cases may be considered, tackling other phases than conceptual design. This may start with feasibility studies, where detailed building geometry is not available. As design gets refined, the level of detail of simulation may increase, and the uncertainties may be reduced. As one gets closer to technical design, it would become more important to consider existing products for HVAC components, which implies a choice between discrete options. This would make automated links with product catalogues desirable. The questions to which simulation may provide answer would also change, from the choice of a system type to the choice of components and their sizing, and the optimization of system control. The outlined calibration method is a first step towards applications in later phases. Simulation may be used in commissioning. The proposed method could also be adapted to support model-based control, using adequate simplifications or meta-models for speedup.

Extensions to adjacent domains. Extensions to other domains relevant for energy performance can be considered. Examples of such domains include detailed air flow simulation (by coupling with multizone airflow models or computational fluid dynamics) and daylight simulation. Simulation in these domains involves different views of the building. Model translation and completion procedures corresponding to these different views could be used. The coupling of the resulting models may represent an additional challenge. Closer to the studied HVAC systems, systems for the provision of sanitary hot water could be modeled using an approach similar to that presented in this work. This would at least be required to model cases of combined heat generation for space heating and domestic hot water. Thermal losses from sanitary hot water distribution, being also present in periods when they cannot be reused, may matter more than losses from space heating distribution.

Simulation-based optimization. Whereas it is assumed in the present work that the choice of the best among several simulated variants should be made by an enlightened professional, one may imagine a modification of the automated method towards simulation-based optimization. A higher number of variants would be simulated, and the selection of more promising variants would be automated. For this approach to be relevant, a number of additional aspects and constraints considered by human decision-makers should be quantified and reflected in the optimization problem. In particular, estimates of the life cycle costs of buildings and HVAC systems should be taken into account.

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Glossary

system A system can be defined as "a regularly interacting or interdependent group of items forming a unified whole" [10]. Examples of systems are the organized group of procedures described in this thesis for the creation of building performance simulation models, or a building and the technical devices installed in it, or an HVAC system, as a subset thereof.

HVAC system Set of interconnected devices used for heating, ventilation and air-conditioning of buildings.

HVAC subsystem We adopt a usual breakdown of HVAC systems into three subsystems with specific functions [15]: delivery, distribution and generation. When present, storage is sometimes considered as a fourth subsystem, or included in generation or distribution.

loop HVAC systems can usually be broken down into loops [11]. We define a loop as a part of the HVAC system with a defined flow direction, one inlet and one outlet, where the outlet is connected to the inlet. There may be several paths from inlet to outlet, which means a loop does not generally correspond to a cycle in the graph theoretical sense, but rather to several cycles (one for each demand component)..

component A basic element of an HVAC system, or the object representing it in a simulation model. With our data model, a component is an instance of the class *GeneralSystemComponent*. Not to be confused with the graph theoretical meaning, for which the full expression of connected component is used.

demand component A demand component is provided some energy from the source. Delivery components are demand components. Other components (storage tanks, water/air coils) may be demand components for one loop and source components for another loop. The adjective is relative to a loop. A demand component can be seen as a load for the source.

source component A source component provides energy to demand components. Generation components are source components. A storage tank is a source component for the loop linking it to delivery components, and a demand component for the loop linking it to a generation component.

supply half loop In a loop, the part of the loop from the source (component supplying energy) to the demand component(s).

return half loop In a loop, the part of the loop from the demand component(s) to the source component.

delivery component A part of the HVAC subsystem responsible for the actual delivery of energy and/or air to the space and/or occupant. A delivery component can be seen as a flow terminal (*IfcFlowTerminal*), at it is a point where the HVAC system interfaces with the building. A synonym for delivery subsystem is emission subsystem [15].

distribution component A part of the HVAC subsystem linking delivery and generation subsystems, from the latter to the former (supply) as well as from the former to the latter (return). The distribution subsystem in this sense does not correspond to the much broader definition of distribution systems in IFC. *IfcDistributionElement* is used not only for distribution in our sense (*IfcFlowSegment*,*IfcFlowMovingDevice*, *IfcFlowFitting*), but also for generation (*IfcEnergyConversionDevice*) and delivery subsystems (*IfcFlowTerminal*). Pumps are usually included in the distribution subsystem, unless they are for instance integrated in a boiler [15].

generation component A part of the HVAC subsystem responsible for the transformation of (primary) energy into the form that will be used. Examples of primary energy can be gas, electricity, or hot water distributed to the building, solid fuels, or environment energy such as solar radiation. The generation subsystem uses it to heat or cool a fluid, mostly water. Generation components correspond to *IfcEnergyConversionDevice*.

group distribution Part of the distribution subsystem responsible for distribution to and from a group of delivery components with the same inlet temperature requirements. The group distribution can be seen as the union of a supply tree and a return tree.

network of potential distribution components Network representing potential components of a group distribution. The nodes correspond to a root, demand components and intermediate vertices. The edges correspond to potential distribution segments, and weighted to represent their cost.

hydraulic circuit Arrangement of (flow) distribution segments and valves controlled in a specific way. Not meant is circuit in the graph theoretical sense of a cycle.

distribution segment Component representing a pipe, a duct, or a section thereof. Distribution segments have a length property, in contrast to valve or pump components..

sizing Determination of the size of a component, not only in terms of geometric dimensions, but also in terms of capacity, e.g. maximum volume flow rate.

Acronyms

AEC architecture, engineering and construction. 22

BEM building energy model. 21

BIM building information modeling. 11, 23

BPS building performance simulation. 6

CAD computer-aided design. 23

CV(RMSE) coefficient of variation of the root-mean-square error. 176, 194, 198

DHW domestic hot water. 209

FMI functional mock-up interface. 30

FMU functional mock-up unit. 30

FZ functional zoning.

gbXML green building XML schema. 23

GDDC group of distribution and delivery components. 88

HP heat pump.

HVAC heating, ventilation and air-conditioning. 27

IDF input data file.

IFC industry foundation classes. 23

MBE mean bias error. 176, 194, 198

MST minimum spanning tree. 85

NPDC network of potential distribution components. 79

OFZ orientation and functional zoning.

OZ orientation zoning.

PZ perimeter/core zoning.

RMSE root-mean-square error. 194

SB space boundary.

SP shortest path. 86

STSP Steiner traveling salesman problem. 87

TSP traveling salesman problem. 87

UML unified modeling language. 113

List of physical symbols

Sign	Description	Unit
A	Area	m^2
C	Heat capacity	J/K
D	Diameter	m
P	Power	W
R	Pressure gradient	Pa/m
$\dot{Q}$	Heat transfer rate	W
$\dot{V}$	Volume flow rate	m^3/s
$\dot{m}$	Mass flow rate	kg/s
η	Efficiency	
ν	Fluid velocity	m/s
ρ	Density	kg/m^3
θ	Temperature	K
c_p	Specific heat capacity	J/(kgK)
f	Conversion factor	
h	Height	m
l	Length	m
p	Pressure	Pa

List of mathematical symbols

E	Set of edges of a graph.
G	Graph or network.
J	Objective function in optimization.
S	Surface.
V	Set of nodes of a graph.
$\mathbf{m}$	Vector of measured values.
$\mathbf{r}$	Vector of reference values.
$\mathbf{s}$	Vector of simulated values.
$\mathbf{x}$	Vector of normalized parameters for calibration.
d	Distance.
k	Number of inputs in method of elementary effects.
p	Number of levels in grid for method of elementary effects.
r	Number of trajectories in method of elementary effects.
v	Node in a graph.
w	Weight of an edge (or a graph).

List of subscripts

PE	primary energy.
a	air.
$circ$	circuit.
c	cooling.
dem	demand.
el	electric.
eq	equivalent.
h	hydraulic.
in	incoming.
nr	non-renewable.
op	operational.
out	outcoming.
ref	reference.
r	return.
s	supply.
z	zone.

Appendices

Appendix A

Related publications

The work described in this thesis has been partially included in several publications previously published at international conferences. A review of approaches for automated building energy performance simulation [248] essentially corresponds to the literature review chapter, and outlined research opportunities pursued in this thesis. The method for automated creation of HVAC distribution subsystem models was presented in [217]. An application of the method to residential buildings and their heating systems was presented in [226]. A study of the impact of zoning on simulation results [249] essentially corresponds to the first section of Chapter 8 on model simplifications.

Appendix B

Parameter definition

B.1 Overview

This appendix presents parameters susceptible of variations in the proposed system. Building performance simulation may require yet many more parameters than are presented here. Among these other parameters, some are fixed to a default value, and some can be extracted from several sources.

In terms of their use in the proposed system: (i) Some parameters are used to customize model creation procedures. (ii) Some parameters are reflected directly in component models, or act as multipliers of default values. (iii) Some parameters are reflected in simulation options.

Not all parameters are used in all cases. One could present parameters as a tree, where some leave parameters would only apply if a given component type is selected and/or if a given simulation option is selected. However a flat structure is easier to present, and more advantageous for applications like sensitivity analysis, which is why we limit the structure to a few lists of parameters.

In terms of their implementation, we distinguish the following types of parameters: (i) numeric (mostly continuous); (ii) boolean (can be considered to be a type of numeric parameter); (iii) string; (iv) string cell. Parameters programmed as strings are actually nominal parameters, where the string can take only a finite set of values. Parameters programmed as string cells are actually strings of nominal parameters.

Numeric parameters are either dimensionless (e.g. radiant fraction), or have a given physical unit. Most numeric parameters have ranges of validity, which can be used for checking. These ranges of validity supposed to apply to most usual cases should be distinguished from the usually narrower ranges applied to specific cases of sensitivity analysis.

B.2 HVAC system parameters

We distinguish four classes of parameters for HVAC systems:

(i) Common parameters, which determine all HVAC systems in terms of the calculation of design loads and what zones should be served by each system. (ii) General HVAC system parameters, which can be applied to any HVAC system, whether hydronic or air-based. (iii) Hydronic system parameters, which can be applied to any hydronic system. (iv) HVAC modeling parameters, which do not relate to real features of HVAC systems, but rather to their modeling. In case a building is served by several HVAC systems, these parameters identically apply to all HVAC systems.

Table B.1: Definition of common HVAC parameters.

Parameter name	Unit	Description
thereIsCoolingSystem		Indicates if a cooling system is present.
mechanicalVentilation		Indicates if a mechanical ventilation is present.
heatingSystemServingScheme		Indicates if there is a system for the whole building, or one by floor.
coolingSystemServingScheme		Indicates if there is a system for the whole building, or one by floor.
ventilationSystemServingScheme		Indicates if there is a system for the whole building, or one by floor.
sizingThBrNbPiercingWalls		For thermal bridges in stationary sizing. See ÖNORM EN 12831 D.4.
sizingThBrNbPiercingFloors		For thermal bridges in stationary sizing. See ÖNORM EN 12831 D.4.
sizingThBrNbExposedSides		For thermal bridges in stationary sizing. See ÖNORM EN 12831 D.4.
sizingTempReduction	K	For estimation of heat-up load. See ÖNORM EN 12831 D.6.
sizingHeatUpTime	h	For estimation of heat-up load. See ÖNORM EN 12831 D.6.

Table B.5: Definition of hydronic system parameters.

Parameter name	Unit	Description
deliverySizingFactor		Sizing factor applied to delivery subsystem, equal to ratio of delivery capacity at design conditions by design load.
generationSizingFactor		Sizing factor applied to generation subsystem, equal to ratio of generation capacity by required capacity at design conditions.
propDistrLossesForGenerationSizing		Factor of maximal distribution losses to be added to demand for generation sizing.

Table B.5: Definition of hydronic system parameters.

Parameter name	Unit	Description
emissionComponent		List of delivery component types ordered by preference.
generationComponent		Generation component type. Possible values for heating: 'BoilerPellets', 'DistrictHeating', 'HeatPumpAirSource', 'BoilerPellets', 'DistrictHeating', 'HeatPumpAirSource'.
generationTemperature	°C	Output temperature of generation component at design conditions.
designLoopTempDiff	K	Temperature difference between output and input temperatures of generation component at design conditions.
thereIsThermalStorage		Indicates if a storage subsystem is present in the hydronic system.
storageVolumeByCapacity	m^3/W	Ratio of storage volume by maximum capacity of generation. Default around 10 liters per kW.
storageGenerationSetpointDifference	K	Difference of generation setpoint and storage setpoint (positive).
storageControlBandwidth	K	Determines allowed domain for storage component outlet temperature, as set point plus/minus the value of this parameter.
controlBandwidth	K	Determines allowed domain for zone temperature, as set point plus/minus the value of this parameter.
coarserHvacZoning		True if HVAC zoning coarser than simulation zoning should be modelled.
hvacZonesCriteria		Name of zone property according to which simulation zones should be grouped into HVAC zones.
hvacZonesConnected		True if only adjacent simulation zones should be grouped into a coarser HVAC zone.
resetCurveXOne	°C	Reset of generation supply temperature based on outdoor air temperature (OAT): outdoor temperature under which supply temperature is equal to design temperature.
resetCurveXTwo	°C	OAT generation temperature reset: outdoor temperature above which supply temperature is equal to resetCurveYTwo.
resetCurveYTwo	°C	OAT generation temperature reset: generation temperature when OAT = resetCurveXTwo.
boilerNominalEfficiency		Nominal efficiency of boiler.

Table B.5: Definition of hydronic system parameters.

Parameter name	Unit	Description
heatDeliveryRadiantFraction		Proportion of heat delivered in the form of radiation.
heatDeliveryDeltaTExponent		For delivery components, n exponent in equation of delivered heat $q = c\,(T_s - T_a)^n$.
minDeliveryCapacity	W	Minimum capacity of a delivery component.
maxDeliveryCapacity	W	Maximum capacity of a delivery component, above which it is split into several delivery components.
lowTempDesignIn	°C	Design inlet temperature for low temperature radiant systems.
lowTempDesignOut	°C	Design outlet temperature for low temperature radiant systems.
lowTempDepthOfSource		Depth of internal source (heating or cooling pipes), as a fraction of second (from zone interior) layer depth.
warmAirDeliveryTemp	°C	Design temperature of air supplied to the zone.
GSHPpipeLengthPerCapacity	m/W	Ground exchanger pipe length per capacity (of heat pump).
GSHPpipeInnerDiameter	m	Ground exchanger pipe inner diameter.
GSHPpipeThickness	m	Ground exchanger pipe thickness.
GSHPpipeThermalConductivity	W/m K	Ground exchanger pipe thermal conductivity.
GSHPsoilThermalConductivity	W/m K	Soil thermal conductivity.
GSHPsoilDensity	kg/m^3	Soil density.
GSHPsoilSpecificHeat	J/(kgK)	Soil specific heat.

Table B.3: Definition of general parameters applicable to hydronic and ventilation systems.

Parameter name	**Unit**	**Description**
flowMovingDeviceSpeed		Indicates if pump (or fan) has constant or variable speed.
pipeInsulationFactor		Indicates insulation thickness of distribution segment, as a proportion of inner diameter.
pipeLengthFactor		Factor by which calculated segment lengths are multiplied.
segmentRadiusFactor		Factor by which calculated segment radiuses are multiplied.
flowMovingDeviceEfficiency		Overall efficiency of flow moving device at design conditions.
flowMovingPowerCoeffZero		Coefficient of flow moving device power as a function of part load ratio x $P = C_0 + C_1\ x + C_2\ x^2 + C_3\ x^3$.
flowMovingPowerCoeffOne		Coefficient of flow moving device power as a function of part load ratio x $P = C_0 + C_1\ x + C_2\ x^2 + C_3\ x^3$.
flowMovingPowerCoeffTwo		Coefficient of flow moving device power as a function of part load ratio x $P = C_0 + C_1\ x + C_2\ x^2 + C_3\ x^3$.
flowMovingPowerCoeffThree		Coefficient of flow moving device power as a function of part load ratio x $P = C_0 + C_1\ x + C_2\ x^2 + C_3\ x^3$.
distributionDistDefEquation		For NPDC edge weights, type of distance definition.
distributionDistDefWeightZ		For NPDC edge weights: coefficient for the z-coordinate.
distributionDistDefWeightShaft		For NPDC edge weights: coefficient for segments in shaft zones.
defaultPipePressureGradient	Pa/m	Default pipe pressure, to speed up calculations. Detailed calculation if empty value.
totalPressureDropFactor		Factor by which linear pressure drops are multiplied to take into account punctual pressure drops.
supplyReturnShiftX	m	Determines offset between supply and return distribution nodes.
supplyReturnShiftY	m	Determines offset between supply and return distribution nodes.
supplyReturnShiftZ	m	Determines offset between supply and return distribution nodes.

Table B.6: Definition of parameters relative to HVAC modeling.

Parameter name	Unit	Description
doConsecutiveSegmentMerging		Merge consecutive distribution segments present in the same zone (S1).
useSimplifiedLoopForTrnsys		Use simplified structure S2 for TRNSYS (for EnergyPlus S2 is used anyway).
mergeZoneDeliveryComponents		Only one delivery component by zone (S3).
deleteDistributionSegments		Do not model distribution segments at all (S4).
useAutosizePlantVolumeForEPlus		Otherwise plant volume calculated from pipe volumes.
pressureDropCalculationMode		Pressure drop calculation only for segments or for other modeled components.
distribTreeMethod		Algorithm for supply and return trees.
intermediateVertices		Intermediate nodes for NPDC.
getPseudoIntermediateNodeInZone		Try and have segments following space boundaries even after simple NPDC.
copySupplyForReturn		Gives the possibility of following supply tree layout for return.

B.3 Building parameters

Building parameters include parameters relative to the whole building and others which may apply to each zone.

Table B.8: Definition of building parameters.

Parameter name	**Unit**	**Description**
groundReflectance		Reflectance of ground outside of the building (albedo).
wallUValue	$W/(m^2K)$	U-value of exterior wall.
roofUValue	$W/(m^2K)$	U-value of roof.
groundUValue	$W/(m^2K)$	U-value of building element to ground.
windowUValue	$W/(m^2K)$	U-value of windows.
windowgValue		g-Value of windows (percentage of absorbed solar radiation).
expAreaFactorForInfil		Determines if infiltration should be proportional to zone volume ($k = 0$) or exposed area ($k = 1$), or both ($0 \leq k \leq 1$).
zoneMixingFactor	(m3/s)/m2	Coefficient for zone mixing rate between zones, as a proportion of shared partition area.
idealAirHeatRecovEff		For ideal loads, (sensible) efficiency of air heat recovery (0 if no air heat recovery).

Table B.10: Definition of zone parameters. Net values are meant for floor areas and space volumes.

Parameter name	Unit	Description
heatingSetPoint	°C	Set point for heating in winter.
internalMassArea	m^2	Equivalent area of internal mass for each square meter of zone floor area.
infiltrationRate	h^{-1}	Air change rate due to infiltration (constant for all conditions).
ventilationPerArea	$m^3/(m^2 h)$	Ventilation rate per floor area.
ventilationPerVolume	h^{-1}	Ventilation rate per space volume.
ventilationPerPerson	$m^3/(s\,person)$	Ventilation rate per occupant.
areaPerPerson	m^2/person	Area per person (at maximum occupancy, otherwise multiplied by schedule value).
onePersonGain	W/person	Heat gain due to one person.
heatGainLight	W/m^2	Heat gain due to lighting.
lightMount		Light mounting (Surface' or 'Suspended') determines fraction radiant vs fraction visible.
heatGainElectEqu	W/m^2	Heat gain due to electrical equipment.

Summary

The system makes use of many parameters, each of which may have an impact on simulation results. The number of parameters may increase significantly if specific domains are considered in greater detail. Work required for parameter input and checking increases accordingly. Sensitivity analysis and parameter screening may be used to reduce the number of parameters in given cases. Rules more elaborate than individual range checking may be applied to gain confidence in parameters with limited effort.

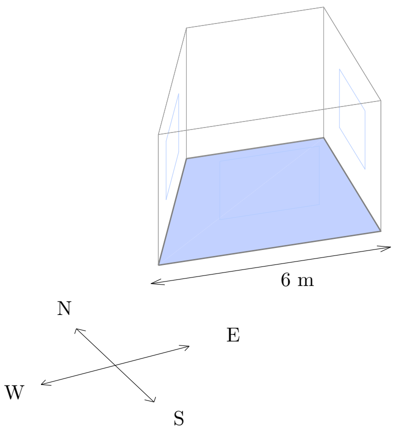
Appendix C

Test buildings

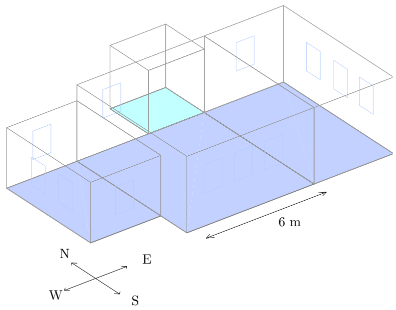
The potential of building performance simulation also lies in its ability to simulate the performance of any arbitrary building. This appendix presents instances of buildings used in this thesis work for illustration, comparisons and tests. These buildings are all residential buildings, and all fictitious, apart from 2f14zR, which represents a real single-family house built as plus-energy building.

Table C.1: Characteristics of example buildings: height h (in m), number of floors n_f, total number of zones n_z, thereof n_{zc} conditioned zones.

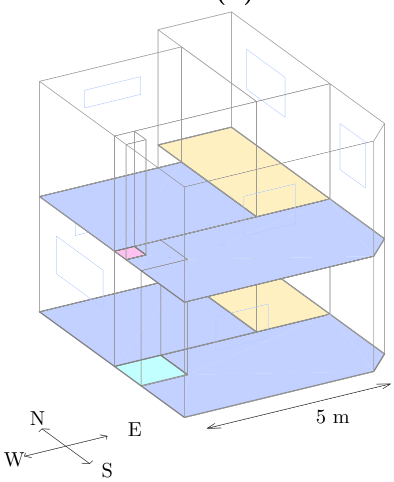
Id	n_f	n_z	**Floor area**	**Description**
1f1zR	1	1	21	Simplest 1-zone building.
1f4zR	1	4	100	Simple 4-zone building.
2f14zR	2	14	174	Plus-Energy House [250, p.92-94].
2f8zR	2	8	84	Simple 2-floor house.
3f35zR	4	35	531	3-floor rectangular building.
5f57zR	6	57	880	5-floor rectangular building.
8f80zR	8	80	1400	8-floor rectangular building.



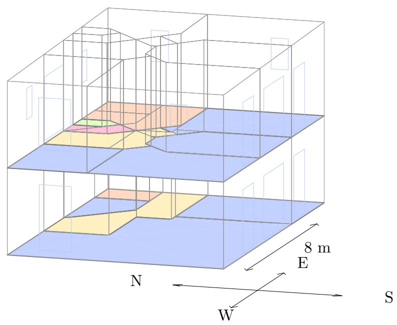
(a) 1f1zR.



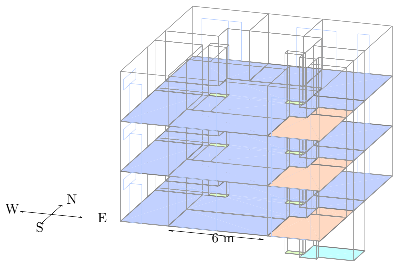
(b) 1f4zR.



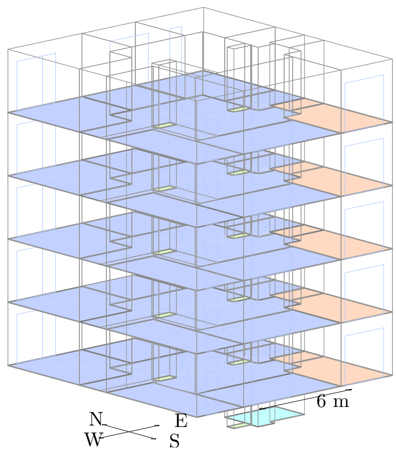
(c) 2f8zR.



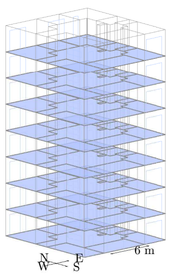
(d) 2f14zR.



(e) 3f35zR.



(f) 5f57zR.



(g) 8f80zR.

Figure C.1: Reference buildings and their space uses.

Appendix D

Detailed parameter screening results

This appendix presents in more detail the parameters used in the parameter screening experiments described in Section 8.3 and the corresponding results.

Table D.1: Parameters and results for sensitivity analysis experiment S_1.

Id	Input parameter	unit	min	max	μ	σ	μ^*
1	boilerNominalEfficiency		0.75	0.85	-2300	192	2300
2	boilerCubicEffCoeffTwo		-0.1	-0.3	1800	812	1800
3	boilerCubicEffCoeffOne		0.1	0.2	-1100	319	1100
4	deliverySizingFactor		0.9	1.2	1000	729	1100
5	boilerCubicEffCoeffThree		0	0.08	-652	290	652
6	heatDeliveryRadiantFraction		0.45	0.75	246	339	338
7	designLoopTempDiff	K	8	16	-293	96	293
8	pipeLengthFactor		1	1.4	254	126	254
9	generationSizingFactor		0.9	1.2	-229	190	229
10	generationTemperature	°C	50	70	187	126	194
11	pipeInsulationFactor		0.1	0.3	-126	137	130
12	propDistrLossesForGenerationSizing		0	1	-36	110	90
13	segmentRadiusFactor		1	1.4	57	19	57
14	resetCurveXOne	°C	0	10	0	0	0
15	resetCurveXTwo	°C	10	20	0	0	0
16	resetCurveYTwo	°C	40	50	0	0	0
17	heatDeliveryDeltaTExponent		1.25	1.35	0	0	0
18	minDeliveryCapacity	W	100	300	0	0	0
19	maxDeliveryCapacity	W	1000	2000	0	0	0

Table D.2: Parameters and results for sensitivity analysis experiment S_2.

Id	Input parameter	unit	min	max	μ	σ	μ^*
1	generationTemperature	°C	40	50	162	42	162
2	generationSizingFactor		0.9	1.2	146	105	150
3	lowTempDesignOut	°C	26	34	51	116	110
4	deliverySizingFactor		0.9	1.2	91	50	91
5	hpNominalCop		4	4.4	−89	11	89
6	lowTempDesignIn	°C	36	44	−33	95	85
7	gshpPipeLengthPerCapacity	m/W	0.06	0.14	−11	31	28
8	gshpSoilThermalConductivity	W/(Km)	0.8	1.6	−17	8.1	17
9	resetCurveXOne	°C	-5	5	15	9.2	15
10	resetCurveYTwo	°C	30	38	12	8.9	12
11	lowTempDepthOfSource		0.05	0.15	11	22	11
12	controlTempRadiantFraction		0	0.6	−9	13	9
13	gshpSoilDensity	kg/m^3	800	1600	−6.9	3.6	6.9
14	gshpPipeThermalConductivity	W/(Km)	0.3	0.5	0.3	9.7	6.8
15	gshpPipeInnerDiameter	m	0.014	0.018	−5.8	6	6.3
16	gshpSoilSpecificHeat	J/(kgK)	2000	2800	−2.5	2	2.5
17	resetCurveXTwo	°C	20	30	1.5	1.1	1.5
18	gshpPipeThickness	m	0.004	0.006	−0.2	1	0.8
19	heatDeliveryRadiantFraction		0.4	0.8	0	0	0

Table D.3: Parameters and results for sensitivity analysis experiment *BS*.

Id	Input parameter	unit	min	max	μ	σ	μ^*
1	heatingSetPoint	°C	18	22	679	120	679
2	boilerNominalEfficiency		0.75	0.85	−344	110	344
3	areaPerPerson	m^2/person	10	20	−332	134	332
4	groundUValue	$W/(m^2K)$	0.3	0.4	251	68	251
5	infiltrationRate	h^{-1}	0.1	0.3	222	75	222
6	groundReflectance		0.2	0.8	−213	30	213
7	heatGainElectEqu	W/m^2	8	12	−190	45	190
8	deliverySizingFactor		0.9	1.2	183	30	183
9	generationSizingFactor		0.9	1.2	181	69	181
10	wallUValue	$W/(m^2K)$	0.2	0.3	171	34	171
11	roofUValue	$W/(m^2K)$	0.2	0.3	141	21	141
12	boilerCubicEffCoeffTwo		-0.25	-0.15	−141	40	141
13	windowgValue		0.5	0.7	−139	31	139
14	boilerCubicEffCoeffThree		0	0.08	−133	37	133
15	boilerCubicEffCoeffOne		0.12	0.2	−130	30	130
16	heatGainLight	W/m^2	5	9	−92	18	92
17	heatDeliveryRadiantFraction		0.45	0.75	−86	34	86
18	windowUValue	$W/(m^2K)$	0.8	1.2	85	11	85
19	propDistrLossesForGenSizing		0	1	61	34	61
20	generationTemperature	°C	50	70	49	22	49
21	pipeLengthFactor		1	1.4	37	20	37
22	designLoopTempDiff	K	8	16	−34	9.3	34
23	segmentRadiusFactor		1	1.4	21	6.4	21
24	internalMassArea	m^2	1	3	−8.7	5.6	9.1
25	onePersonGain	W/person	80	100	−7.8	4.9	7.8
26	pipeInsulationFactor		0.1	0.3	3.5	9.5	7.5
27	resetCurveYTwo	°C	40	50	6	4.5	6
28	resetCurveXOne	°C	-5	5	5.1	5.5	5.1
29	infiltrationRate	h^{-1}	0.2	0.5	3	0.8	3
30	resetCurveXTwo	°C	10	20	2.4	4.5	2.4
31	expAreaFactorForInfil		0	1	0	0	0
32	zoneMixingFactor	$(m^3/s)/m$	0	0.001	0	0	0
33	ventilationPerArea	$m^3/(m^2h)$	0.2	0.3	0	0	0
34	heatDeliveryDeltaTExponent		1.25	1.35	0	0	0
35	minDeliveryCapacity	W	100	300	0	0	0
36	maxDeliveryCapacity	W	1000	2000	0	0	0

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Advanced	MATLAB
CAD	AutoCAD, SketchUp, Rhino/Grasshopper
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