# A Method for Automated Generation of HVAC Distribution Subsystems for Building Performance Simulation

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## Abstract

Building performance simulation (BPS) may provide valuable support to the planning of more energy efficient buildings, but the effort needed to create a complete model can hinder this potential. In particular, an idealized representation of HVAC systems is often used instead of a more explicit and insightful model, because of the difficulty of creating the latter. While automated methods are available for the translation of building geometry for BPS, or for the sizing of delivery components, there is no generally accepted way of determining the HVAC distribution subsystems. This paper presents a method allowing models of these subsystems to be automatically created for the purpose of energy simulation. Based on an input consisting of a zoned building model and sized delivery components, networks of potential distribution components are determined and components corresponding to subsets of these networks are created and sized. The output is a component-based model of delivery and distribution HVAC systems, to be completed with generation components and translated into an input for a building performance simulation engine. The method is tested in a case study where its results are compared to an existing heating system for an office building.

## Introduction

Error-prone and labor-intensive manual preparation of input models is an obstacle to the use of building performance simulation (BPS) in early design stages. The automated generation of simulation models from available data is a promising solution. However, the translation of data regarding heating, ventilation and air-conditioning (HVAC) systems into simulation models is challenging, and such data are generally incomplete in early design stages. An approach allowing planners to evaluate the performance of integrated building and HVAC concepts is to derive approximated models of the latter from available building information, based on rules emulating the traditional design and sizing of these systems. While automated sizing of delivery and generation components is common, the research presented here focuses on the distribution subsystems linking them, more often neglected until now.

This paper proposes an automation-ready and simulation-oriented method for the determination of HVAC distribution subsystems, based on the determination of networks of potential distribution components.

After a review of relevant literature, the second part of this paper details the scope and requirements of the method. The third part presents the steps of the method itself. This is followed by a case study and discussion.

## Related work

### HVAC system modeling

HVAC systems are commonly decomposed in generation, storage, distribution and delivery subsystems (CEN 2007).

In building energy simulation, HVAC systems may be represented at different levels of abstraction (Trčka and Hensen, 2010): in conceptual system modeling, the systems are totally abstracted and assumed to deliver the exact amount of energy needed to maintain set point conditions (ideal loads). System-based modeling uses systems with fixed configurations and control strategies, with the possibility of specifying some parameters such as efficiency factors and capacities. In component-based modeling, a system is defined based on interconnected components with their own models. Equation-based modeling, with equations representing each considered physical process, makes even finer granularity and greater flexibility possible (Wetter 2009). The presented method targets component-based modeling. It could also be used for equation-based modeling, where equations are often encapsulated in components, or for system-based modeling, by extracting system characteristics from a richer component-based model.

Considering the approach used to derive the model, one can differentiate between white box models based on first principles applied to the modeled system and data-driven black box models. HVAC system models often combine several approaches, first principles being mainly used for heat and mass transfer components, and empirically obtained equations being preferred for generation components (Trčka 2008, p.12).

Integrated simulation with component-based modeling of HVAC systems may provide more valuable insight than building simulation with ideal loads (Korolija et al. 2011), and this all the more if both building and HVAC systems can be modelled in high resolution (Clarke et al. 2015). However, this exacerbates challenges associated with simulation model creation.

### Data integration

Data exchange in the context of building and HVAC system simulation represents a particular challenge because of the different professionals involved and their particular views.

The COMBINE project proposed to deal with the challenge of data exchange by developing an Integrated Data Model. Within its scope, it was shown how energy analysis could be carried out on a central building model, and its results used to size ducts designed in an integrated CAD tool (Mellotte et al. 1995). The SEMPER system (Mahdavi et al. 1996) aimed at seamless communication between a design model and several domain-specific simulation models, including one for HVAC system performance. For this purpose, SEMPER used a component-based approach and a categorization of components corresponding to the subsystems mentioned above.

Building information modeling (BIM) can allow simulation models to be derived consistently from a shared representation of the building (Hitchcock & Wong 2011). In particular, the translation of building geometry from BIM data into a form usable for BPS has been formalized with the concept of space level boundaries (Bazjanac 2010). Algorithms have been proposed to deal with automated partitioning of first level space boundaries to obtain second level space boundaries (Rose and Bazjanac 2015). However, current BIM formats do not enable the same kind of data translation for HVAC models as for building geometry.

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 (Pinheiro et al. 2016). Despite successive extensions of their data model, the Industry Foundation Classes (IFC) still cannot satisfy data requirements for BPS (Liu et al. 2013, Wimmer et al. 2014).

BIM-to-BPS approaches for HVAC modeling have thus resorted to an intermediate format representing a specific extension of IFC, such as SimModel (O'Donnell et al., 2011), in order to be able to store more of the data relevant for BPS. Such an intermediate format can be used in a third-party tool bridging the gap between BIM and BPS, such as the Simergy interface for EnergyPlus (Basarkar et al., 2012). In addition to custom modifications, such tools offer ways to enhance productivity such as grouping and autosizing functions.

### System sizing

Current BPS tools such as EnergyPlus (U.S. Department of Energy 2016) or OpenStudio (Guglielmetti et al. 2011) give access to autosizing features for different components. Sizing begins with an ideal load simulation run for a sizing period, resulting in the determination of zone design loads, which can be followed by the successive sizing of delivery and generation components.

One limitation of sizing in EnergyPlus is that pump components may be autosized with regard to their maximum flow rate, but not to their pressure head, which also determines pump power. Indeed, pump head calculation would require pressure drops in the distribution subsystem to be estimated, and this subsystem cannot be modeled explicitly using autosizing.

### Automated distribution layout

A central issue when creating models of distribution subsystems is to determine their layout, and in particular to route pipes or ducts connecting other components.

Brahme et al. (2001) proposed to use a design agent operating on a nodal representation of a building to generate HVAC specific views. This design agent uses heuristic rules based on common practice in air-based systems, and a hierarchy of distribution segments, including five levels from a “vertical branch” to “terminal branches”. With the assumption of a unique vertical branch and the use of a two-dimensional grid for each floor, these rules may not be applicable to arbitrary building shapes and system types.

Medjdoub et al. (2009) combined case-based reasoning and constraint programming for layout planning in the case of fan coil systems. The focus was not on simulation but on interactive support for CAD.

The problem of finding distribution layouts for HVAC systems is similar to design problems in other domains, such as the design of very-large-scale integrated (VLSI) systems, where routing between thousands of components needs to be determined (Held et al. 2011).

## Approach

### Objectives

Following the review of literature, distribution subsystems still seem to be a weak link in existing procedures for automated creation and sizing of HVAC models for simulation. This paper develops a method for creating models of distribution subsystems for use in integrated building and HVAC simulation. The models created in this way are expected to facilitate more accurate HVAC simulation, by allowing component-based models to be created with minimal additional input effort for the user. The intended use would be simulation during the concept design stage as defined in the RIBA plan of work (Sinclair 2013), so as to evaluate outline proposals for HVAC systems made during this stage and help prepare updated proposals for the next stage.

Simulation is to be carried out using an existing building performance simulation tool. Target tools for the implementation of the method are EnergyPlus (U.S. Department of Energy 2016) and TRNSYS (TRNSYS 2010). While TRNSYS is a prime example of component-based modeling, the loop-based HVAC model structure required by EnergyPlus makes it a hybrid of component-based and system-based modeling (Fisher et al. 1999).

The method fits in a typical workflow for the creation of, respectively, delivery, distribution and generation subsystems (Figure 1). Prior steps of the envisaged workflow include the determination of a zoned building model as required for thermal simulation, the calculation of design loads, and the determination and sizing of delivery components.

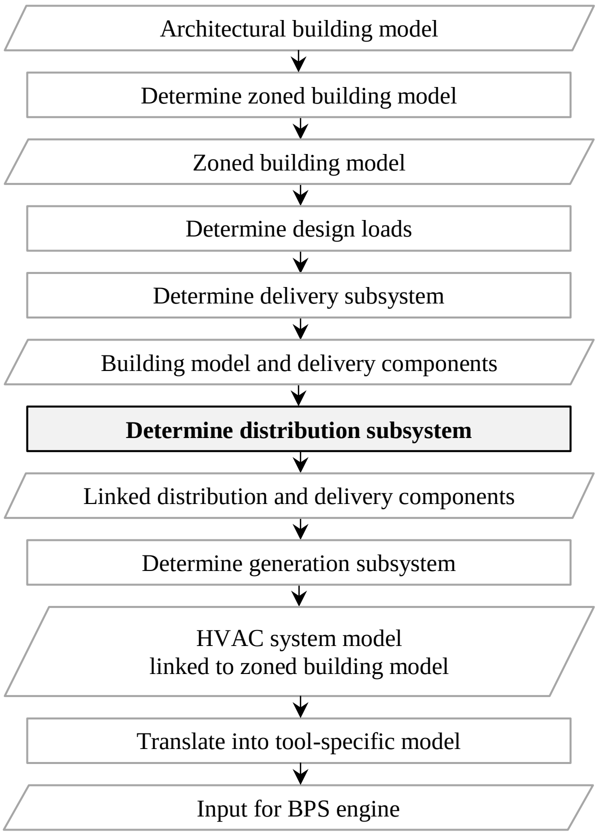


*Figure 1: Inclusion of the presented method in a workflow for detailed HVAC system simulation.*

In subsequent steps, the HVAC system model is completed with the addition of a generation subsystem. A control scheme is defined. The complete model is finally translated into a tool-specific simulation model.

## Scope

The method is applicable to most central HVAC systems, with either air or water as a heat carrier, and for cooling as well as heating. Its feasibility is illustrated and tested with hydronic heating systems. The modelled systems should have distinct supply and return parts. This restriction excludes one-pipe systems, but such systems are hardly installed any more (Recknagel et al. 2007). The method applies to the secondary side of HVAC systems, as opposed to the generation side.

In accordance with the target tools, the objective is to create component-based HVAC system models. We expect the level of detail of these models to be relevant for the concept design stage. It would be higher than the one accessible with ideal loads or system-based HVAC simulation, but lower than the one achievable with equation-based modeling. In particular, we assume system control not to be modeled so explicitly as to represent sensors or communication devices. As a consequence, the main components of distribution subsystems are distribution segments (pipes or ducts), valves where more than two segments meet, and flow moving devices (pumps or fans). Flow rates are determined by the action of valves and flow moving devices. It is assumed that no dynamic pressure simulation will be carried out.

## Input model

The input for the described method is a model of a building and associated delivery components. The input building model is a zoned building model populated with the data necessary for ideal load simulation, including building constructions and internal loads. Figure 2 illustrates an input building model composed of 8 zones with four different functions. Building geometry includes second level space boundaries under the form of polygons without holes.

Delivery components sized accordingly are also assumed to be part of the input, as illustrated in Figure 3. Each delivery component is situated in and serves exactly one building zone. It represents a link between the zone and the HVAC system. Three-dimensional positions of delivery components and their inlet and outlet ports are assumed to be known.

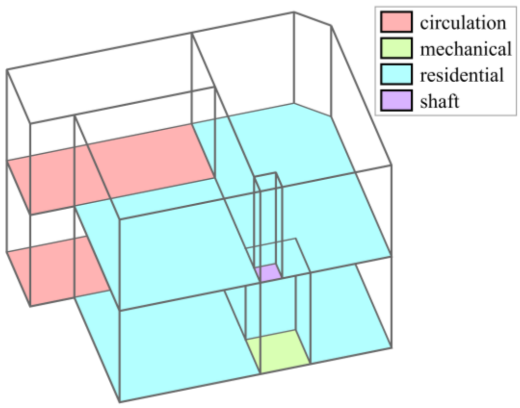


*Figure 2: Zone uses for simple example input model.*

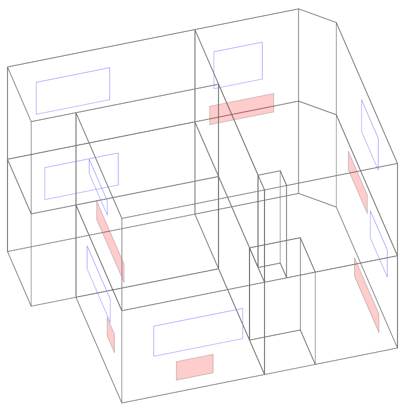

*Figure 3: Delivery components (radiators) in example input model.*

Delivery components are arranged into groups of components, where components of each group share the same fluid and design inlet temperature. This grouping is related to the function and type of delivery components, and independent of building zones. A zone may be served by delivery components belonging to different groups, for instance for heating and cooling. In the example of Figure 3, all delivery components are of the same type and belong to the same group. Also part of the input data for the method are parameters related to network generation.

### Output model

The output of the described method consists of the input model enriched with sized distribution components, forming a network of components with inlet and outlet relations. Each distribution segment component is attributed to one building zone, for heat losses to be accounted for during simulation.

## Method

### Overview

In response to the above requirements, we present a graph-based method for automated generation of HVAC distribution subsystem models. Starting from the input model, networks of potential distribution components linking groups of delivery components to inlet and outlet are determined. Tree subgraphs of these networks are computed according to desired properties of distribution structures. Corresponding distribution components are then instantiated and sized. Finally, these components are linked to generation and delivery system components. Granularity and realism of a layout are controlled by parameters.

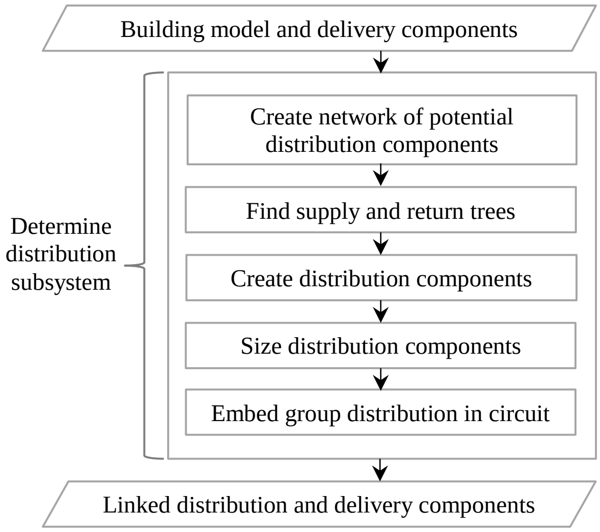


*Figure 4: Main steps of the presented method.*

The method may be applied to a single group of delivery components spanning the whole building, as in the presented example, or successively to several groups serving respective parts of the building, for instance floors.

### Create network of potential distribution components

We introduce a network of potential distribution components (NPDC), an undirected edge-weighted graph in which the supply (respectively return) tree is found, as described in the next section. For each distribution group, separate instances of NPDC are defined for supply and (if applicable) return. In many cases of hydronic systems, these two instances are similar and variations mainly due to distances between inlet and outlet ports of delivery components. For air-based systems, there may be an NPDC for return air independent from the supply one, or no return subsystem at all.

The nodes in an NPDC are an inlet and an outlet node (fixed in advance), delivery nodes corresponding to connection ports of delivery components, and intermediate nodes. There is a trade-off between the number of intermediate nodes and realism of a layout. The role of intermediate nodes is to make the NPDC connected and, along with a given selection of edges, to obtain a realistic layout. A high number of intermediate nodes may make the NPDC more complex and be a drawback for computation. Two types of intermediate nodes are considered: zone centroid and space boundary vertex nodes. For convex zones, intermediate nodes corresponding to zone centroids may be used, as illustrated in Figure 5. They are useful for non-conditioned zones, such as shaft zones, to ensure a possible path between delivery components in conditioned zones. Choosing geometric vertices of zone boundary polygons as intermediate nodes, as illustrated in Figure 6, allows more realistic layouts to be obtained, that do not penetrate occupied spaces. In the case of walls without thickness, as in the space representation used in the presented example and case study, and as opposed to a more detailed IFC model, these intermediate nodes may be offset towards the zone interior to account for the thickness of building elements.

The edges in an NPDC correspond to potential distribution segments (pipe or duct sections). Edges are only created between pairs of nodes belonging to the same zone or two adjacent zones. Edges only connect pairs of intermediate nodes corresponding to space boundary vertices if they are part of the same space boundary, or belong to corresponding space boundaries. In the latter case, the (short) edge represents an opening between two zones through some building element, and can be weighted accordingly. This way, the distribution subsystem is bound to run along space boundaries.

Generally, the weighting of edges should represent the cost of selecting a given distribution segment, and broadly correlates with the geometric distance between nodes. Options to vary weights include choosing a base distance (Euclidean or Manhattan), coordinate weighting (particularly for the z-coordinate) and location-specific weighting (for instance for the lowest floor or shaft zones).

We assume the NPDC to be connected, which should be the case at least if the zones of the considered building are connected and intermediate nodes are used.

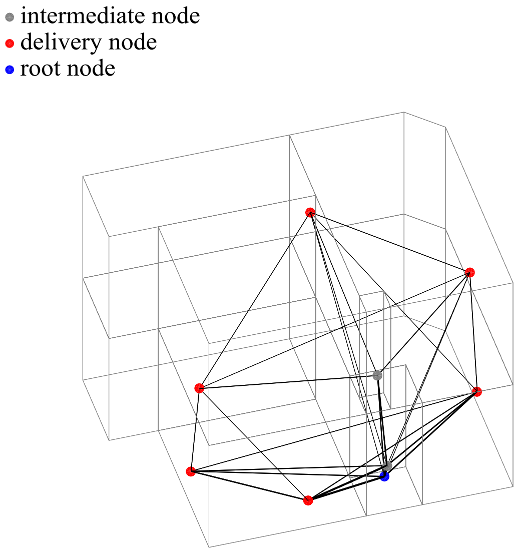


*Figure 5: NPDC for supply with technical zone centroids as intermediate nodes: 9 nodes, 52 edges.*

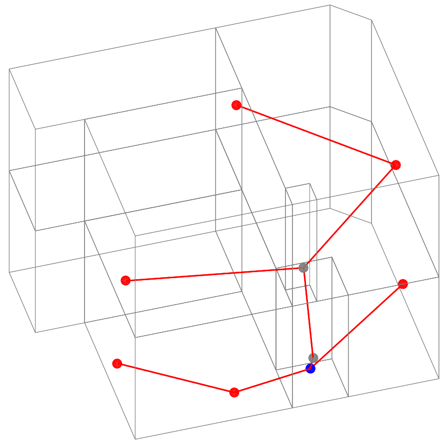

*Figure 7: Supply tree corresponding to minimal spanning tree on NPDS in figure 5: 9 nodes, 8 edges.*

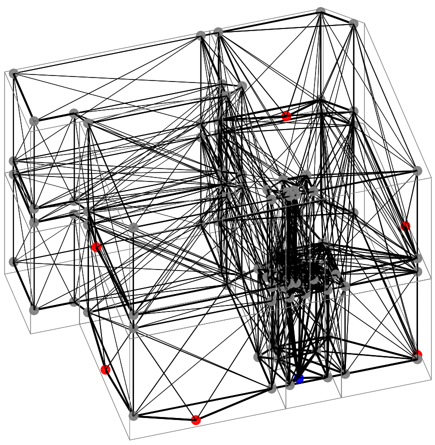

*Figure 6: NPDC with space boundary vertices as intermediate nodes: 101 nodes, 1510 edges.*

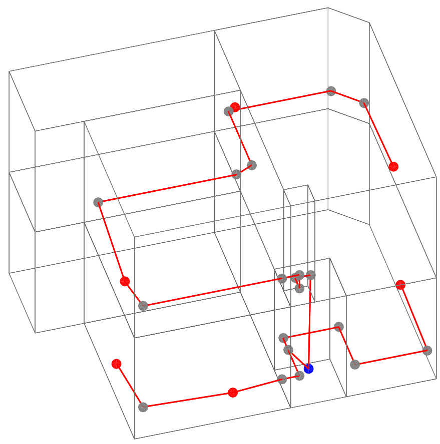

*Figure 8: Supply tree corresponding to minimal spanning tree on NPDS in figure 6: 25 nodes, 24 edges.*

**Find supply and return trees**

The creation of the NPDC is followed by the determination of supply (respectively return) trees. These are acyclic directed subgraphs of the NPDC having the distribution group inlet (respectively outlet) as root and some delivery nodes as leaves. We consider two main problem definitions allowing such a tree to be computed.

The shortest path problem consists in finding the shortest (in terms of the NPDC weighting) path from the inlet to each delivery vertex.

The minimum spanning tree problem consists in finding a subgraph of the NPDC spanning all nodes with a minimum sum of edge weights.

Algorithms exist to solve both the shortest path problem and the minimum spanning tree problem in polynomial time with regard to the number of nodes (Dijkstra 1959, Graham & Hell 1985).

Supply trees obtained from the respective NPDCs illustrated in Figure 5 and Figure 6 are shown in Figure 7 and Figure 8.

**Create distribution components**

From the supply and return trees, the actual distribution components - distribution segments and valves - can be instantiated and linked with each other and with the already defined delivery components, forming a group of distribution and delivery components (GDDC). This is done following a set of rules, which can 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.

Supply (respectively return) tree nodes are transformed into distribution components with a point-like geometric representation. If the number of child nodes and associated delivery components is 2 or more, the node is transformed into a valve component. Otherwise, it corresponds to a turn. Turn components may be used for pressure drop calculations, but are unnecessary for the targeted simulation environments.

For delivery nodes, a connection pipe component is created and added between the valve or turn component and the actual delivery component.

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.

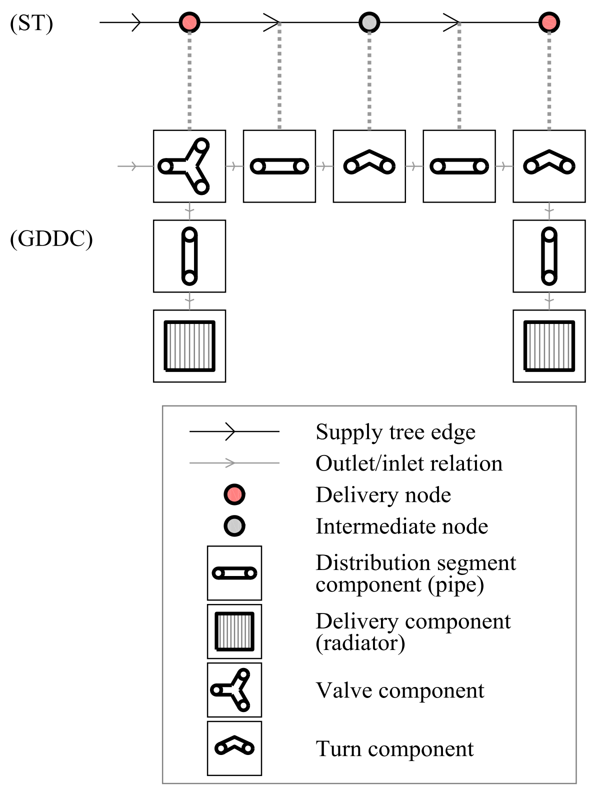


*Figure 9: Example of graph transformation at distribution component creation. From supply tree (ST), part of NPDC, to group of distribution and delivery components (GDDC).*

These rules result in the instantiation of components and the specification of their inlet-outlet relationships.

**Size distribution components**

The next step is the sizing of these components, particularly of distribution segments. First, maximum flow rates in each component are determined. In the simple case of simultaneous maximum loads, the maximum flow rate through a supply (respectively return) component is equal to the sum of maximum flow rates through the delivery components downstream (respectively upstream) of it. Determining this can be done recursively for all components. This information is also useful for the later addition of controls, where flow rates at diverting valves are to be split according to heat demands in downstream delivery components.

**Embed in circuits**

The GDDCs created in the previous step do not include flow moving devices, as these may depend on how flow rates and/or temperatures are controlled to provide or remove adequate amounts of heat. In this step, GDDCs are embedded in circuits, which we define as the specific arrangements of valves, flow moving devices and bypass segments used to achieve such control. We focus on some basic forms of hydraulic circuits frequently encountered in practice (VDI 2014) and illustrated in Figure 10.

A throttling circuit represents the simplest case, where the inlet (respectively outlet) of the GDDC can be directly connected to the outlet (respectively inlet) of the generation subsystem and flow varies simultaneously in the whole system. In a diverting circuit, flow coming from the generation outlet can be partially diverted into a bypass, leading to variable flow in the GDDC and constant flow on the generation side. In a mixing circuit, flow coming from the GDDC outlet can be mixed with flow coming from the generation outlet, leading to constant flow but variable temperatures in the GDDC, and variable flow on the generation side. The choice of a circuit type depends on both generation and delivery subsystems. For instance, a mixing circuit is usually preferred with floor heating if required delivery temperatures are lower than those supplied by the generation subsystem.

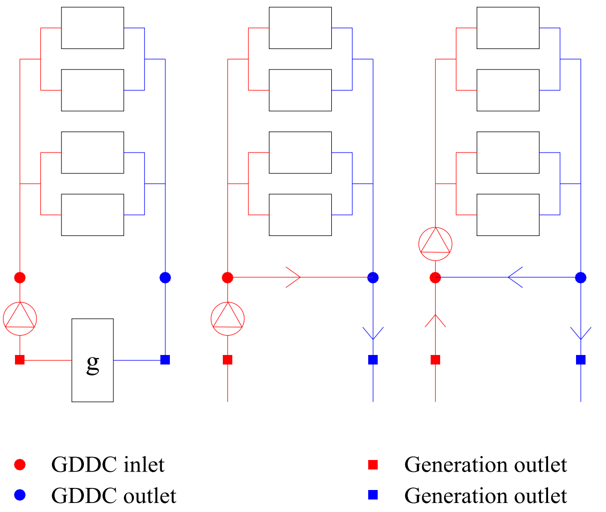


*Figure 10: Insertion of GDDC in hydraulic circuit. GDDC in throttling circuit (left) with generation component (g), diverting circuit (center) and mixing circuit (right).*

Flow moving components are sized based on maximum flow rates and estimated maximum pressure drops. Maximum pressure gradients are calculated for each distribution segment, based on diameter, expected inner material and maximum flow rate. At this stage, a coefficient can be used to account for all punctual flow resistances corresponding to direction changes, branchings and valves.

## Case study

### Overview

In this section, we apply the method 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. Cooling and mechanical ventilation are not available.

Plans of the heating system are available in 2d line drawings. This case study focuses on the six uppermost floors, which include offices and are served by the heating system. The zoned building model is generated automatically from an architectural building model by a space modeling system (Suter et al. 2014). The system merges spaces in the architectural building model into thermal zones based on their functions and orientations. The orientation of a space is determined by the relations of its openings to distinct external spaces.

The considered floors have similar plans, with a cellular office layout, a staircase at each extremity of the L-shape, and offices mainly distributed alongside a long corridor joining both staircases. Modeled zone functions are illustrated in Figure 11.

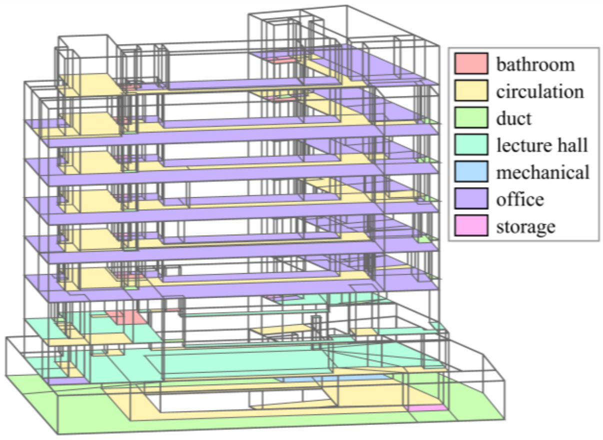


*Figure 11: Input for case study: zone functions.*

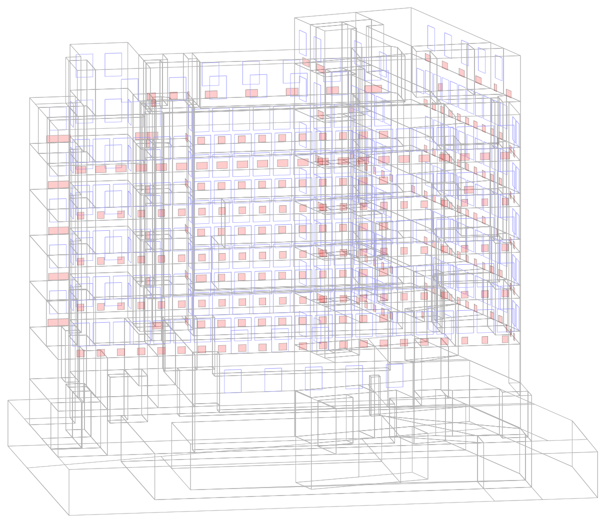

*Figure 12: Input for case study: zoned building model and delivery components.*

In order to avoid redrawing them from two-dimensional plans, we take delivery components to be the output of an automated heuristic method, positioning one radiator under each window. In addition, these radiators are sized to meet calculated design heat loads for each conditioned zone (ON 2003). The resulting radiator components are illustrated in Figure 12. In comparison, the real heating system, illustrated in Figure 13, does not feature a radiator for each window.

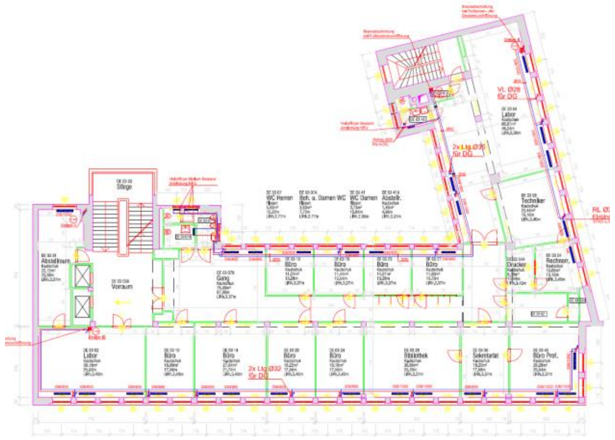

*Figure 13: Existing floor plan (third floor). Radiators in blue.*

The system being a hydraulic system, distribution segments are pipes and flow moving devices are pumps. The method is applied with three sets of parameters, listed in Table 1, varying the choice of intermediate nodes in the network of potential distribution components and the tree-finding algorithm.

*Table 1: Generation parameters*

| | A | B | C |
|---|---|---|---|
| Intermediate nodes | non-conditioned zone centroids | space boundary vertices | space boundary vertices |
| Tree finding algorithm | minimum spanning tree | minimum spanning tree | shortest path |

Simulations are carried out with EnergyPlus, using models obtained according to the assumptions of Table 2. Heat generation is ensured by a single boiler component.

*Table 2: Simulation models*

| Id | HVAC modeling approach | Pipe lengths |
|---|---|---|
| CB-existing | component-based | From existing system |
| CB-A | component-based | From results A |
| CB-B | component-based | From results B |
| CB-standard | component-based | Standard values |
| CB-0 | component-based | No pipes |
| Ideal | ideal loads | - |

## Results

The application of the method to the case study building with different generation parameters yields models differing in their number of elements, as summarized in Table 3, in the characteristics of the modelled system, and in their simulated behavior. Resulting distribution layouts are compared with each other and with the existing layout.

*Table 3: Numbers of network elements with generation parameters of Table 1*

| | A | B | C |
|---|---|---|---|
| NPDC nodes | 371 | 3477 | 3477 |
| NPDC edges | 12832 | 33873 | 33873 |
| Supply tree edges | 321 | 826 | 758 |
| Pipe components | 1210 | 2210 | 2082 |

As expected, the pipe layout obtained with parameters A (Figure 14) is less realistic than the one obtained with parameters B (Figure 15), in that it crosses the interior of zones.

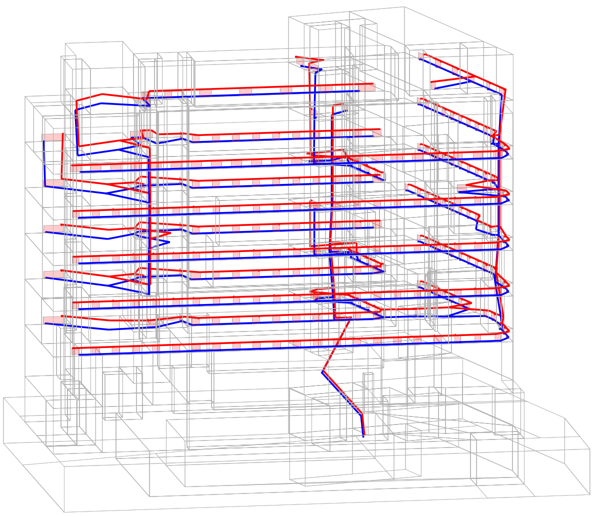

*Figure 14: Resulting pipe layout with parameter set A.*

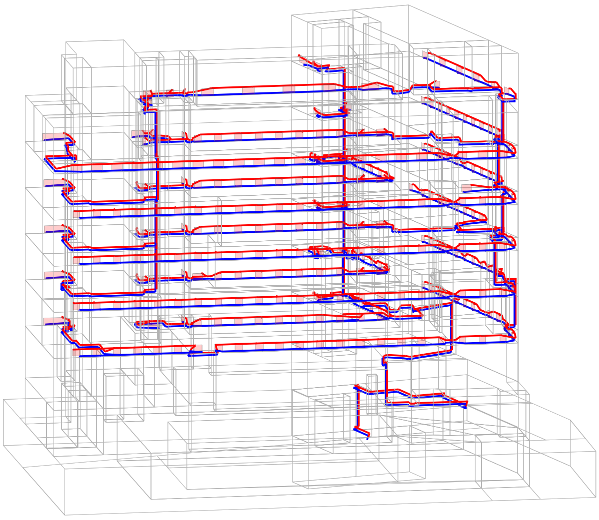

*Figure 15: Resulting pipe layout with parameter set B.*

Pipe lengths obtained with the presented method are compared with pipe lengths estimated from drawings of the existing heating system, and default values stated in a standard. The Austrian standard H5056 for calculation of heating system energy use (Austrian Standards Institute, 2011) provides reference pipe lengths as a function of building floor area. As appears from Figure 16, pipe lengths obtained with the three parameter sets vary significantly. Pipe lengths with parameter sets A and B are closer to those in the existing system than the default values from the standard, which tend to overestimations. Total pipe lengths using the shortest path algorithm (C) are even more overestimated, as taking the shortest path for each delivery component leads to a star-like structure with high total length.

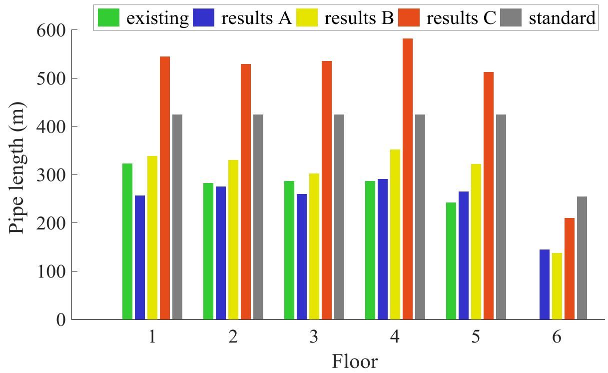


*Figure 16: Sums of pipe lengths (supply plus return) on considered floors according to, respectively, existing system documentation, results of the method with three different sets of parameters, and default values of standard H5056.*

In Table 4, other variables are compared to data from the existing system. The diameter of the main pipe and the maximum flow rate through it do not vary with the distribution layout, as they only depend on total design heat load and system temperatures. The shortest path algorithm (C) results in a shorter critical path, and consequently lower pressure drops and pump power.

*Table 4: System characteristics*

| | Existing | Results | | | Standard |
|---|---|---|---|---|---|
| | | A | B | C | |
| Pipe length floors 1-5 (km) | 1.42 | 1.34 | 1.64 | 2.70 | 2.12 |
| Main max flow rate ($m^3/h$) | 21.4 | 16.9 | 16.9 | 16.9 | - |
| Main distribution pipe DN | 100 | 81 | 81 | 81 | - |
| Pump maximal power (W) | 800 | 513 | 606 | 421 | 592 |

The high maximal power of the installed pump in comparison not only to our results but also to the standard value might indicate some oversizing of the existing system.

Figure 17 shows the influence of distribution system model on simulated heating energy. Distribution losses are calculated as heat supplied by the boiler minus delivered energy (heat delivered by the radiators). They are for a good part – but not entirely – recovered for heating. As a consequence, delivered energy decreases with increasing pipe lengths, while total energy use increases.

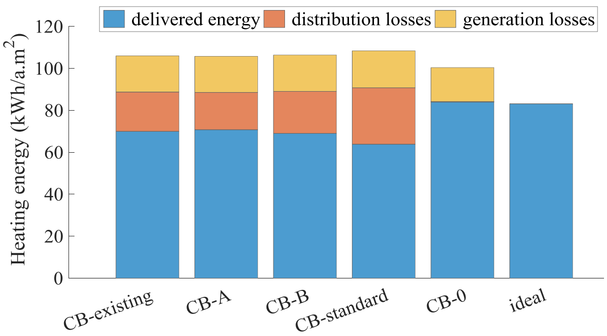


*Figure 17: Annual heating energy results for the six models of Table 2.*

### Discussion

The results show that the method can be applied to an existing medium-sized building equipped with a water-based heating system.

A difference with other graph-based methods is the lack of hierarchy between vertices when determining the layout. Still, the method results in structures typical of heating systems, including riser pipes and connection pipes. Parameters such as z-weighting may steer the results towards various typologies.

The minimum spanning tree as a tree-finding algorithm seems to lead to more realistic layouts than the shortest path algorithm, with which the total lengths are excessive.

Choices like the selection of intermediate vertices have a decisive impact on the resulting layout, and on the computing effort. Space boundary corners as intermediate vertices may allow geometrically satisfactory pipe routes following space boundaries to be found, but they significantly increase graph size and computing time. With energy performance simulation as aim, the user may want to sacrifice geometric correctness for a quicker assessment of pipe lengths and diameters, especially if space boundaries are not precisely defined, as might be the case in early design stages.

The presented case study dealt with a water-based heating system with a single GDDC, typical of European systems. Air-based systems, which are predominant in North America, would represent a very different case. For one thing, they may return air through ductwork or architectural plenums, or be limited to supply, in which case the return part of the method should be omitted. Another key to applying the method to air-based systems is the possibility of successively determining several GDDCs serving different zones. For instance, there would be a separate GDDC for the air distribution from each air handling unit. Also, the sizing procedure would be more challenging for systems performing multiple functions, for instance heating, ventilation and cooling, and more generally for systems where maximum loads for different components are not simultaneous.

## Conclusion

A new method to generate models of potential HVAC distribution networks within buildings was defined, which could allow these subsystems to be modeled more explicitly in integrated building and HVAC simulation than it is usually done, with limited additional expense.

The method can be applied to any zoned building model that could otherwise be used for ideal load simulation, provided that the location and size of delivery components are known.

Applying the method to air-based systems, which have a different structure and for which losses associated to distribution subsystems are often higher than in hydraulic systems, should be of interest.

In future work, the impact of different levels of modeling detail in distribution subsystems and other subsystems, as well as in thermal zoning, may be evaluated and compared.

In the future, BIM data including HVAC systems may also be used to compare results obtained with this method and complement them.

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