Decision tree for early-stage design of hybridGEOTABS office buildings

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Abstract. Hybrid GEOthermal heat pump system coupled to Thermally Activated Building Systems (hybridGEOTABS) utilises the high thermal capacity of TABS to smooth out the building thermal loads and downsize the production units. Moreover, hybridGEOTABS has achieved remarkable carbon emissions saving. However, the optimal design of hybridGEOTABS is not achieved with current design methodologies. This article provides a decision tree for early-stage design of hybridGEOTABS office typology. To derive the decision tree, a design methodology which has been previously developed and verified was applied on nearly 40,000 office building case studies with variety of parameters such as climate, insulation level, and internal gains. The methodology exploits multi-zone dynamic simulation of building energy performance and optimal control of TABS for peak-shaving to offer an optimal sizing of the HVAC components. To analyse the results of the numerous simulations and to drive the decision tree, supervised machine learning, specifically a classification technique, was deployed. The application of the decision tree is exemplified in this article using three case studies. The decision tree also enables architects to practice the influence of different parameters on the sizing and performance of the HVAC system. Thus, designers may use it to optimise the building physical design to increase the possible share of geothermal system as a sustainable core for providing thermal comfort in buildings.

Keywords. hybridGEOTABS, ground source heat pump, TABS, optimal design, early-stage design, decision tree, energy performance optimization
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1. Introduction

GEOTABS is a combination of a geothermal heat pump and thermally activated building systems (TABS). TABS is a radiant heating and cooling emission system in which the heating/cooling pipes are embedded in the mass of the building elements (for example, concrete floors), activating them as thermal storage. This thermal storage enables the decoupling of demand and supply moments on an intraday time window, as well as the shave of demand peaks, both of which are advantageous for providing flexibility. TABS can provide very low-temperature heating (as low as 22-30°C) and high-temperature cooling (as high as 15-23°C) by converting entire floor or ceiling surfaces into heavy-weight emission systems. These temperatures are similar to those found in the ground's shallow layers, allowing geothermal heat pumps to operate at high efficiency. The geothermal source acts as a seasonal storage facility, allowing heat to be extracted during the heating season and injected again during the summer. The hybridGEOTABS concept deploys GEOTABS core as a sustainable heating, cooling, and air conditioning (HVAC) system supplemented with secondary heating and/or cooling emission systems to maintain thermal comfort when TABS is not the most efficient emission system. When the building thermal loads fluctuate significantly, TABS may have difficulty providing efficient thermal comfort. At the production level, complementary energy sources can help to maintain the thermal balance of the geothermal source, increase financial flexibility, and improve the system's environmental performance. The key components of hybridGEOTABS are ground source heat pump (GSHP), passive cooling heat exchanger (PCHX), borefield, TABS, and secondary systems in heating and cooling modes depicted in Fig. 1. A secondary emission system such as fan coil unit (FCU) is also considered to assist TABS. hybridGEOTABS is a flexible and future-proof HVAC concept that provides comfort to buildings by utilising hybrid renewable energy systems and activating the building's thermal storage capacity [1].

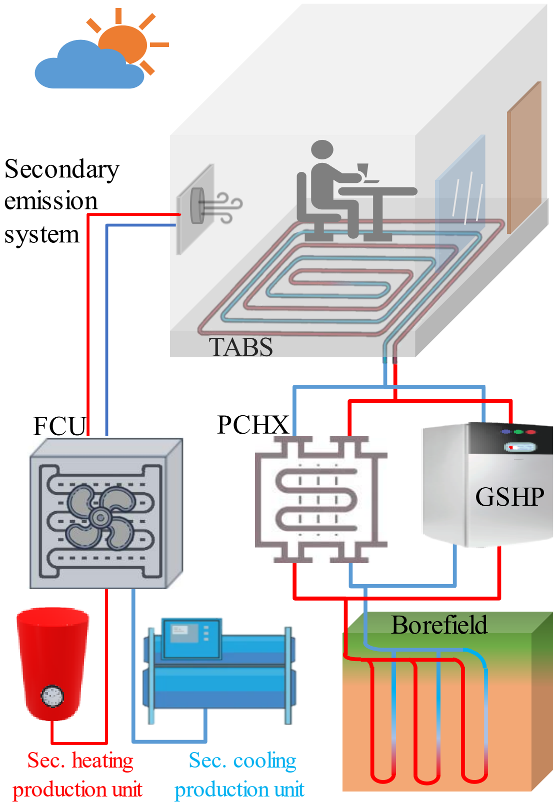

Fig. 1 key components of hybridGEOTABS [2]

The design of a hybrid and storage-integrated system such as hybridGEOTABS, consequences challenges during the HVAC-design. The main questions are what shares of the heating and cooling demands can be optimally covered by GEOTABS and secondary system respectively, and what are the resulting sizes of the key HVAC-components (the heat pump, geothermal borefield and secondary system). As a result of their thermal inertia, and if optimally controlled, the heat inputs to the TABS can be smoothed out over time, resulting in peak shaving and reduced size of the heat pump. On the other hand, as it takes some time to charge and discharge this thermal storage, a sudden change from heating to cooling mode of the system would lead to energy losses. Therefore in such situations, it is often more desirable to engage a secondary fast-reacting emission system (e.g. fan coil units, air handling systems, radiators…). Yet, another element to consider is the effect of the optimal control on the component sizing and load shares. An optimal control strategy optimises the system performance, and has knowledge of the building and system properties and behaviour (by using a model) and of future disturbances (by using predictions such as weather predictions).

The aforementioned dynamic aspects influence the sizing and load share of the hybridGEOTABS system. As a result, the critical conditions for the sizing of the system(s), typically appearing at the warmest and coldest days of the year, are no longer valid for hybridGEOTABS buildings and will lead to an oversizing of the system and increased investment costs. Furthermore, optimal load split between the two systems cannot be answered by only observing the critical moments of the year. Therefore, classical steady-state heat loss calculations are insufficient for sizing hybridGEOTABS.

Instead, the state-of-the-art design of GEOTABS buildings today relies on detailed, case-by-case dynamic building energy simulations (BES), performed by experts. Moreover, detailed design procedures are available when the building design has been finalised and when sufficient detailed information of the building is available. As a result, feedback from the HVAC designer to the architect might require an architectural correction with significant financial impacts on the building's design.

Alternatively, an early-stage design methodology rely on limited number of inputs from the designer and deliver sufficient data to assess the optimal design of the building and the HVAC and, if needed, alter the design accordingly. However, simplified design methodologies for innovative HVACs are not available. Hence, designers inevitably deploy the methodologies developed for conventional HVACs which results in inaccurate estimation of the design indicators, such as energy use, key components nominal power, costs, and environmental impacts.

This paper briefly recapitulates a simulation-based design methodology. The methodology incorporates the dynamic behaviour of the building and the HVAC as an indispensable part of hybridGEOTABS optimal design. The methodology offers optimal energy use and sizing through efficient use of high thermal capacity of TABS. Accordingly, the key components are sized. The methodology was applied on over 40,000 of office building case studies to provide pre-engineering data for designers. The data were analysed using a supervised machine learning technique. The outcomes are presented in this paper as an early-stage design decision tree.

In section 2.1, it is explained how the simulations have been run for thousands of case studies to provide pre-engineering results. The systematic approach for analysing the outcomes of thousands of simulations is elaborated in section 2.2. The results section starts with excerpt of intermediate outcomes of the simulations (section 3.1) to give insight how the final decision tree was developed. Section 3.2 documents the final early-stage design decision tree. Three case studies are introduced in 4.1 to exemplify the application of the decision tree section 4.2.

2. Methodology:

2.1 Simulation-based design methodology

The first step in sizing the components of an HVAC system is estimating the building's heating and cooling (peak) loads. In general, the load can be calculated statically using existing standards or dynamically using BES tools. Varity of studies (such as [3]) have revealed a significant impact of dynamic behaviour of the building, HVAC-system, and control of hybridGEOTABS buildings on the design. Thus, the simplified early-stage design procedure, which is a decision tree in this article, must be built upon the results that account for the dynamic behaviour of the building and HVAC.

Mahmoud et al. [4, 5] provided a BES database of time series of dynamic building simulation result for one year. They conducted a building stock analysis and organised building physical and geometrical parameters to achieve thousands of different office building designs in three climates. As a result, their database is enriched with a remarkable amount of building design possibilities. They characterised building geometrical design with 176 different archetypes using building geometrical parameters such as total surface area, number of floors, layout, height, width, and length. Moreover, they defined variety of insulation, internal gains, and window to wall ratio. They developed a python code to call the simulation program (Modelica) to automatically model a building using high level building parameters from the database. Then, the Modelica model runs hourly simulations for each case study of their database. Their database was chosen as the starting point to develop pre-engineering design decision trees.

Sharifi et al. [7] developed an algorithm called optimal load split algorithm (OLSA) to optimally split the building thermal load between the TABS and the secondary system on an hourly level. Their algorithm contains an optimisation core inside and a surrogate model of the TABS and building [6] to simulate the dynamic behaviour of them with low mathematical complexity. They achieved to keep the calculation time of their algorithm in the order of a minute so that it can be applied on thousands of case studies from the aforementioned database. OLSA guaranties thermal comfort and minimum energy use. It also utilises the load-shifting ability of TABS to shave the building thermal loads peaks. Consequently, OLSA facilitates optimal design of hybridGEOTABS, while it is not a sizing tool. Thus, the outcomes of OLSA must be post-processed to achieve the final sizing of hybridGEOTABS components.

The post processing methodology was developed and verified as elaborated in [8]. It removes the high thermal peaks of the heat pump and the borefield by smoothing out the time series of the thermal loads. The smoothing is allowed thanks to the high thermal inertia of TABS. Accordingly, central moving average of the heat pump power time series with a 24 hours interval was applied. This avoids oversizing of the borefield and the heat pump. The borefield length was estimated according to standard VDI [9]. Note that if the annual borefield thermal loads in heating and cooling modes are not balanced, the secondary system is used to cover the excessive load that will cause the imbalance. Sharifi et al. [3] showed that the financial viability of hybridGEOTABS is threatened when the imbalance part of the building thermal load is supplied with the borefield. This is due to the fact that the thermal imbalance between heating and cooling can adversely affect the system performance. The imbalance can decrease or increase the borefield temperature, also called depletion of the borefield. The imbalance can be solved in variety of ways; for instance, increasing the borefield length, regeneration of the borefield, and using a secondary system to cover the imbalance part of the demand. However, these options must be evaluated in the detailed design stage. Finally, the CO_2 emissions were also estimated using the system efficiencies and conversion factors reported in the Appendix.

2.2 *Meta-analysis methodology*

The entire simulation-based design methodology was verified as elaborated in [10]. The methodology was later translated to an automated python code. The code reads the data from the BES database and automatically calls the OLSA and thus optimally splits the load between the primary system (GEOTABS) and the secondary system. Then, it calculates the design indicators such as energy use, components maximum load, and CO_2 emissions with the explained post-processing steps. The code was used to design hybridGEOTABS for all the case studies from the BES database. This provided a rich database that relates the predictor variables (design variables such as climate, insulation level, glazing area) to the predicted parameters (design indicators such as energy use, components sizing, and CO_2). The whole dataset can be statistically divided to subgroups according to their similarities. To find the similarities in subgroups of the dataset, recursive partitioning technique was used. Recursive partitioning is a classification technique and a subsection of supervised machine learning technique [11]. Accordingly, a predictor variable is chosen and the data are split to two or more subgroups

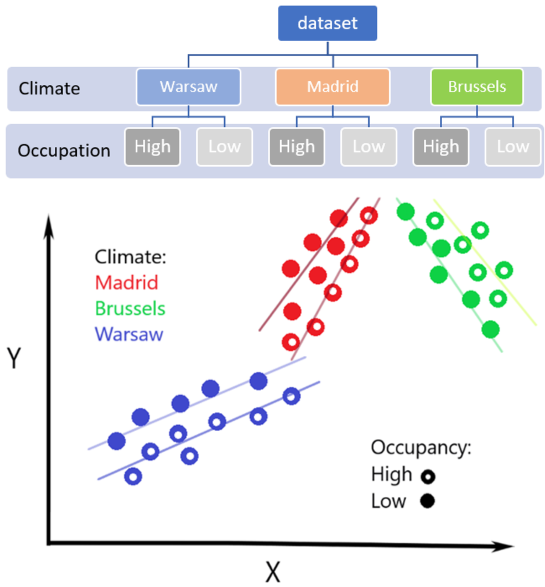

Fig. 2 Partitioning approach leading to a decision tree [8]

(branches) according to the values of the predictor. A line is regressed to the data to relate the predicted variables and predictor parameter. For instance, if the predictor is "climate", the dataset is divided to subgroups of Warsaw, Madrid, and Brussels (Fig. 2, on the top) as the three climates that were used in the simulations. Statistical tests are performed between branches and if the null-hypothesis is rejected, the subgroups are significantly different and the predictors is considered a root for the tree. Next, another predictor variable is chosen and partitioning into subgroups is repeated. The final outcome will be a decision tree whose final subgroups are the fitted regression lines for subgroups (Fig. 2).

To systematically apply the methodology on the dataset, an R code was developed and the function "*ctree*" from the package "*partykit*" was used [12]. The function *ctree* builds the tree by applying statistical tests on the dataset to find the optimum meaningful subsets of the data. It finds the optimum split based on a greedy algorithm looking for the variable that meets the growing criterion better than the other variables in each step. The function has different stop criterion. Naturally, a bigger tree always brings more accuracy. However, the interpretation of a bigger tree is not easy and the amount of branches can become prohibitive. Considering the main target of developing the decision tree, we aimed at a rather small and easily interpretable decision tree. Therefore, we manually controlled the decision tree development whereas the size of tree was chosen as the stop criterion to prevent having a vast decision tree.

3. Results

3.1 Intermediate results

Fig. 3 shows violin plots that conducts a relation between heat pump specific power (vertical axis) and the distribution of the cases studies according to their climate, insulation level, and occupancy rate. The violin graph depicts the difference between heat pump sizing that is caused by differences in building parameters. For instance, the design for high and low dense occupancy is different despite the fact that the box-plot (inside the violins shows) a symmetrical distribution in one group. This means that the right side of the violins might be significantly different with the left side. As another example, with high dense occupancy for medium insulated cases in Brussels, the graph shows two distinct groups. These high-level observations confirm the relationship between the specific heat pump size of the building design characteristics.

3.2 Early-stage design decision tree

Fig. 4 documents the final decision tree for the office typology. Note that in the decision tree, L"," M", and "H" respectively stand for "Low", "Medium" and "High" for different parameters. The parameter's value associated to "Low", "Medium", and "High" for is documented in Annex . The decision tree requires the designer to find its building using the climate, insulation level, occupancy rate, window-to-wall ratio, and shading system and accordingly guides the user towards the design indicators which are listed in Table 4 in Appendix.

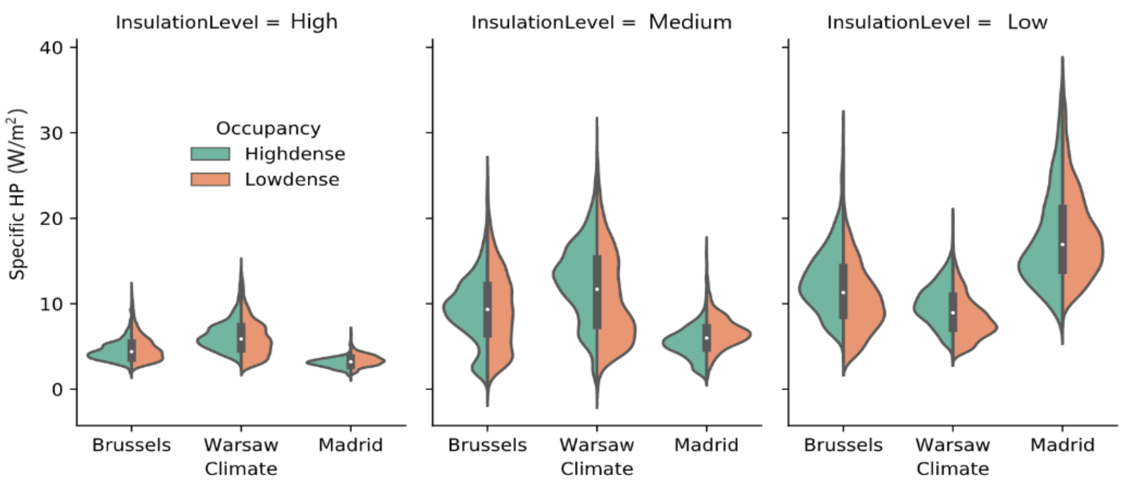

Fig. 3 Distribution of the specific maximum HP power in office cases related to different design parameters

Fig. 4 hybridGEOTABS early-stage design decision tree for office buildings

4. Application of the decision trees

4.1 *Case studies*

Three case studies are introduced to exemplify the use of the decision tree. The three cases are located in **Brussels** with similar geometrical parameters as listed in Table 2. To practice the influence of different physical parameters, a combination of the parameters were chosen to form three random design A, B, and C as listed in Table 3.

Table 2 *Geometrical properties of the three case studies*

Geometrical variables	***Value***
Conditioned area (m²)	*2390*
Volume (m³)	*8532*
Heat loss surface area (m²)	*4325*
Height (m)	*6.4*
Number of floors	*2*
Window to wall ratio (%)	*40*
Compactness	*1.9*

Table 3 three groups of building design A, B, and C used as case studies

Case	**Insulation**	**Occupancy**	**Shading**	**Orientation**
A	Medium	Low-dense	yes	North
B	High	High-dense	yes	North
C	Low	High-dense	No	West

4.2 *hybridGEOTABS design using decision trees*

Using the proposed decision tree, hybridGEOTABS was designed for the three case studies. As the decision tree mostly provides the design indicator values per unit of conditioned floor area, the estimated values from the tree were multiplied by the conditioned area (2390 m²) where applied and the absolute values were derived. The estimated design indicators for the three case studies are listed in Table 1. The values are rough approximations used in the early-stage of the design procedure. We used the maximum value of the box in the box-plots (the 75% quartile of the distribution) for each indicator. The designer may decide to use the maximum value of the whiskers for a more conservative estimation. Moreover, it is possible to use more conservative scenarios for one indicator, e.g the secondary system in heating and a less conservative scenario for the (usually more expensive) primary system.

In comparison to the maximum steady-state thermal load of the building, as a traditional way of sizing HVAC components, a remarkable downsizing of the components is observed. The thermal balance of borefield (second indicator) shows that case *C* is definitely heating dominated and case *B* is cooling dominated. Case *A* seems the best design as the GEOTABS share is the highest and the CO_2 emission and saving is high.

Table 1 design indicators derived from the decision tree

Case study	***A***	***B***	***C***
Total heat demand (kWh/m2/y)	55	40	105
Share of heating form the total annual load (%)	60	10	85
GEOTABS share (%)	90	25	65
Heat pump power (kW)	31	12	35
Borefield length (m)	950	430	1195
Secondary system power in heating (kW)	24	18	71
Secondary system power in cooling (kW)	43	60	84

5. Discussion

The decision tree offers an easy-to-use tool for the designers to practice optimal design of hybridGEOTABS. The financial design indicators associated with the technical design indicators can be easily derived from the results. The tool offers all the means to estimate operational and investment costs of each design. This option was not elaborated in this article due to the limitation on the article length.

The borefield length was estimated using a simplified method that did not involve dynamic simulations. As a result, a conservative assumption was used to ensure thermal balance in the borefield and avoid long-term consequences. However, in imbalanced cases, this conservative assumption limited the share of GEOTABS. Hence the results should be interpreted as the hybridGEOTABS concept's minimum possible improvement in terms of sustainability. The designer can utilise the decision tree to possibly change the building design and increase the share of the renewable core of the HVAC concept. Thus, the share of GEOTABS can appear higher in the detailed design.

This work assumed conventional HVAC solutions such as a gas boiler and chiller to simplify and generalise the problem. To improve environmental performance even further, the designer is encouraged to use additional renewable sources such as solar panel and solar boilers in secondary systems and/or envisage an air source heat pump as the secondary system.

6. Conclusion

Combination of geothermal heat pumps with thermally activated building systems (GEOTABS) is applicable to every building if a secondary system is potentially assumed in the design procedure. Then the concept is called hybridGEOTABS. hybridGEOTABS design contains challenges that cannot be overcome with existing methodologies. The current methodologies are either based on steady-state calculation methodologies which are inaccurate, or case specific detailed design procedures which are inaccessible. This paper documented a decision tree for the use of early-stage design of hybridGEOTABS. The tree was derived from the database built upon results from dynamic simulations of 40,000 case studies. The aforementioned dynamic thermal loads were used for developing a fast and automated sizing methodology for hybridGEOTABS components. As a first important step, an optimal load splitting algorithm called OLSA, developed in-house was used to split the building thermal load between the primary and the secondary system. OLSA guarantees the thermal maintaining thermal comfort and takes into account the dynamic thermal behaviour of TABS. The main outcomes of the OLSA are time series of the primary and the secondary system power for one year. The time series are then used were used for sizing the key components of hybridGEOTABS and estimating the environmental performance for the case studies in the database. Meta-analysis of the data was carried out using classification technique.

The final outcome of the whole procedure is a decision tree providing the most crucial inputs for the designer to consider in the early-stage of design. While using the decision tree for design is very fast and easy, the results are close to the results coming from detailed and time consuming algorithms, and are thus an added value for the designer to assess the feasibility of hybridGEOTABS for their design. Moreover, architects can see the influence of different parameters on the sizing and performance of the system. Thus, they may use it to optimise the building physical design to increase the possible share of GEOTABS as a sustainable core for the building heating and cooling energy use. The application of the decision was exemplified with three case studies. It was shown how the decision tree guides the designer to compare the impact of the different building parameters on the design of the hybridGEOTABS.

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Appendix

This appendix documents four tables containing assumed efficiencies for the production systems, CO_2 conversion factors, primary energy factor, and building parameters used in the modelling.

Table 4 Description of the design indicators reported decision tree.

Design indicator	Description
Energy demand (kWh/m²/year)	sum of net heating and cooling demands of the building assuming an ideal heating and cooling system (22-24°C indoor temperature range)
GEOTABS share (%)	share of the heating and cooling demands covered by GEOTABS
Borefield thermal balance	relative frequency of heating dominated (red), balanced (green) or cooling dominated (blue) cases in that subgroup of the database
CO_2-emissions (kgCO2/m²/year)	estimated CO_2-emissions for heating and cooling the building
CO_2-savings (%)	savings in CO_2-emissions as compared to a non-GEOTABS scenario (100% of heating and cooling provided by a boiler and chiller)
HP-power (W/m²)	specific power of the heat pump per conditioned floor area
Borefield length (m/m²)	length of the geothermal borefield (m) per conditioned floor area (m²)
Sec Sys power in heating (W/m²)	specific power of the secondary heating system per conditioned floor area
Specific Q_{design} in heating (W/m²)	steady-stated heating demand of the building reported as a common indictor
Sec Sys power in cooling (W/m²)	specific power of the secondary cooling system per conditioned floor area
Specific Q_{design} in cooling (W/m²)	quasi steady-stated cooling demand of the building reported as a common indictor

Table 5 Primary energy and CO_2 emission conversion factors

	Primary energy factor Total (-)	CO_2 emissions factor (g/kWh)
Natural Gas	1.1 [13]	220 [13]
Electricity EU 2020	2.0 [14]	260 [14]

Table 6 Production efficiencies for the different systems

Type of production unit	*efficiencies*
SPF Heat pump heating (primary heat production)	6
SPF Heat pump cooling (Cold production)	5
Gas boiler (secondary heat production)	0.95
Secondary emission system	0.95
Electric chiller (Cold production) EER	3
Passive cooling (Cold production)	20

Table 7 Summary of the parameters used in the modelling and simulation

Parameter	Decision tree label		value
Window to wall ratio	High		20%
	Medium		40%
	Low		60%
Orientation (large facade)	S		South
	W		West
Shading System	YeSh		No-Shading
	NoSh		External screen is on at 150 (W/m^2)
Envelope performance	Low	Envelope U-value	0.5 (w/m^2.k)
		Window U-value	2.5(w/m^2.k)
		Glass g-value	0.6
		air-tightness n50	5.0 (h^{-1})
	Medium	Envelope U-value	0.27 (w/m^2.k)
		Window U-value	1.5 (w/m^2.k)
		Glass g-value	0.56
		air-tightness n50	2.0 (h^{-1})
	High	Envelope U-value	0.15 (w/m^2.k)
		Window U-value	0.8 (w/m^2.k)
		Glass g-value	0.4
		air-tightness n50	0.6 (h^{-1})
Building mass	Low		390 (kg/m^2)
	High		630 (kg/m^2)
Internal heat gains	Low	Density	1 Person/20m^2
		Occupancy	5.0 (W/m^2)
		Lighting	8.0 (W/m^2)
		Appliances	5.5 (W/m^2)
		Total	18.5 (W/m^2)
	High	Density	1Person/10m^2
		Occupancy	10.0 (W/m^2)
		Lighting	8.0 (W/m^2)
		Appliances	15.0 (W/m^2)
		Total	33.0 (W/m^2)
Ventilation flow rate	Constant		36 (m^3/h)

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