DEVELOPMENT OF AN ALGORITHM FOR THE AUTOMATIC ADJUSTMENT OF THE HEATING CURVE OF A HEAT PUMP HEATING SYSTEM

Advisor: Prof. Luca Molinaroli
Advisor: Prof. Hatef Larijani Madani
Co-advisor: Dr. Davide Rolando

Master thesis by:
Antonio Andricciola  matr. 852411

Academic Year 2016-2017
Acknowledgments

I would like to thank both Politecnico and KTH for this precious experience since it gave me the possibility to enrich my personal and professional background. In particular, I would like to thank my advisors prof. Molinaroli and prof. Madani and the co-advisor dr. Davide Rolando for their advices and their help in this project. Last but not the least, I would like to thank all the people that supported me in this path making the ups happier and the downs more bearable.

This work is related to the project “Smart Control Strategies for Heat Pump Systems” within the EffSys Expand program, co-funded by the Swedish Energy Agency together with industrial project partners. The authors acknowledge Danfoss Heat Pumps AB, IVT-Bosch, Nibe, Bengt Dahlgren, Nowab AB, ETM Kylteknik AB, Hesch Automation and ElectroTest AB for the support to this project.
Index

Acknowledgments ........................................................................................................... I

Index .................................................................................................................................. III

Index of figures .................................................................................................................... V

Index of tables ...................................................................................................................... VIII

Abstract ............................................................................................................................... 1

Sommario ............................................................................................................................. 2

Introduction ............................................................................................................................ 3

Chapter 1: Literature review ............................................................................................... 5

1.1 Energy consumption ........................................................................................................ 5

1.2 Heat pump systems .......................................................................................................... 7

1.2.1 General description .................................................................................................... 7

1.2.2 Ground-source heat pumps (GSHP) ......................................................................... 10

1.2.3 Coupling heat pump-building ............................................................................... 11

1.3 Heating curve and heat pump systems control ............................................................... 14

1.4 Thermal comfort ............................................................................................................. 16

1.5 Buildings’ thermal inertia .............................................................................................. 16

Chapter 2: Work description ............................................................................................... 21

2.1 Building .......................................................................................................................... 21

2.1.1 Building models ....................................................................................................... 21

2.1.2 Models’ energy classification and A-class building .............................................. 27

Estimation of DHW demand for the calculation of the energy class ............................. 28

A-class building .................................................................................................................... 29

2.1.3 Buildings’ thermal inertia ....................................................................................... 29

2.1.4 Thermal time constant test ..................................................................................... 32

2.2 Distribution systems ...................................................................................................... 34

2.2.1 Radiators .................................................................................................................. 34

Sizing and radiator curve ................................................................................................. 35

Capacitance check ............................................................................................................. 36

2.2.2 Floor heating ............................................................................................................ 37

Sizing ................................................................................................................................. 38

Floor heating curve and capacitance check ....................................................................... 39
# Index

2.3 Heating curve ................................................................. 41  
2.4 Heat pump ................................................................. 44  
   2.4.1 Model layout ......................................................... 44  
   2.4.2 Basic control ......................................................... 45  

Chapter 3: Algorithm to adjust the curve ................................... 47  
3.1 Algorithm presentation ................................................... 47  
3.2 Working principle ......................................................... 48  
3.3 Algorithm and thermal inertia ........................................... 51  
   3.3.1 How inertia affects algorithm .................................. 51  
   3.3.2 Attempts to account for thermal inertia in the algorithm .... 53  
3.4 Solar compensation ....................................................... 56  

Chapter 4: Results ................................................................. 59  
4.1 Tests description ........................................................... 59  
4.2 Performance indexes ....................................................... 59  
4.3 Comparison 5-points curve vs. reference curve ..................... 60  
4.4 Comparison adjusted curve vs. reference curve .................... 62  

Conclusions and future developments ......................................... 63  

Bibliography ................................................................. 65
Index of figures

Figure 1: Example of how the heating curve for a specific building has changed over a period of 4 years. ................................................................. 3

Figure 2: Total and residential energy consumption behaviour for the time span 1993 – 2013 in the world. The picture is taken from [3]. .................................................. 6

Figure 3: Residential energy consumption global and divided for each GNI group in the time span 1993 – 2013. The picture is taken from [3]. .................................................. 6

Figure 4: Building energy end-uses for U.S., China and EU in 2010. Energies are expressed in Exajoule: EJ=10^{18} J. The picture is taken from [2]. ................................. 6

Figure 5: Representation of heat pump general scheme (left) and heat pump working principle (right). ................................................................. 7

Figure 6: Simple ideal cycle on the p-h diagram. .................................................. 9

Figure 7: Example of vertical closed loop heat exchange system for a GSHP. The picture is taken from [9]. ................................................................. 11

Figure 8: Example of building heat demand vs ambient temperature throughout the heating season. The picture is taken from [12]. .................................................. 12

Figure 9: Example of the coupling between a building and three different heat pumps where the balancing point is the same. The picture is taken from [13]. ......................... 13

Figure 10: Example of heating curve. ................................................................. 14

Figure 11: Example of thermal transient with ambient temperature equal to 0°C, initial indoor temperature equal to 20°C and time constant equal to 181 h. ......................... 17

Figure 12: Scheme of multiple lumped capacitance model considering the air inside the envelope. ................................................................. 18

Figure 13: Example of damping and time-shift (or phase lag) for a sinusoidal outdoor temperature. The picture is taken from [26]. ............................................................. 18

Figure 14: Model layout for the calculation of yearly heating demand. ...................... 25

Figure 15: Threshold values of specific energy consumption for new buildings in Stockholm which use electric heating from BBR BFS 2016:6. The picture is taken from [31]. ........................................................................................................ 27
Figure 16: Comparison between the behaviour of a “heavy building” and a “light building” in TRNSYS® with a harmonic outdoor temperature and the default settings. ........................................ 29

Figure 17: Outcome of the simulation for the “heavy building” in TRNSYS® using a constant outdoor temperature equal to 0°C and the default settings. .............................. 30

Figure 18: Analytical solution of the single lumped capacitance model for the “heavy building”. .......................................................................................................................... 31

Figure 19: Comparison between analytical solution and simulation result for the “heavy building” when $C_{air}$ is set equal to $C_{env}$. ................................................................. 31

Figure 20: Comparison between the simulated room temperature and the one calculated with the lumped capacitance model (and an average outdoor temperature) for the “existing building” during three days in January. .............................................. 33

Figure 21: Supply temperature vs emitted power for D-class radiators; characteristics displayed in Tab.10. .......................................................................................... 36

Figure 22: Comparison between return temperature of two radiators with different capacity subjected to the same change in supply temperature ..................................... 37

Figure 23: Floor heating sizing according to UNI EN 1264, given: pipe spacing, type of flooring and specific heat demand. The picture is taken from [34]. ......................... 39

Figure 24: Scheme of the model used to find the floor heating curve. .............................. 40

Figure 25: Heating demand vs. ambient temperature over the whole year for all the building models. ............................................................................................................ 41

Figure 26: Scattered heating curve for each building model. ........................................... 42

Figure 27: Example of average and median heating curve. ............................................. 42

Figure 28: 5-points heating curve for each building model. ......................................... 43

Figure 29: Room temperature against outdoor temperature used as a feedback to adjust the heating curve. ................................................................................................. 43

Figure 30: Scheme of the heat pump model used in TRNSYS®. ..................................... 44

Figure 31: Example of the whole system model for a building with floor heating. ................................................................. 45

Figure 32: Practical example which gave birth to the research question. For a specific installation the heating curve was changed 6 times in 4 years. .......................... 47
Figure 33: Example of the effect on indoor temperature of a good heating curve or a high-performance controller. ................................................................. 49

Figure 34: Example of the effect on indoor temperature of a heating curve providing a supply temperature higher than required. ................................................. 49

Figure 35: Schematic representation of the first version of the algorithm. ....................... 50

Figure 36: New version of the algorithm dealing with reduced coefficients. ................. 51

Figure 37: Application of the 36-coefficients algorithm over the period January-February. ............................................................................................................. 52

Figure 38: Corrective coefficients vs. frequency of outdoor temperatures for the period January-February. ................................................................. 52

Figure 39: Application of the 5-coefficients algorithm updating the curve once a week over the period January-February. ............................................................. 53

Figure 40: Outdoor temperature profile vs. indoor temperature profile for each building model while heating system is on. ................................................................. 54

Figure 41: Example of how the outdoor temperature profile is turned into a step function and then delayed. ................................................................. 54

Figure 42: Example of how indoor temperature evolves when outdoor temperature is constant and supply temperature is changed stepwise. ............................................. 55

Figure 43: Example of how indoor temperature evolves when supply temperature is constant and outdoor temperature is changed stepwise. ............................................. 55

Figure 44: Comparison between indoor temperature and specific average solar radiation for a range of outdoor temperatures going from -20°C to 15°C. ....................... 57

Figure 45: Example of coincidence between indoor temperature peaks and solar radiation peaks. ............................................................................................................. 57

Figure 46: Definition of reference heating curve both for a building with radiators and a building with floor heating. ................................................................. 59

Figure 47: Difference between 5-points curve and reference curve for each building model. ............................................................................................................. 61
Index of tables

Table 1: Envelope characteristics and transmittances adopted for the existing building. Comparisons between model values and TABULA reference values. .......................... 21

Table 2: List of parameters used in the building simulations and comparison with TABULA values. ........................................................................................................ 23

Table 3: Models’ heating demand calculation and comparison with TABULA data. Values are related to a reference floor area of 106 m$^2$. ......................................................... 24

Table 4: Models’ heating demand calculation and comparison with TABULA data. Values are related to a reference floor area of 212 m$^2$. ......................................................... 26

Table 5: Models’ heating demand calculation and comparison with TABULA data. Values are related to a reference floor area of 53 m$^2$. ......................................................... 26

Table 6: Energy classification of building models according to Boverket. ............... 28

Table 7: $\tau$ values calculated for each building model both considering and neglecting ventilation losses. ....................................................................................................... 32

Table 8: Comparison between the simulated and analytical $\tau$ values. Time span for the simulation is three days in January. ................................................................. 33

Table 9: Distribution system and new nomenclature for each building model. .......... 34

Table 10: Radiator characteristics for D-class and $B_{\text{rad}}$-class taken from Myson website. .................................................................................................................. 35

Table 11: Active layer input data required by the software and their description. ........ 38

Table 12: Structure of floor heating adopted in this work. ........................................ 38

Table 13: Variation in performance indexes using the 5-points curve instead of the reference curve. ................................................................. 60

Table 14: Variation in performance indexes using the adjusted curve instead of the reference curve. ................................................................. 62
Abstract

This work deals with the problem of choosing the correct heating curve for a certain building package (envelope plus distribution system). This topic is particularly relevant in countries like Sweden where heating curve is the most common way to control heat pumps. The analysis, involving four building models with respective distribution systems (two have floor heating and two radiators) and a variable speed GSHP, shows how, for a fixed location, the proper heating curve changes considering different building envelopes and different emitters. It is highlighted, therefore, how the adoption of a generic heating curve for all the buildings can cause discomfort and energy inefficiency. An algorithm to adjust the curve is then presented, and the results are compared with the reference case. The algorithm manages to improve comfort considerably and, for the A-class building, also SPF increases a lot (12.5%). The whole study was performed by means of TRNSYS® neglecting the DHW demand.

Keywords: Automatic adjustment; Heat pump; Heating curve; TRNSYS
Sommario

Questo lavoro verte sulla scelta della corretta curva di compensazione climatica per un certo pacchetto di edificio (involucro più sistema di distribuzione). Questa tematica è particolarmente rilevante in paesi come la Svezia in cui la curva di compensazione è il metodo più diffuso per controllare le pompe di calore. L’analisi, che coinvolge quattro modelli di edificio con rispettivi sistemi di distribuzione (due hanno pavimento radiante e due radiatori) e una pompa di calore geotermica a velocità variabile, mostra come, per una certa località, la curva di compensazione cambia considerando differenti involucri di edificio e differenti terminali. Viene messo in luce, perciò, come l’adozione di una curva di compensazione generica per tutti gli edifici, può provocare discomfort ed inefficienza energetica. Un algoritmo per modificare la curva è quindi presentato ed i risultati sono stati confrontati con la situazione di riferimento. L’algoritmo riesce a migliorare considerevolmente il comfort e per l’edificio di classe A anche l’SPF cresce molto (12.5%). L’intero studio è stato eseguito con TRNSYS® trascurando la richiesta di acqua calda sanitaria.

Parole chiave: Correzione automatica; Pompa di calore; Curva di compensazione climatica; TRNSYS
Introduction

In the last few years heat pump technology has been spreading quite rapidly. This phenomenon is due to different factors like the need to de-carbonize the heating sector and the possibility to ease the integration of renewables in the electric grid thanks to peak shifting. According to HEPA, 1,000,000 heat pumps were sold in the European market (+12%) during 2016 and the stock of 9,500,000 units contributed to save 27.1 Mt of CO₂ and 135 TWh of energy in the same year [1]. Nowadays new and improved control strategies are explored aiming to reach, in addition to the abovementioned objectives, a lower energy consumption in buildings without affecting end-user thermal comfort. Building sector is a big share of total energy demand, accounting for about 40% of it, if the analysis is limited to U.S. or E.U. and with a fast growth worldwide, year by year, due to developing countries [2]. This thesis work, carried out at Royal Institute of Technology in Stockholm, focuses on the topic of heating curves which is a very common way to control heat pumps in Northern Europe.

Objective

The final objective is to find a criterion to adjust the adopted heating curve when it does not fit the system. This is not just a theoretical matter, but a practical problem: it happened that, over a period of 4 years, the heating curve for a building has been changed six times, as shown in Fig.1

![Figure 1: Example of how the heating curve for a specific building has changed over a period of 4 years.](image-url)
Many houses in Sweden do not have indoor thermostat, so using the right heating curve is crucial to get comfort and energy efficiency, without mentioning that heating curves are often the starting point for advanced control strategies. Just recently indoor temperature sensors started to be installed and the proposed algorithm represents a way to use this information to cope with the issue raised before. The advantages of the proposed solution are: (i) it is a real-time algorithm so can be implemented in the real practice, (ii) it does not involve additional components (other than the indoor sensor) and (iii) the code can be easily written on pre-existing controllers.

In conclusion, four buildings with their distribution system are modelled in TRNSYS® environment and the scenarios adopting two different heating curves are analysed. Then, an algorithm is presented and the potential benefits are shown with respect to the standard case.

**Thesis outline:**

The thesis is organized in the following chapters:

- Chapter 1 discusses the literature review and state of art
- Chapter 2 deals with the work description
- Chapter 3 presents the algorithm and its implementation
- Chapter 4 shows the results
- Conclusions and future developments
Chapter 1: Literature review

1.1 Energy consumption

Recently, energy consumption has become a sensitive topic for several reasons: global warming, environmental pollution and the decrease of fossil fuels reservoirs. In order to cope with these problems, many efforts have been put on the study and development of technologies exploiting renewable sources, but without an improvement in energy efficiency, it is very difficult to achieve the desired goals in such a short period of time. Many researches show that global energy consumption has been steadily increasing: for example, in [3] a time span of 10 years (from 1993 to 2013) is considered and the analysis is made using two criteria: a geographical one (world is divided in 11 regions) and an economical one (four groups of countries are defined according to their gross national income or GNI). The general trend and the behaviour of every GNI group are depicted respectively in Fig.2 and Fig.3. A big share of the total energy consumption is constituted by the building sector: this is between 25% and 30% [2] (just residential sector neglecting services), with peaks of 40% in USA and EU. Acting on the building sector allows both big savings and the possibility to reduce global CO₂ emissions in a more effective way. Indeed, many countries managed to achieve their environmental commitments partially displacing the most polluting industries to other countries where standards are low. On the other hand, residential sector is difficult to displace so results of the policies applied to it are more trustworthy [3,4].

As mentioned above, both the global and residential energy consumption are rising, the latter especially due to LMI (lower medium income) and UMI (upper medium income) countries. It is evident that there is a relationship between the wealth of a nation and its energy needs and this suggests that the fast growth of developing countries will continue to boost the energy demand also in the next years.
Being more specific, HVAC systems account for almost half of buildings energy consumption and approximately from 10% to 20% of total energy consumption in developed countries. Currently the main portion of both residential and services energy demand is devoted to space heating, as shown in Fig.4, however the situation is probably going to change. Taking into consideration other factors like the growth of global population and global warming, the model of Isaac et al. [5] indicates that, in the reference scenario, the residential heating demand would decrease by 34% and the cooling demand would increase by 72% by 2100; this is due to a warmer climate and an increasing ownership of air conditioners in countries like China and India.

![Figure 2: Total and residential energy consumption behaviour for the time span 1993 – 2013 in the world. The picture is taken from [3].](image1)

![Figure 3: Residential energy consumption global and divided for each GNI group in the time span 1993 – 2013. The picture is taken from [3].](image2)

![Figure 4: Building energy end-uses for U.S., China and EU in 2010. Energies are expressed in Exajoule: EJ=10^18J. The picture is taken from [2].](image3)
One strategy to get a reduction of building energy demand is implementing and applying the so called near-zero-energy-building (NZEB) concept: this is the purpose of the European Directive 2010/31/Eu on Energy Performance of Buildings, whose targets will be mandatory from 2020. There is not a unique definition for a NZEB building yet, but it usually involves one or more renewable power sources (photovoltaic most of the cases), good building envelope characteristics and other generators. Electrical heat pumps fit well in this kind of system: they simplify the integration of photovoltaic generators in the grid, decoupling heat demand from electricity production with the help of a storage (water tank or the building itself). This way they maximize on-site electricity consumption, decreasing CO₂ emissions as well. A complete review of the multiple benefits exploiting heat pumps in a smart grid perspective can be found in [6]

Heat pumps coupled with NZEB have been investigated in the Annex 40 of the Heat Pumping Technologies Program (HPT) of the International Energy Agency (IEA): simulation studies and field monitoring across different countries confirm that, despite the different economic and climatic boundary conditions, heat pumps range among the most energy-efficient and cost-effective systems for NZEB.[7]

1.2 Heat pump systems

1.2.1 General description

A heat pump is a device which extracts heat from a low temperature system (cold heat source) and rejects it to a high temperature system (hot heat sink) thanks to external power. Fig.5 represents the general scheme of a heat pump and its working principle.

![Diagram of a heat pump](image)

*Figure 5: Representation of heat pump general scheme (left) and heat pump working principle (right).*
If $T_1$ is the high-level temperature and $T_2$ is the low-level temperature, the efficiency (or coefficient of performance) of a reverse Carnot cycle is:

$$COP_{id} = \frac{T_1}{T_1 - T_2}$$

(1)

This means that the higher is the temperature difference between the systems (sink and source), the lower is the efficiency. Carnot cycle is taken as reference because it is the most performing cycle under the same temperature levels, in a real case COP will be even lower. If the useful effect is $\dot{Q}_1$ and the driving power is $\dot{W}$, its value is calculated as:

$$COP = \frac{\dot{Q}_1}{\dot{W}}$$

(2)

If the calculation is extended over the whole heating or cooling season (involves energy and not power), the same index is called SPF (seasonal performance factor)[8].

Under a thermodynamic point of view, heat pumps are reverse Rankine cycles, operating with a phase-changing fluid called “refrigerant”. The fluid receiving the useful effect is the “primary fluid” while the one allowing the correct operation of the machine is the “secondary fluid”. Heat pumps are classified according to the types of primary and secondary fluid (air-to-water, air-to-air …) and to the type of driving power they require (absorption systems or vapour compression systems). As concerns the choice of the heat source, the possibilities are: air, water and ground. There are pros and cons for both air and water (a detailed description of ground-source heat pump is done in the next sub-section): air is always available but its heat transfer coefficient is quite low so, at fixed heat transfer rate, larger surfaces are needed. Outdoor air temperature has a high variability during the year, this means that the temperature difference between evaporator and condenser can become very high decreasing heat pump efficiency. Moreover, during winter, there is the problem of frost formation on the evaporator, which worsens performances even more. On the other side, water has a higher heat transfer coefficient and its temperature during the year doesn’t change much, but it’s not available everywhere [8].
Generally speaking, the working points of a vapour compression system can be described as follows:

1. Refrigerant at low pressure extracts heat from the source and evaporates achieving saturated (or superheated) vapour condition
2. Vapour, after passing through the compressor, becomes a high temperature and high pressure vapour.
3. Refrigerant releases heat to the heat sink and condenses until it’s a high pressure, high temperature (saturated or subcooled) liquid
4. Liquid passes through an expansion valve which decreases both its pressure and temperature

Many systems include the possibility to have both heating and cooling as useful effect, in this case a reversing valve is needed because refrigerant flows in opposite directions [9].

Fig.6 shows an example of the described points on the p-h diagram. The considered cycle is a simple ideal cycle, but its shape varies if the system is real or the configuration is advanced.

![Figure 6: Example of simple ideal cycle on the p-h diagram.](image)
1.2.2 Ground-source heat pumps (GSHP)

As explained in [9] geothermal energy is used in three main ways: electricity generation, direct heating and indirect heating or cooling via geothermal heat pumps. These three processes use respectively high, medium and low temperature sources: the first two are the product of thermal flows from the earth core collected in the water and the rocks, while low temperature sources are closer to ambient temperature and are attributable to solar radiation and ambient air.

High and medium temperature sources are deep within the earth, and their depth affects whether they are economically convenient or not. Low temperature sources are abundant and at relatively small depths; for this reason, and for the fact that temperature underground is almost constant throughout the year (geothermal gradient is around 30°C km\(^{-1}\) for depths between 6 m -100 m), GSHP became an interesting option for cooling and heating buildings.

There are different types of GSHP [10]:

- **GWHP** ground-water heat pumps, known also as open-loop systems, are the original type of GSHP. They use ground water that is then discharged to a suitable receptor. These are very simple systems with little space required, but the disadvantages are that the source may have a limited availability and/or a poor chemical quality.

- **GCHP** ground-coupled heat pumps, or closed-loop systems. They have the advantage of overtaking the problem of water availability and low chemical quality. In these systems heat absorption and rejection is obtained by high-density polyethylene pipe heat exchanger buried in vertical boreholes or horizontal trenches. In the case of vertical borehole GCHP systems (Fig.7), the ground heat exchanger is typically composed of (30.5 m-120 m)-deep, and (76 mm-127 mm)-diameter boreholes backfilled with material that prevents contamination of ground water and with a (19 mm-38 mm)- diameter U-shape pipe in which the mixture water and anti-freeze flows. In horizontal GCHP systems, ground heat exchanger is composed of a series of (19 mm-38 mm)-diameter and (121.9 m-182.9 m)-length parallel pipe, in horizontal (0.91 m-1.83 m)-deep boreholes. This superficial position of the pipes makes the COP oscillate more throughout the year due to influences of outdoor air temperature.

- **SWHP** surface water heat pump, in two configurations:
  - Closed-loop in which heat rejection-extraction is positioned at an optimized depth within a pond, lake etc.
  - Open-loop in which water is extracted from the surface-water body and then is discharged to a receptor

- **SWC** standing column well where water is pumped out and in a standing deep well bore.
According to Lund et al. [11] the worldwide installed capacity of GSHPs is about 33GWt and their annual energy use is over 55TWh. The number of countries with this kind of installation increased from 26 in 2000 to 43 in 2010. Sweden is in the top five countries for both the largest capacity installed and the largest energy use.

1.2.3 Coupling heat pump - building

Building heating demand, i.e. the amount of heat needed to keep indoor temperature constant, varies with outdoor temperature. It depends essentially on the quality of the building envelope, but also on many other factors like: solar radiation, wind speed, internal gain and building thermal inertia [12]. As highlighted in Fig.8, the building heating demand versus outdoor temperature is represented by a cloud of points, with the scattering due to all the factors mentioned before:
If an air-to-water (or air-to-air) heat pump is considered, its heating capacity has an opposite trend with respect to building heating demand, i.e. it increases with outdoor air temperature, with a straight-line behaviour. The intersection between the two curves is called “balance point”, therefore, the “balance temperature” is the ambient temperature for which the heat pump capacity equals the building heating demand: for lower temperatures heat pump cannot satisfy completely the building needs, for higher temperatures the heat pump works at partial load (on-off cycles or lower compressor frequency) [8].

Fig.9 shows the coupling of a building with three different air-to-water heat pumps: single speed single compressor (HP), single speed multiple compressors (MSHP), variable speed compressor (IDHP) [13]. In this specific case, the balance point is the same because all the heat pumps are sized on the building peak demand.
Usually single speed heat pumps are sized to cover 55%-70% of the peak demand (the remaining is supplied through an electrical heater) while variable speed machines are sized to cover more or less the whole peak demand [12].

Figure 9: Example of the coupling between a building and three different heat pumps where the balancing point is the same. The picture is taken from [13].
1.3 Heating curve and heat pump system control

Although there are a lot of studies and articles about advanced control strategies for heat pumps, like model-based control and predictive control, a little is said on standard control concepts.

A common element in many control strategies is the so-called “heating curve”, a relation between the outdoor temperature and the supply or return temperature needed to satisfy the heating demand [14]. Heating curves are generally straight lines, with the possibility to change their inclination or offset (curve is shifted in parallel) to make them fit to the building needs. This feed-forward kind of control system is often coupled with a feed-back control (like a room temperature sensor or thermostatic valves) to account for internal gains [15,16]. Some manufacturers like Danfoss gives the possibility to change the heating curve at $T_{\text{outdoor}} = -5^\circ\text{C}, 0^\circ\text{C}$ and $5^\circ\text{C}$ [17], so their shape can also be a polygonal chain, as shown in Fig.10.

![Example of heating curve.](image)

Standard control logics aim to keep the actual supply (or return) temperature as close as possible to the one given by the heating curve [14]. Hysteresis and rule-based logics are common with single-speed heat pumps while PID is used with variable-speed heat pumps [13].
Fischer and Madani [6] give a summary of the different existing control approaches. They start with the most simple “non-predictive methods”: rule-based methods, where the control action is chosen with an “if-then” statement, and predefined schedules. This kind of control is the most common in the building energy management nowadays because rules design is relatively simple and performances quite good. Of course, efficiency losses and comfort violations can not be completely avoided. Later they deal with advanced strategies like “model predictive control (MPC)” or “model-free predictive control”. MPC use a model of the physical system to find an optimal control trajectory over the whole prediction horizon; the benefits are the possibility to include forecasts, to handle system constraints and to track multiple objectives, but the downsides are a higher computational effort (higher hardware requirements) and the difficulties in modelling, which may not be a trivial problem. Model-free predictive methods exploit forecasts avoiding the complexity of a model, with decisions made through prior engineering knowledge; however, results might not be optimal and rules not flexible enough to cover all the cases. Just to give an idea, two examples are now presented.

A load-shifting control strategy is investigated by Allison et al. [18]; this MPC predicts the following day’s heating demand and it runs the heat pump during off-peak periods to deliver the heat pre-charging the floor heating system.

Kandler et al. [19] in their work introduce a control strategy on two levels: the lower level is an MPC which minimizes a cost function taking into consideration: residual load, grid stability and electricity price. The higher level is a comfort-controller used for safety reasons to avoid discomfort for the user.

Some control strategies varying supply temperature are proposed by Huchtemann [16]: a rule-based control, that subtracts to the heating curve an offset calculated measuring the position of radiators’ thermostatic valves; a PI controller which aims to keep the thermostatic valves completely open (no heating curve needed) and a MPC receiving as inputs the indoor temperature, the outdoor temperature and their predictions. The output is an estimation of the heating demand, so of the required supply temperature, for the prediction horizon (no heating curve needed). An attempt to improve specifically heating curve control is the work of Hoogmartens and Helsen [20] who performed a parametric study on the standard case (heating curve with hysteresis) for a GCHP feeding an underfloor heating system.

Even with a complementary feed-back control, it is important to adopt the correct heating curve as highlighted in [21]
1.4 Thermal comfort

Thermal comfort is based on Fanger’s theory and in particular on PMV and PPD indexes. PMV, or predicted mean vote, is the mean value of the votes of a large number of people on the ISO scale (+3= hot, +2= warm, +1= slightly warm, 0= neutral, -1= slightly cool, -2= cool, -3= cold). The condition “too hot” or “too cold” is defined respectively by the votes +3,+2 and -3,-2, and PPD represents the percentage of voters feeling discomfort (too hot or too cold). Other factors affecting comfort are: air velocity, vertical temperature gradient, warm or cool floors, radiant temperature asymmetry, metabolic rate. People may be dissatisfied due to local discomfort or lack of general comfort; it is difficult to have a unique relationship between the intensity of some parameters and the percentage of people finding the condition unacceptable. Initially the comfort requirement was PPD<10% and -0.5<PMV<0.5, however with the revision of EN 7730 (and ASHRAE 55) different comfort levels have been defined and, for each category of building, it has been also suggested how to reach them [22].

A simpler approach considers just indoor temperature, stating that comfort is preserved if temperature stays inside an acceptability range. Thanks to its simplicity this method is widely used in scientific literature.

1.5 Buildings’ thermal inertia

Thermal inertia is the capacity of a system to store heat, while thermal time constant is an index expressing how rapidly a thermal transient happens. An electrical analogy can be made: heat flow, \( \dot{q} \), is modelled as a current through the resistance \( R \) charging or discharging a storage mass \( C \) (modelled as a capacitor) thanks to the temperature difference between the system (\( T \)) and the ambient (\( T_a \)) [23,24].

\[
\dot{q} = C \frac{dT}{dt} \quad \text{[W]} \tag{3}
\]

\[
\dot{q} = -\frac{T - T_a}{R} \quad \text{[W]} \tag{4}
\]

Combining these two equations, the solution is:

\[
\Delta T = \Delta T_o \cdot e^{-\frac{t}{RC}} \quad \text{[K]} \tag{5}
\]

Time constant is defined as the time required to fulfil 63% of the transient when ambient temperature changes step-wise and it is calculated as follows:

\[
\tau = RC \quad \text{[h]} \tag{6}
\]
Fig. 11 graphically represents an example of (5) with ambient temperature equal to 0°C, initial indoor temperature equal to 20°C and time constant equal to 181 h.

![Graph](image)

**Figure 11:** Example of thermal transient with ambient temperature equal to 0°C, initial indoor temperature equal to 20°C and time constant equal to 181 h.

In a composite system like a building, made of multiple layers and different materials, all the parts must be accounted. Moreover, the thermal resistance that appears in the time constant definition, should include both conduction and ventilation losses [23]:

\[ C = \sum \rho_i \cdot c_i \cdot V_i \quad [\text{J/K}] \quad (7) \]

\[ R = \frac{1}{U_{\text{cond}} + U_{\text{vent}}} \quad [\text{K/W}] \quad (8) \]

A limitation of this approach is that all the parts in the envelope should be at the same temperature, while rapid temperature changes only affect the external layers. However, if relatively slow variations are considered (ex. days), the whole envelope can be thought at the same temperature [24].
This model is called single lumped capacitance model, because just one thermal capacitance is considered (envelope) but more of them can be introduced in the model (multiple lumped capacitance) [25]. For example, one can decide to add thermal capacity of indoor air (Fig.12).

![Figure 12: Scheme of multiple lumped capacitance model considering the air inside the envelope.](image)

If outdoor temperature \( (T_{\text{out}}) \) is not constant but it has a sinusoidal profile, the effect of thermal inertia can be seen through damping and time-shift (Fig. 13) [26].

![Figure 13: Example of damping and time-shift (or phase lag) for a sinusoidal outdoor temperature. The picture is taken from [26].](image)
Thermal inertia has a relevant impact on heating of buildings and can be used in advanced control strategies to reduce costs. An example is “load management” or “peak-shifting”: it means storing heat during night (off-peak periods) and using it during the day. Since electricity is a common heating source, this helps reducing electricity demand peaks during daytime when both households and industries need it. Another beneficial effect is the decoupling between electricity production from renewables and heat demand, maximizing on-site consumption. Moreover, if an air-to-water or air-to-air heat pump is considered, pre-charging the building when outside temperature is higher can improve machine efficiency. Some papers focus on the topic of intermittent heating (shutting down the heating system for a certain time relying on the fact that, in heavy buildings, indoor temperature swings are small) with different conclusions. According to [27] intermittent heating allows to save energy, but the heating system needs to be oversized to reach comfort conditions in the shortest amount of time after the cooling-down phase. Of course, to get the best results an adequate strategy must be chosen according to building thermal inertia. On the other hand, [28] introduces a model to investigate the effects of increased building thermal capacity and the results show that, for heavy buildings, required heating capacity is usually reduced, but energy consumption in case of intermittent heating remains more or less the same (sometimes is even increased).
Chapter 2: Work description

2.1 Building

2.1.1 Building models

The work started with the modelling of three buildings through TRNBuild, an interface of TRNSYS®, which is a multi-purpose simulation software used in particular to assess the performances of thermal energy systems. For all the models the location is Stockholm and a simplified representation is adopted: one thermal zone, flat roof and 4 walls facing respectively to North, South, East and West. TABULA [29] has been used as reference for many parameters like: area of walls, roof, floor, windows, and the transmittance of the envelope itself, but also for infiltration rate, ventilation rate and internal gains. However, nothing is specified about layers’ thickness and materials, so they were chosen as reasonable as possible also relying on common architectural knowledge. TABULA webtool gathers data about European residential buildings, which are classified in typologies according to size, age and other criteria; calculations of potential savings by implementing refurbishments are displayed as well. Type 56, or “Multi-zone” component, allows the exchange of information between TRNSYS® types and TRNBuild.

Table 1: Envelope characteristics and transmittances adopted for the existing building. Comparisons between model values and TABULA reference values.

<table>
<thead>
<tr>
<th>Wall type</th>
<th>Materials</th>
<th>Thickness [m]</th>
<th>$U_{\text{model}}$ [W/(m$^2$*K)]</th>
<th>$U_{\text{TABULA}}$ [W/(m$^2$*K)]</th>
</tr>
</thead>
</table>
| External walls | ▪ Plaster  
▪ Lightweight concrete      | 0.315         | 0.574                           | 0.6                              |
| Roof      | ▪ Gypsum plaster  
▪ Mineral wool  
▪ Roof deck  
▪ Bitumen  
▪ Tiles     | 0.19           | 0.282                           | 0.29                             |
| Floor     | ▪ Spruce pine  
▪ Floor screed  
▪ Polystyrene  
▪ Concrete slab  
▪ Mineral wool  
▪ Hardcore    | 0.52           | 0.262                           | 0.28                             |
| Door      | Oak                             | 0.04          | 2.73                            | 3                                |
Reference data are related to a typical Swedish single-family house from 60s’ (existing building) and two of its possible refurbishments (usual and advanced). The usual and advanced refurbishments are obtained adding a certain amount of insulation material to the opaque surfaces and changing the windows; this way overall transmittance, and consequently heating demand, decreases. Tab.1 shows the envelope characteristics adopted for the “existing building”; the modelling strategy for the opaque surfaces consists in changing layers thickness and typology so that U values match with TABULA ones. As concerns transparent surfaces, in TRNBuild it is complicated and time-consuming building a window type from scratch. Since an overdetailed modelling goes beyond the scope of this thesis, a window type with a transmittance as close as possible to the reference one has been chosen from the software library. Tab.2 summarizes all the parameters used in the models; some of this information can be retrieved directly from TABULA website as previously mentioned. Both for the usual and the advanced refurbishment, TABULA indications, about the thickness of the insulation to add, are followed. For the windows, the criterion is the one presented above.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Existing building</th>
<th>Usual refurbishment</th>
<th>Advanced refurbishment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Model</td>
<td>TABULA</td>
<td>Model</td>
</tr>
<tr>
<td>$U_{wall}$ [W/(m²*K)]</td>
<td>0.57</td>
<td>0.6</td>
<td>0.36</td>
</tr>
<tr>
<td>$U_{floor}$ [W/(m²*K)]</td>
<td>0.26</td>
<td>0.28</td>
<td>0.21</td>
</tr>
<tr>
<td>$U_{roof}$ [W/(m²*K)]</td>
<td>0.28</td>
<td>0.29</td>
<td>0.12</td>
</tr>
<tr>
<td>$U_{window}$ [W/(m²*K)]</td>
<td>2.83</td>
<td>2.34</td>
<td>0.81</td>
</tr>
<tr>
<td>$U_{door}$ [W/(m²*K)]</td>
<td>2.73</td>
<td>3</td>
<td>1.16</td>
</tr>
<tr>
<td>$ACH_{vent}$ [1/h]</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>$ACH_{inf}$ [1/h]</td>
<td>0.4</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Convective gains [W/m²]</td>
<td>2.1</td>
<td>no info</td>
<td>2.1</td>
</tr>
<tr>
<td>Radiative gains [W/m²]</td>
<td>0.9</td>
<td>no info</td>
<td>0.9</td>
</tr>
<tr>
<td>Total gains [W/m²]</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>$S_{wall}$ [m²]</td>
<td>28 (112 total)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$S_{floor}$ [m²]</td>
<td>125</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$S_{roof}$ [m²]</td>
<td>125</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$S_{door}$ [m²]</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$S_{glazed}$ [m²]</td>
<td>22</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$S_{glazed,EST}$ [m²]</td>
<td>5.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$S_{glazed,WEST}$ [m²]</td>
<td>5.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$S_{glazed,NORTH}$ [m²]</td>
<td>4.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$S_{glazed,SOUTH}$ [m²]</td>
<td>6.2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Verification of building models

Models’ verification is carried out comparing models’ annual heating demand with the one present on TABULA for each class of buildings. Heating demand is calculated in TRNSYS® through TRNBuild heating type: given a set-point for indoor temperature the software creates a fictitious internal source which keeps room temperature equal to the desired value. Weather conditions are included in the model by means of “Type15-6” which is fed with data from Meteonorm®. It provides, for the chosen location, the so called “typical meteorological year”: temperature, solar radiation and all the other weather parameters are calculated through statistical methods from historical series. In Fig.14 the layout of TRNSYS® model is showed. Yearly heating demand is worked out integrating the hourly output over the whole simulation period (a year) and diving it for the reference floor area of 106 m² (Tab.3); deviation is calculated through (9).

\[
\text{Deviation} = \frac{\text{Simulated value} - \text{TABULA value}}{\text{TABULA value}} \tag{9}
\]

It’s important to understand that TABULA doesn’t give the right values, but just an indication of the heating demand for a category of dwellings. Inside this category, single buildings can have slightly different features, which means different heating demands, and TABULA tries to account for all of them. This is the reason why the analysis is called verification, not validation, and the difference between simulations and TABULA values is called deviation and not error. Stated that, models are considered acceptable because deviation is lower than 20%.

<table>
<thead>
<tr>
<th>Building class</th>
<th>Model heating demand [kWh/m²]</th>
<th>TABULA heating demand [kWh/m²]</th>
<th>Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing building</td>
<td>214</td>
<td>198</td>
<td>8%</td>
</tr>
<tr>
<td>Usual refurbishment</td>
<td>116</td>
<td>142</td>
<td>-19%</td>
</tr>
<tr>
<td>Advanced refurbishment</td>
<td>105</td>
<td>116</td>
<td>-10%</td>
</tr>
</tbody>
</table>
Figure 14: Model layout for the calculation of yearly heating demand.
Verification of building models varying the envelope geometry

To be sure that results do not depend on the chosen geometry, other two verification tests were carried out modifying the floor (and roof) area; walls’ area is calculated considering a square floor while the height stays unchanged (10):

\[ S'_{\text{wall}} = \sqrt{S'_{\text{floor}} \times 2.5 \text{ m}^2} \]  \hspace{1cm} (10)

A proportional corrective factor is needed to have coherent reference values, this is the ratio between the new exchange area and the old one. The proportion glazed-over-opaque surface for each wall is kept the same.

Floor area is doubled (Tab.4):
- \( S'_{\text{floor}} = 250 \text{ m}^2 \)
- Proportional factor: 0.91
- New reference area: 212 m²

Floor area is halved (Tab.5):
- \( S'_{\text{floor}} = 62.5 \text{ m}^2 \)
- Proportional factor: 1.13
- New reference area: 53 m²

Table 4: Models’ heating demand calculation and comparison with TABULA data. Values are related to a reference floor area of 212 m².

<table>
<thead>
<tr>
<th>Building class</th>
<th>Model heating demand ([\text{kWh/m}^2])</th>
<th>TABULA heating demand ([\text{kWh/m}^2])</th>
<th>Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing building</td>
<td>204</td>
<td>181</td>
<td>13%</td>
</tr>
<tr>
<td>Usual refurbishment</td>
<td>116</td>
<td>130</td>
<td>-11%</td>
</tr>
<tr>
<td>Advanced refurbishment</td>
<td>106</td>
<td>106</td>
<td>0%</td>
</tr>
</tbody>
</table>

Table 5: Models’ heating demand calculation and comparison with TABULA data. Values are related to a reference floor area of 53 m².

<table>
<thead>
<tr>
<th>Building class</th>
<th>Model heating demand ([\text{kWh/m}^2])</th>
<th>TABULA heating demand ([\text{kWh/m}^2])</th>
<th>Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing building</td>
<td>267</td>
<td>224</td>
<td>19%</td>
</tr>
<tr>
<td>Usual refurbishment</td>
<td>143</td>
<td>160</td>
<td>-11%</td>
</tr>
<tr>
<td>Advanced refurbishment</td>
<td>130</td>
<td>131</td>
<td>-1%</td>
</tr>
</tbody>
</table>
The results show that maximum deviation is still 19%. Since TABULA is the best reference to rely on in the context of this work, it has been shown that building models give acceptable results even with changes in geometry.

### 2.1.2 Models’ energy classification and A-class building

Energy classification of building models is performed with the purpose to link the cases analysed in this work with real cases. In other words, moving from the single building to its energy class (a group of buildings) it is possible to generalize the results (buildings from the same energy class are expected to behave in a similar way). Criteria for the classification are given by Boverket (Swedish National Board of Housing, Building and Planning) [30].

Boverket is a central government authority in the fields of housing and buildings, which supervises town and country planning in Sweden from legislative, procedural and architectural perspectives.

As can be read on the website, each class is defined by a range of energy consumption (EP), whose boundaries correspond to multiples or submultiples of the requirement that applies to new buildings. Threshold values for dwellings erected today are issued by Boverket itself in the building code BBR (BFS 2016:6) [31] and depend on the location and the type of generation system. Since the case study refers to single-family houses located in Stockholm and coupled with a heat pump, limits are the ones displayed in Fig.15.

<table>
<thead>
<tr>
<th>Dwellings</th>
<th>The building’s specific energy use (kWh per m² at the rate of energy use)</th>
<th>Installed electric input for heating [kW]</th>
<th>Average thermal transmittance ( U_m ) [W/m² K]</th>
<th>The building envelope’s average air leakage at 50 Pa pressure difference [l/s m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single-family houses</td>
<td>55</td>
<td>4.5</td>
<td>0.40</td>
<td>According to Section 9:25</td>
</tr>
<tr>
<td>Single-family houses where ( A_{smp} ) is less than 50 m²</td>
<td>No requirement</td>
<td>No requirement</td>
<td>0.33</td>
<td>0.6</td>
</tr>
<tr>
<td>Multi-dwelling blocks</td>
<td>50</td>
<td>4.5</td>
<td>0.40</td>
<td>According to Section 9:25</td>
</tr>
<tr>
<td>Multi-dwelling blocks where ( A_{smp} ) is 50 m² or larger and that to the predominant part (&gt;50 %, ( A_{smp} )) contain apartments with a residential area of at most 35 m² each</td>
<td>55</td>
<td>4.5</td>
<td>0.40</td>
<td>According to Section 9:25</td>
</tr>
</tbody>
</table>

*Figure 15: Threshold values of specific energy consumption for new buildings in Stockholm which use electric heating from BBR BFS 2016:6. The picture is taken from [31].*
Some remarks are needed:

- The area considered to get the specific energy consumption is the whole floor area (the whole building is heated up to a temperature greater than 10°C).
- Electricity consumption is calculated using an average COP of 3.5.
- Energy consumption includes: heating, cooling, DHW, building’s property energy but in this work only heating and DHW are considered.

**Estimation of DHW demand for the calculation of the energy class**

The estimation of DHW yearly demand is only used to calculate a more precise value of the building energy consumption and so, to assign an energy class that is closer to reality. According to [32] the consumption of DHW on average is 35% of the whole tap water consumption, which is about 190 l/person*day. Since all the analysed models are single-family houses, with the assumption of 4 people per family, the daily amount of DHW is:

\[
\hat{V}_{DHW} = 190 \left[ \frac{i_w}{\text{per*day}} \right] \times 4 \left[ \text{per} \right] \times 0.35 \left[ \frac{i_{DHW}}{i_w} \right] \quad [l/day] \tag{11}
\]

Energy is calculated assuming an average temperature difference of 35°C, an average COP=3.5 and a time span (Δt) of a year (4):

\[
E_{DHW} = \frac{\hat{V}_{DHW} \times c \times \Delta T \times \Delta t}{COP \times 125m^2} \quad \left[ \frac{kW\,h_{el}}{m^2} \right] \tag{12}
\]

As mentioned before, the specific energy use accounting for both heating and DHW, defines the energy class of each model (Tab.6):

<table>
<thead>
<tr>
<th>Building model</th>
<th>Energy class</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing building</td>
<td>D</td>
</tr>
<tr>
<td>Usual refurbishment</td>
<td>B</td>
</tr>
<tr>
<td>Advanced refurbishment</td>
<td>B</td>
</tr>
</tbody>
</table>
A-class building:

To cope with the current trend of low-energy dwellings, an A-class building model is added to the study. The methodology is the following: the parameters of the “advanced refurbishment” are modified through a trial and error procedure, until the constraint on A-class energy consumption is met ($E_{use} < 27.5 \text{ kWh/m}^2$) [30,31]. The main changes are the following ones:

- Infiltrations are reduced to $0.1 \text{ h}^{-1}$.
- Windows are changed with lower transmittance ones ($0.4 \text{ W/m}^2\text{K}$).
- Insulation thickness of the roof is increased by $0.18 \text{ m}$.
- Walls insulation is replaced with $0.085 \text{ m}$ of polyurethane.

2.1.3 Buildings’ thermal inertia

As concerns thermal inertia, if simulations are performed with the default values, results in TRNSYS® are not coherent with the theory. Just to highlight that, two new building models are introduced in the study: a “heavy building” and a “light building”. The latter is characterized by the so called “massless layer”, a feature in TRNBuild which guarantees negligible thermal inertia of the building envelope. Fig. 16 shows simulation results obtained imposing a harmonic outdoor temperature profile.

![Figure 16: Comparison between the behaviour of a “heavy building” and a “light building” in TRNSYS with a harmonic outdoor temperature profile and the default settings.](image)
The effect of damping can be seen, but not the difference in delay since the two temperature profiles (for the heavy and light building) are basically in synch. After retrieving its thermal time constant (τ), which is equal to 181 h, the “heavy building” undergoes to another test. In the new test, outdoor temperature is kept constant and equal to 0°C, while initial indoor temperature is set to 20°C; single-lumped capacitance model indicates that the transient should finish after about 5τ but, as displayed in Fig.17, the result of the simulation is different from what it is expected.

![Figure 17: Outcome of the simulation for the “heavy building” in TRNSYS® using a constant outdoor temperature equal to 0°C and the default settings.](image)

This is because calculations in TRNSYS® are affected by a parameter in TRNBuild: the thermal capacity of the air node (C_{air}). This is set by default equal to 1.2 times the volume, but it should be changed according to the situation. The problem is now finding a suitable value for C_{air} such that the simulation gives acceptable results.

To solve the issue, single-lumped capacitance model is taken as reference and a trial and error procedure is carried out. In other words, C_{air} is changed until the outcome from the simulation gets close “enough” to the analytical solution (Fig.18).
When $C_{\text{air}}$ is set equal to $C_{\text{env}}$, internal surface temperature profile almost overlaps with the analytical solution and indoor temperature behaves coherently with the multiple-lumped capacitance model; the simulation is now consistent (Fig. 19).

*Figure 18: Analytical solution of the single lumped capacitance model for the "heavy building".*

*Figure 19: Comparison between analytical solution and simulation result for the “heavy building” when $C_{\text{air}}$ is set equal to $C_{\text{env}}$.*
For each building model, \( \tau \) value is calculated with (6); this information gives an idea on how indoor temperature evolves with time (temperature swings and delay) (Tab.7). Values without considering ventilation are reported as well because they will useful in the next subsection.

<table>
<thead>
<tr>
<th>Building model</th>
<th>( \tau_{\text{vent}} ) [h]</th>
<th>( \tau_{\text{novent}} ) [h]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing building</td>
<td>146</td>
<td>211</td>
</tr>
<tr>
<td>Usual refurbishment</td>
<td>230</td>
<td>363</td>
</tr>
<tr>
<td>Advanced refurbishment</td>
<td>195</td>
<td>327</td>
</tr>
<tr>
<td>A-class</td>
<td>241</td>
<td>436</td>
</tr>
</tbody>
</table>

### 2.1.4 Thermal time constant test

The calculation of \( \tau \) via (6) requires the knowledge of many construction details (material and thickness of all the envelope layers) not easy to get especially for old buildings; for this reason, a simple test is introduced to retrieve \( \tau \) value analysing indoor temperature behaviour. Test is thought to be run when no one is inside, because heating system must be shut down; eventually time constant is evaluated thanks to (13). Fig.20 shows results for the “existing building” and a simulation period of three days in January.

This time span has been chosen for two reasons:

- In the lumped capacitance model, outdoor temperature is constant, however in a real case, this condition is never achieved. If outdoor temperature doesn’t vary much (like in winter), it can be approximated by the average over the whole period.
- Solar radiation can influence indoor temperature a lot; since its value during January in Stockholm is basically zero, \( \tau \) retrieved through the test will be closer to the analytical one.

\[
\tau = t / \ln \left( \frac{\Delta T_0}{\Delta T_t} \right) \quad [\text{h}] \tag{13}
\]
Test was performed for all the building models and results compared with the values in column $\tau_{\text{vent}}$ of Tab.7 (Tab.8). Deviation is about 30% in 3 cases over 4, this means that there is a link between the outcome of the test and the calculated time constant; the discrepancy can be overcome maybe through a corrective coefficient. Anyway, one should not forget that with different boundary conditions results would have been different: it’s advisable to check the variability of these values before generalizing their use.

![Figure 20: Comparison between the simulated room temperature and the one calculated with the lumped capacitance model (and an average outdoor temperature) for the “existing building” during three days in January.](image)

<table>
<thead>
<tr>
<th>Building type</th>
<th>$\tau_{\text{calculated}}$</th>
<th>$\tau_{\text{simulated}}$</th>
<th>Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing building</td>
<td>211</td>
<td>220</td>
<td>5%</td>
</tr>
<tr>
<td>Usual refurbishment</td>
<td>363</td>
<td>477</td>
<td>31%</td>
</tr>
<tr>
<td>Advanced refurbishment</td>
<td>327</td>
<td>416</td>
<td>26%</td>
</tr>
<tr>
<td>A-class</td>
<td>436</td>
<td>558</td>
<td>28%</td>
</tr>
</tbody>
</table>
2.2 Distribution systems

The type of terminals has a relevant impact on the control strategy of the heating system, because different terminals exploit different heat transfer mechanisms so they have different needs. In this work two types of terminals are investigated: radiators and floor heating. Tab.9 summarizes the situation for all the “building packages” (envelope plus distribution system) and introduces a new nomenclature that will be adopted from now on:

Table 9: Distribution system and new nomenclature for each building model.

<table>
<thead>
<tr>
<th>Building type</th>
<th>Distribution system</th>
<th>New nomenclature (energy class)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing building</td>
<td>Radiators</td>
<td>D-class</td>
</tr>
<tr>
<td>Usual refurbishment</td>
<td>Radiators</td>
<td>B_{rad}-class</td>
</tr>
<tr>
<td>Advanced refurbishment</td>
<td>Floor heating</td>
<td>B-class</td>
</tr>
<tr>
<td>A-class</td>
<td>Floor heating</td>
<td>A-class</td>
</tr>
</tbody>
</table>

2.2.1 Radiators

Radiators are modelled in TRNSYS® through Type 162, which needs some input parameters like: the power exchanged at $\Delta T=60^\circ$C, the heat capacity and the radiator’s exponent.

As concerns the heat transfer rate at $\Delta T=60^\circ$C ($\dot{Q}_{\Delta T=60}$), it is a convention implying that the amount of heat transferred must be calculated with a difference between radiator’s fluid mean temperature and room air temperature equal to 60°C (ex. $T_{\text{supply}}=85^\circ$C and $T_{\text{return}}=75^\circ$C while $T_{\text{room}}=20^\circ$C).

This is because radiators are basically heat exchangers, so it applies (14) and (15):

$$\dot{Q} = UA\Delta T_{lm}$$  \hspace{1cm} (14)

$$\Delta T_{lm} = \frac{(T_{\text{supply}} - T_{\text{return}})}{\ln((T_{\text{supply}} - T_{\text{room}})/(T_{\text{return}} - T_{\text{room}}))}$$  \hspace{1cm} (15)

For a fixed $UA$ value, the higher is $\Delta T_{lm}$, the higher is the heat transfer. Nowadays radiators are used with lower temperature levels than the ones mentioned above, especially if they are coupled with heat pumps. Typically, $T_{\text{supply}}=55^\circ$C and $T_{\text{return}}=45^\circ$C, so that $\Delta T_{\text{lm,n}}=30^\circ$C. If $\dot{Q}_n$ is the heat transfer rate, which is equal to required one, it is possible to retrieve $\dot{Q}_{\Delta T=60}$ thanks to (16), with $r$ that is the radiator’s exponent (usually 1.3).
\[ \dot{Q} = \dot{Q}_n \times \left( \frac{\Delta T_{lm}}{\Delta T_{lm,n}} \right)^r \]  

(16)

The other input parameter, thermal capacity, accounts for both the fluid and the metal constituting the radiator. It also depends indirectly on the maximum temperature used in the radiator because the lower is the average radiator temperature, the lower is \( \Delta T_{lm} \), the higher is the number of sections needed to satisfy the heat demand (if the number of columns is kept constant) so the overall mass.

**Sizing and radiator curve**

Heating system is usually not sized on the peak heating demand (i.e. the amount of heat required by the building at the lowest outdoor temperature) but it is slightly undersized because the few hours per year in which these extreme conditions are reached don’t justify the additional expense of a bigger system.

In this work, radiators are sized according to (17); sizing parameters are taken from Myson website [33] and summarized in Tab.10:

\[ \dot{Q}_{sizing} = \dot{Q}_{needed}(-18^\circ C) \times 0.9 \quad \text{[kW]} \]  

(17)

<table>
<thead>
<tr>
<th>Sizing parameters</th>
<th>D-class</th>
<th>B_rad-class</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \dot{Q}_{sizing} ) [kW]</td>
<td>8.16</td>
<td>4.9</td>
</tr>
<tr>
<td>( n_{columns} )</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>( n_{sections} )</td>
<td>28</td>
<td>16</td>
</tr>
<tr>
<td>Height [mm]</td>
<td>450</td>
<td>450</td>
</tr>
<tr>
<td>( \dot{Q}_{\Delta T=30} ) [kW]</td>
<td>9.44</td>
<td>5.39</td>
</tr>
<tr>
<td>( \dot{Q}_{\Delta T=60} ) [kW]</td>
<td>23.57</td>
<td>13.27</td>
</tr>
<tr>
<td>( m_{tot} ) [kg/h]</td>
<td>780</td>
<td>464</td>
</tr>
<tr>
<td>C [kJ/K]</td>
<td>1376</td>
<td>1072</td>
</tr>
<tr>
<td>Radiator exponent</td>
<td>1.3</td>
<td>1.3</td>
</tr>
<tr>
<td>Radiative share of total power</td>
<td>0.2</td>
<td>0.2</td>
</tr>
</tbody>
</table>

*Table 10: Radiator characteristics for D-class and B_rad-class taken from Myson website.*
In order to build the heating curve of the system, an important step is finding the terminal curve. As concern radiators, this is done in TRNSYS® through a simulation involving just Type 162: imposing a value for room air temperature (like its thermal capacity is infinite) supply temperature is constantly increased and information about emitted power is collected. The simulation result for the “D-class radiators” (distribution system of D-class building) is shown in Fig. 21.

![Graph](image)

*Figure 21: Supply temperature vs emitted power for D-class building radiators; characteristics displayed in Tab. 10.*

**Capacitance check**

As for the envelope, a check on terminals dynamic behaviour has been performed: two radiator models, with fixed room air temperature and same characteristics apart from thermal capacity, are fed with a step-wise supply temperature, then return temperature is plotted. Simulation shows that the radiator with higher capacity (chosen capacities are 1400 [kJ/K] and 1000 [kJ/K]) reaches steady-state later and this is consistent with theory as reported in Fig. 22.
2.2.2 Floor heating

Floor heating technology is very common nowadays because it usually guarantees a greater comfort compared to radiators. Moreover, the lower working temperatures make this solution particularly indicated when the generation system is a heat pump.

Contrary to radiators, floor heating has not been modelled with a specific type, but as a part of the envelope through the so called “active layer”. While defining the opaque surfaces of a building, it is possible to choose this type of layer if a radiant surface is desired. In such a case, the other layers of the same surface must satisfy some constraints, for example for floor heating:

- Flooring resistance must be low enough not to reduce excessively radiative heat transfer: $R_{flooring} \leq 0.15 \text{ m}^2\text{K/W}$
- Insulating resistance must be high enough not to increase excessively heat losses towards the ground: $R_{ins} \geq 0.825 \text{ m}^2\text{K/W}$
- The thickness and type of materials must be such that the response time is realistic (thermal inertia)

*Fig.22: Comparison between return temperature of two radiators with different capacity subjected to the same change in supply temperature.*
Tab.11 and Tab.12 display respectively the input data required by the program to characterize the active layer and the adopted floor heating composition.

Table 11: Active layer input data required by the software and their description.

<table>
<thead>
<tr>
<th>Input</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>D_{out} [m]</td>
<td>Pipe outer diameter</td>
</tr>
<tr>
<td>t [m]</td>
<td>Thickness of the pipe</td>
</tr>
<tr>
<td>d [m]</td>
<td>Distance between two diameters (centre to centre)</td>
</tr>
<tr>
<td>k_{mat} [W/(mK)]</td>
<td>Material conductivity</td>
</tr>
<tr>
<td>c [kJ/(kg*K)]</td>
<td>Fluid (water) specific heat</td>
</tr>
<tr>
<td>m_{in} [kg/h]</td>
<td>Fluid mass flowrate</td>
</tr>
<tr>
<td>T_{in} [°C]</td>
<td>Inlet (or supply) temperature</td>
</tr>
<tr>
<td>n_{part}</td>
<td>Number of partitions (if specific flowrate is lower than threshold value, circuit must be split in n_{part} circuits in series otherwise a correct heat exchange is not guaranteed)</td>
</tr>
</tbody>
</table>

Table 12: Structure of floor heating adopted in this work.

<table>
<thead>
<tr>
<th>Layer type</th>
<th>Thickness [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spruce pine</td>
<td>0.01</td>
</tr>
<tr>
<td>Gypsum mortar</td>
<td>0.06</td>
</tr>
<tr>
<td>Active layer</td>
<td>0.02</td>
</tr>
<tr>
<td>Gypsum mortar</td>
<td>0.02</td>
</tr>
<tr>
<td>Polystyrene</td>
<td>0.12</td>
</tr>
<tr>
<td>Concrete slab</td>
<td>0.12</td>
</tr>
</tbody>
</table>

Sizing

Sizing is performed according to the standard UNI EN 1264 (Fig.23) [34]; inlet temperature is chosen considering:

- Pipe spacing
- Flooring type
- Specific heat demand

Nominal temperature difference between supply and return is 5 K and nominal mass flowrate is calculated adding up to the heat demand the heat losses towards the ground or the surrounding environment (if system is not placed at ground floor).
Specific heat demand is not calculated as for radiators, but considering the outside temperature suggested by Boverket in [35].

**Floor heating curve and capacitance check**

Since it is not possible analysing floor heating separately from the rest of the system, both the capacitance check and the floor heating curve test are difficult to perform. The main obstacle is that boundary conditions (room air temperature and inner surfaces temperature) can not be imposed but are continuously calculated by the software. This means that:

- Without the same conditions a comparison (with different capacities) is not meaningful
- When building the terminal’s curve, exchanged heat will be influenced not just by supply temperature but also by all the other factors (room air temperature, inner surfaces temperature and outside temperature)

As concerns the curve, a simplified model has been introduced where boundary conditions are constant and convection is neglected (Fig.24). In the scheme green resistances are radiative resistances (grey body and view factor) while the orange one is the conductive resistance towards the ground. Since the view factor (radiant surface-other walls) is 1 and with the hypothesis of black body and $A_{env} > A_{floor}$, (20) is obtained.
\[
\Delta T = \frac{\dot{Q}_{\text{fluid}}}{m * c}
\]

\[
T_{\text{av,fluid}} = T_{\text{supply}} - \frac{\Delta T}{2}
\]  

\[
\dot{Q}_{\text{fluid}} = \dot{Q}_{\text{rad}} + \dot{Q}_{\text{lost}} = A_{\text{floor}} \left( \frac{T_{\text{av,fluid}} - T_{\text{ground}}}{R_{\text{ground}}} + \sigma \left( T_{\text{av,fluid}}^4 - T_{\text{in, sup}}^4 \right) \right)
\]  

Figure 24: Scheme of the model used to find floor heating curve.

These equations were solved in an iterative way. The obtained relation linking \( T_{\text{supply}} \) to \( \dot{Q}_{\text{emitted}} \) is not precise, because a lot of approximations have been made, but it was useful to build a “starting” heating curve, which is then corrected through a trial and error procedure.
2.3 Heating curve

The heating curve is a function relating outdoor temperature with terminals’ supply temperature and it is used to modulate the heating capacity provided by the generation system according to the building needs. A simple example of heating curve is a straight line connecting two points (ex. supply temperature for an outdoor temperature of 15°C and supply temperature for the lowest temperature during winter). The idea of a straight line descends from the assumption that building heating demand changes linearly with outdoor temperature but Madani et al. [12] showed that this is a more complicated matter (due to building thermal inertia and solar radiation the real shape is a cloud of points). In TRNSYS® was possible, with the aid of the heating type, finding the cloud-of-points heat demand over the whole typical meteorological year for each building model (Fig.25).

![Figure 25: Heating demand vs. ambient temperature over the whole year for all the building models.](image)

It is useful to remember that, even if they belong to the same energy class, B-class and B_rad-class building have different envelopes other than different terminals, therefore the respective graphs are slightly different. The next step is matching building heating demand with the power provided by the distribution system; the result is a relation between terminals’ supply temperature and outdoor temperature (the heating curve), which has the shape of a cloud of points (Fig.26).
Interpolating this cloud of points is not a trivial matter: a possibility may be calculating the average or the median of the corresponding supply temperature values for each integer of outdoor temperature (Fig.27); however, in real practice, a polygonal chain with just 5 points is used, therefore the final shape will be like Fig.28.

Figure 26: Scattered heating curve for each building model.

Figure 27: Example of average and median heating curve.
As mentioned before, heating curve for A-class and B-class building are the product of a trial and error procedure: starting from the scattered heating curve, points were shifted up or down until the graph $T_{\text{room}}$ vs $T_{\text{out}}$ did not show a homogeneous cloud around 20°C (Fig.29)

![Graphs of heating curves for A-class and B-class buildings.](image)

*Figure 28: 5-points heating curve for each building model.*

![Graph of room temperature against outdoor temperature.](image)

*Figure 29: Room temperature against outdoor temperature used as a feedback to adjust the heating curve.*
2.4 Heat pump

2.4.1 Model layout

The heat pump analysed in this work is a variable speed GCHP. It is modelled with a macro (Fig.30) that takes as inputs: load temperature and mass flowrate (conditions at the inlet of the condenser), source temperature and mass flowrate (conditions at the inlet of the evaporator), compressor frequency, control function (device is on or off) and required supply temperature. Outputs are: condenser and evaporator capacities, compressor power, temperatures at the outlet of the condenser (T_supply) and of the evaporator. Thanks to the inputs, outputs are retrieved, through a 3D interpolation from a “performance map”, made by a collection of real \( \dot{Q}_{\text{cond}} \) and \( \dot{P}_{\text{comp}} \) for specific values of source temperature, load temperature and compressor frequency [36]. Each heat pump has been sized as explained in the distribution system section just scaling the given performance map with a proportional factor.

Borehole heat exchanger is modelled through Type557a, available in the TESS library. A lot of parameters can be set, but just the most relevant were checked (and in case corrected) to guarantee proper working conditions and realistic final results.

Figure 30: Scheme of the heat pump model used in TRNSYS®.
2.4.2 Basic control

Since this work deals with a variable speed heat pump, the adopted control strategy is a heating curve coupled with a PI controller. In other words, the controller changes the compressor frequency (so the power released at the condenser) to keep the actual $T_{\text{supply}}$ as close as possible to the one calculated by the heating curve (Type81): if the heating curve fits the considered building package, indoor temperature should stay not very far from the set-point. An example of the whole system can be seen in Fig.31; in all the models DHW demand is neglected.

Moreover, to make the heat pump behaviour more realistic and to reduce the number of on-off cycles, two constraints have been added:

- Heat pump turns off only if the frequency is lower than minimum frequency (36.7 Hz) for more than 15 minutes
- Heat pump turns on only if frequency is higher than minimum frequency (36.7 Hz) for more than 15 minutes, besides when it turns on it works at the minimum frequency for 15 minutes.

![Figure 31: Example of the whole system model for a building with floor heating.](image-url)
Chapter 3: Algorithm to adjust the curve

3.1 Algorithm presentation

The idea of the algorithm has its roots in the need of finding a way to adjust the heating curve when it does not fit the system. As explained in the introduction, choosing the correct curve is not a trivial task especially without a simulation tool like TRNSYS®. It may be useful recalling the practical example which gave birth to the research question of this study (Fig.32): analysing the data given by some companies, there was an installation in which the heating curve was changed 6 times in 4 years without an apparent criterion.

![Figure 32: Practical example which gave birth to the research question. For a specific installation the heating curve was changed 6 times in 4 years.](image)
Even if coupled with a feedback control, like the thermostat in [21], a bad heating curve does not guarantee neither comfort nor proper working conditions. Without mentioning that, when used as parameter in advanced control strategies, not appropriate curves can worsen results quite much. This algorithm exploits the feed-back from indoor temperature to modify the points of the curve through some corrective coefficients. The main advantages are:

- It is a real-time method, so can be implemented in the real practice
- Since it is an adaptive algorithm, there are no limitations in its use because it adapts to the situation
- Thanks to its simplicity, it can be easily written on pre-existing controllers; it doesn’t need additional components (just the indoor temperature sensor) and may be a good solution in case of retrofitting
- Some advanced control strategies use heating curve as a control parameter so a good heating curve is important to achieve good results

It is important to underline that the algorithm has a numerical nature, because the corrective action is purely based on additional coefficients. This means that overall performances are improved, but the shape of the adjusted curve can be non-intuitive; for example, it can have a jagged profile or parts in which supply temperature increases though outdoor temperature increases.

### 3.2 Working principle

If the building heating demand was a straight line and both terminals and heat pump had no inertia, a good heating curve could maintain the indoor temperature exactly equal to set-point. In reality, a lot of factors affects building demand, so heating curve is considered good when indoor temperature stays as close as possible to the set-point, in a certain acceptability range: in this work the band is 1 °C around 20°C (the set-point) (Fig.33). Whether other disturbances as solar radiation are taken into consideration, it is possible to refine even more the strategy and get better results (solar compensation will be presented later in the chapter).
Focusing just on the relation outdoor temperature-indoor temperature, whenever the latter deviates from the behaviour in Fig.33, heating curve should be corrected because it means that supply temperature was higher or lower than the required one (Fig.34).

Figure 33: Example of the effect on indoor temperature of a good heating curve or a high-performance controller.

Figure 34: Example of the effect on indoor temperature of a heating curve providing a supply temperature higher than required.
In Fig. 34 all the points are shifted up with respect to the reference situation, but it may be that indoor temperature crosses the acceptability boundaries just for a specific range of outdoor temperatures. Recording continuously $T_{\text{room}}$ and $T_{\text{out}}$, controller can identify what is the outdoor temperature when indoor temperature is deemed to cause discomfort, then it corrects heating curve accordingly. The check on indoor temperature is performed every hour.

The first version of the algorithm works with 36 corrective coefficients, one for each integer of outdoor temperature (-20;15), as shown in Fig.35:

![Diagram showing the first version of the algorithm.](image)

**Figure 35: Schematic representation of the first version of the algorithm.**

Though this approach is not very practical, since heating curves aren’t characterized by 36 points, it highlights some interesting information which helps understanding how the system responds. A more realistic version of the algorithm calculates the coefficients as before, but updates the curve with a different time-step (ex. every week) after reducing the 36 coefficients to 5. A scheme of the algorithm and the logic to retrieve the reduced coefficients is displayed in Fig.36.
### 3.3 Algorithm and thermal inertia

#### 3.3.1 How inertia affects algorithm

An example of the 36-coefficients algorithm can be seen in Fig.37. The simulation period is two months, January and February, and the “proper” curve is the one that gives good results in terms of comfort. The starting curve is adjusted mainly in the central part, while for too low or too high outdoor temperatures there is no correction. At low temperatures, this is due to thermal inertia plus the fact that such temperatures are not frequent during the considered period (and in general during the year); on the other hand, at high temperatures the absence of correction is due to the fact that no outdoor temperature with such a high value is registered in the reference period. Effects of outdoor temperature are felt in the indoor environment with a delay because of thermal inertia; the outcome is that, even if discomfort is caused by a certain $T_{\text{out}}$ (in particular to $T_{\text{supply}}$ associated to it), controller may register and correct another one instead: heating curve is more likely to be adjusted for high-frequency outdoor temperatures (Fig.38). Fig. 37 shows an adjusted curve with some spikes: they are caused by the effect of thermal inertia and highlight the numerical nature of the method. The same situation with the 5-coefficients version of the algorithm is depicted in Fig.39; this time the adjusted curve has smoother profile than the one in Fig.37. The act of reducing the coefficients decreases the effect of thermal inertia, because each coefficient is not related anymore to a single value of outdoor temperature, but to a range of outdoor temperatures.
Chapter 3

Figure 37: Application of the 36-coefficients algorithm over the period January-February.

Figure 38: Corrective coefficients vs. frequency of outdoor temperatures for the period January-February.
3.3.2 Attempts to account for thermal inertia in the algorithm

Various attempts were made to find a parameter which could lump the effect of thermal inertia and account for it in the algorithm, however it is not an easy task because indoor temperature is influenced by too many parameters so it is difficult to forecast. Fig.40 depicts the indoor temperature profile for all the building models (when the heating system is on) and compare it with outdoor temperature profile. The negative peak after about 400 h is because the heat pump is not sized to cover the peak demand (and outdoor temperature reaches -20°C twice between 200 h and 400 h): it is not difficult to imagine that a similar effect is observed if $T_{\text{supply}}$ is lower than the one required for that $T_{\text{out}}$. The idea was finding the delay between outdoor temperature negative peak and indoor temperature negative peak and use this information in the algorithm to improve the correction process. In particular, yearly outdoor temperature profile from the typical meteorological year was turned into a stepwise function, shifted in time (Fig.41) and then fed to the algorithm (the value of the step was calculated as the average over a certain period). Passing to a stepwise profile makes outdoor temperature stay constant for a while, so it should be easier for the controller to detect the desired $T_{\text{out}}$ even without a precise value of delay. However, the simulations including the delay in the control action did not give positive results; the problem is that this kind of evaluations can not be generalized.
Chapter 3

The algorithm recognizes discomfort when $T_{room}$ goes out from the range $20 \pm 1^\circ C$, but indoor temperature is never perfectly constant and equal to the setpoint. If $T_{room}$ is close to the boundary, even a relatively small peak could go outside the acceptability range: in this case the delay to consider should be quite low (ex. delay can not be the same if $T_{room}$ crosses the boundary starting from a value of $19.5^\circ C$ or a value of $20.5^\circ C$).

**Figure 40:** Outdoor temperature profile vs. indoor temperature profile for each building model while heating system is on.

**Figure 41:** Example of how the outdoor temperature profile is turned into a step function and then delayed.
Moreover, the behaviour of the building envelope alone is way different than the behaviour of the coupling building plus heating system. In the latter, the entity of the oscillation in indoor temperature is essentially due to the difference between the actual $T_{\text{supply}}$ and the required $T_{\text{supply}}$; however this information is not known in advance. Fig.42 and Fig.43 show how indoor temperature evolves in two different cases.

In Fig.42 indoor temperature is brought to 21.5°C thanks to an appropriate $T_{\text{supply}}$, then supply temperature is changed stepwise so that the new $T_{\text{room}}$ at steady state is 20°C. Outdoor temperature is kept to 0°C for the whole test.

In Fig.43, indoor temperature is brought to 21.5°C thanks to an appropriate $T_{\text{supply}}$, then outdoor temperature is changed stepwise from 0°C to -5°C (this time supply temperature is kept constant during the whole test).

**Figure 42**: Example of how indoor temperature evolves when outdoor temperature is constant and supply temperature is changed stepwise.

**Figure 43**: Example of how indoor temperature evolves when supply temperature is constant and outdoor temperature is changed stepwise.
Chapter 3

In both cases there is a difference between buildings with floor heating and with radiators: while buildings with radiators reflect what said about thermal inertia (transients for D-class building are faster than B\text{rad}-class building), it is not evident in buildings using floor heating, because part of the envelope becomes a heating source so what explained before does not apply anymore.

The last attempt was trying to apply the delay just in specific situations. It has already been mentioned that if indoor temperature increases or decreases when heating system is on, it is because supply temperature is not the appropriate one. Therefore, if $T_{\text{room}}$ grows more than 21°C it means that there is a problem with the current $T_{\text{supply}}$ and to fix it, the controller should register the current $T_{\text{out}}$. On the other hand, the delay should be applied if indoor temperature is higher than 21°C and starts decreasing: this means that now supply temperature is such that $T_{\text{room}}$ is brought back in the acceptability range, but due to thermal inertia it takes time to restore comfort. The opposite can be said when indoor temperature goes below 19°C: this time the delay should be applied during the heating-up phase. Anyway, the biggest obstacle is still choosing which value of delay to adopt: due to its variability all these considerations turn out to be not so effective and very difficult to implement in the real practice.

3.4 Solar compensation

It has been already pointed out that heating curve compensates the effect of outdoor temperature, but also solar radiation has a relevant impact on indoor temperature. A good heating curve keeps indoor temperature homogeneously distributed around the set-point for all the outdoor temperatures, however in Fig.44 is evident how, on average, $T_{\text{room}}$ is higher if solar radiation is higher. Even with the proper $T_{\text{supply}}$, discomfort can be reached if there is a high level of solar radiation (Fig.45). The algorithm can fix the curve also in response to the effect of solar radiation, but in this way, the adjustment creates discomfort for the same outdoor temperatures when radiation is not present. A smarter solution to this problem, is the so-called “solar compensation”: heating curve is temporary shifted down in proportion to solar radiation values; this preserves comfort and guarantees savings.
Figure 44: Comparison between indoor temperature and specific average solar radiation for a range of outdoor temperatures going from -20°C to 15°C.

Figure 45: Example of coincidence between indoor temperature peaks and solar radiation peaks.
Chapter 4: Results

4.1 Tests description

For the four building models, simulations are performed with the 5-points curve, introduced in the previous chapters (Fig.28), and a reference heating curve represented by a straight line (Fig. 46): as for the 5-points curve, temperature levels depend on the type of distribution system however, this configuration does not take into consideration differences among buildings. After comparing the results, the potential benefits exploiting the algorithm are investigated.

![Diagram](image.png)

*Figure 46: Definition of reference heating curve both for a building with radiators and a building with floor heating.*

4.2 Performance indexes

Comparisons involve both energy savings and comfort, for this reason two indexes are adopted: the already mentioned seasonal performance factor (SPF) (21) and the dead-band deviation (DBD) as concerns comfort. DBD expresses in a single value how much is the deviation and for how long it happens (22), therefore the lower is DBD the greater is comfort

$$\text{SPF} = \frac{\int \dot{Q}_{\text{cond}}}{\int \dot{P}_{\text{comp}}}$$ \hspace{1cm} (21)

$$\text{DBD} = \begin{cases} 
\sum_i (T_{\text{low},i} - T_{\text{act},i}) \cdot (t_i - t_{i-1}) & \text{if } T_{\text{act},i} < T_{\text{low},i} \\
\sum_i (T_{\text{act},i} - T_{\text{up},i}) \cdot (t_i - t_{i-1}) & \text{if } T_{\text{act},i} > T_{\text{up},i}
\end{cases}$$ \hspace{1cm} (22)
Two different acceptability ranges are considered (two different DBD are defined) to show different levels of discomfort:

- **DBD\(_1\)**: half band is 1°C (20°C ± 1°C)
- **DBD\(_2\)**: half band is 2°C (20°C ± 2°C)

The indexes variation is always calculated with respect to the reference curve results:

\[
Deviation_{sp} = \frac{5 - points\ curve - reference\ curve}{reference\ curve} \quad (23)
\]

\[
Deviation_{adj} = \frac{adjusted\ curve - reference\ curve}{reference\ curve} \quad (24)
\]

If deviation is around ±2% it is deemed negligible (unreliable) because in a real situation boundary conditions vary compared to simulated ones and this can slightly change values of performance indexes, nullifying the potential improvements if they are too low.

### 4.3 Comparison 5-points curve vs. reference curve

Tab. 13 shows indexes variation comparing the 5-points curve and the reference curve case (23) for a simulation period that goes from 1\(^{st}\) October to 30\(^{th}\) April. B-class building has no DBD\(_2\) variation because with both curves the value is 0 so (23) has no meaning.

<table>
<thead>
<tr>
<th></th>
<th>D-class</th>
<th>B(_{rad}) - class</th>
<th>B-class</th>
<th>A-class</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPF</td>
<td>-0.5%</td>
<td>0%</td>
<td>-2%</td>
<td>7.3%</td>
</tr>
<tr>
<td>DBD(_1)</td>
<td>-51%</td>
<td>4%</td>
<td>-21%</td>
<td>-99%</td>
</tr>
<tr>
<td>DBD(_2)</td>
<td>-92%</td>
<td>-4%</td>
<td>-</td>
<td>-100%</td>
</tr>
</tbody>
</table>
The most relevant improvements are obtained for the A-class building (energy and comfort) and D-class building (just comfort) while for the others there is no such a difference between the two curves. This outcome can be better understood when the curves are put in the same graph: for D-class and A-class building the difference between them is more evident (Fig.47).

![Graphs showing temperature changes for different class buildings](image)

*Figure 47: Difference between 5-points curve and reference curve for each building model.*

The most important range of outdoor temperatures in this kind of evaluation is the one that goes approximatively from -15°C to 5°C. Temperatures lower than -15°C are infrequent so they do not affect so much the overall performance for the whole heating season. For temperature greater than approximatively 5°C heat pump starts cycling because demand is lower than 30% of peak demand (frequency is lower than minimum frequency).
4.4 Comparison adjusted curve vs. reference curve

Keeping in mind the potential benefits changing the reference curve for A-class and D-class buildings, in this section the results from the application of the algorithm are analysed. Curve is updated every 7 days, deviation is calculated with (24) and the simulation period is the same as before (Tab.14).

<table>
<thead>
<tr>
<th></th>
<th>D-class</th>
<th>B_{rad} - class</th>
<th>B-class</th>
<th>A-class</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPF</td>
<td>-1.9%</td>
<td>0.7%</td>
<td>-3.3%</td>
<td>12.5%</td>
</tr>
<tr>
<td>DBD_1</td>
<td>-69%</td>
<td>-55%</td>
<td>31.2%</td>
<td>-94.5%</td>
</tr>
<tr>
<td>DBD_2</td>
<td>-100%</td>
<td>-100%</td>
<td>-</td>
<td>-100%</td>
</tr>
</tbody>
</table>

The expected effects are achieved and there is also an improvement in comfort for the B_{rad} - class building, while a worsening in performances is observed for B-class building. This is because, for that particular building, the frequency in updating the curve is too low (since the starting situation is not far from the desired one, a too strong corrective action might have a negative effect). Indeed, going from an updating frequency of 7 days to one of 2 days the results improve (SPF= -2.7%, DBD_1 = -2.5%) even though they are still worse than the 5-points curve case. Moreover, solar radiation in April is quite high so all the results could be improved including temporary shifting of the curve.

It is worth noticing that comfort always improves since indoor temperature basically never goes out of the boundaries ± 2°C and energy savings are increased in 1 case over 4.
Conclusions and future developments

This work deals with the modelling of a heat pump heating system for four buildings with different envelopes and different distribution systems. The purpose is showing for each building package (envelope plus distribution system) the effects on performances of adopting two different heating curves (a “reference” heating curve and the one retrieved from simulated data) highlighting what are the potential improvements. Then an adaptive algorithm to adjust the curve is proposed and the achievable benefits with respect to the reference case are analysed.

Simulations showed that:

- In 2 cases over 4 the reference heating curve can be improved
- Applying the algorithm, comfort always improves (in particular temperature never goes out of the boundaries ± 2°C)
- Applying the algorithm, the variation in SPF can be considered not relevant apart from the A-class building where the increase is 12.5%
- Due to thermal inertia the corrections are concentrated in the range of outdoor temperatures which are more common during the examined period, producing a jagged profile in the adjusted curve; however, with the 5-coefficients version of the algorithm this effect is decreased.
- In the presented tests, the algorithm updates the curve every 7 days, but this parameter can be changed according to the situation. If no specific information is provided, updating frequency should be set to a higher value (ex. every 3 days)
- To refine the algorithm, solar compensation should be included otherwise the adjustments can create discomfort for the same outdoor temperatures when solar radiation is not present

Future developments

It would be interesting understand how time constant values vary changing test’s boundary conditions (assess reliability). The knowledge of building thermal inertia can be used in different ways:

- To adjust the algorithm parameters to that specific building and enhance its effects
- To plan off periods for the heat pump to cope with the absence of the user or with ancillary services in a smart-grid perspective

Another aspect to further investigate is solar compensation to avoid unnecessary modifications to the heating curve.
Bibliography


[12] H. Madani, J. Claesson, and P. Lundqvist, "Capacity control in ground source heat pump systems part II: Comparative analysis between on/off controlled and variable


