On the use of numerical simulation for the improvement of the conception and operation of energy systems in buildings and communities

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Preface

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I also want to thank my parents, my family, my friends for supporting me in so many ways. And finally, a special thanks to my wife and my children, who were particularly exposed to disturbances during the preparation of this report.

Content

ABSTRACT

To date, the building sector represents more than 40% of the final energy consumption in France (and also in Europe) and represents thus one of the key responsibles of greenhouse gas emissions.

The ratio of the energy consumption of the building sector is continuously increasing with about 1% per year.

As an example, in the residential sector, energy for heating and the production of domestic hot water represents approximately 85% of the global final energy consumption.

Many research and actions have been carried out on the optimisation of building envelopes and components of energy systems. However, although a great potential of energy reduction has been shown in theory, the topic of energy systems and their control and management is still too much left aside.

A change of this situation has recently started by:

- The start of energy performance contracts of buildings which, by nature, must include energy management in the risk analysis

- The initiative of “smart grid” projects that aim in the optimisation of energy fluxes on a building, district level and even community level

- In general, the efforts in terms of energy efficiency and REN&R systems have been enlarged from a building level to the neighbourhood, district or even city level.

The research undertaken and presented in this report is completely in line with the objective of the improvement of energy management and the rational use of fossil energy (and thus the increase of REN&R sources) in buildings, districts and cities.

The document presents this work in four main chapters:

- a typology of energy systems and the French building stock as well as statements on the improvement potential of their conception, energy management and control.

- tools and methods that have been developed for the conception, test and optimisation of the control and energy management of systems. These tools are a) numerical simulation, b) in-situ or lab evaluation and c) hardware in the loop approaches.

- modelling/simulation approaches and suggested modelling choices depending on the simulation objectives.

- specific adaptations of these tools for testing control systems and some examples of innovative optimisation algorithms.

This works tends to present an overview on energy systems and particularly the use of numerical simulation to increase energy efficiency at system, building and district level.

In the last paragraph on perspectives, approaches that could be undertaken in the future to ensure better accuracy of numerical simulation are presented.

INTRODUCTION

Numerical simulation is being developed since the early 80’s [Klein et al., 1980] in order to assist in better conception, energy management and control of energy systems in buildings.

Since this period of first models, mainly due to better calculation performances, the level of detail of modelling is still increasing. From first R-C models, based on electrical-thermal analogy (which remain still a good choice in many cases), we have arrived at a point where calculation time and effort is not the main issue anymore, except for CFD calculations in specific configurations such as natural ventilation for example. The modelling and simulation community is thus changing from the research that has been oriented by the main question “how can we reduce the level of detail of all phenomena to be able to calculate a problem” to the opposite which is “now that we are able to calculate all in detail, how can we obtain all the necessary parameters to run the calculations”.

The main question today is thus not anymore how to describe physics in a simplified way, to be able to obtain a result in an acceptable time, but how to really profit from these more detailed models that we use.

On the other hand, simulation could and should be used more and more to assist different processes in the planning, construction and operation phase of an energy system. This includes also to assist in the development of appropriated test facilities for testing energy system performances that get more and more complex. In recent developments, since the late 1990’s, emulation, which is itself a simulation approach, gets more and more popular and needs the use of simulation models with an appropriate level of detail related to the objectives of the study.

The objective of this document is thus to underline the great potential that provides numerical simulation and to try to give some advices on the good modelling options, depending on the simulation objectives.

Fields where numerical simulation should be better integrated in the global process can be found in the whole life cycle of an energy system: planning, conception, sizing and operation do to date not profit fully from the huge potential of numerical simulation.

In the planning and conception stage, better and more appropriated tools are needed, mainly by adapting the user interfaces closely to the user needs and thus making their use less dependent on the user and thus the global process more efficient. Uncertainty has also to be part of the simulation tool by providing not a fixed value for the result anymore, but a range (or area or volume) in where real results are thought to be located in.

Sizing of equipment also needs more appropriated tools. In many cases of small buildings, sizing is done by using very simple rules. Numerical simulation, if the associated additional costs could be managed, would be a very good option. This can be done during the conception process if simulation tools are automatically included.

In the operation phase, again, the role of numerical simulation must obtain a bigger role if we want to go towards an optimised control and energy management strategy. This process is fully ongoing to date with the development and generalisation of low-cost (also called smart) metering solutions thus allowing their widespread use. The large number of available data allows data scientists to suggest new control algorithms combining low-cost monitoring with advances software algorithms. These control algorithms give the new potential to not only measure and identify bad performances, but to fully implement corrective measures in real time and in a closed-loop and even predictive methodology. The potential of improvement in the global efficiency of energy systems can then be significant in many cases.

Also, in the case of classic (reactive) control algorithms (proportional, integral, derivative and combinations of them), simulation could be used for the online tuning of the optimal parameters.

However, to trust blind in data science with the aim of converting bad installations into performing ones is a big error. The role of data science should be to optimise an installation that has been properly designed and sized and not to solve errors in conception and sizing or bad performances that have not been understood otherwise.

Globally we can state that simulation can represent an extremely cost and time effective way to improve the performance of energy systems. It is also the main subject of this document that is meant to help in modelling and simulation choices in the real world.

The next paragraph on the objectives of this document will clearly define the specific objectives of this document.

OBJECTIVES OF THIS REPORT

As stated in the introduction, this document shall give advice and examples on the appropriate use of numerical simulation depending on simulation objectives.

The main objectives of this document are thus to:

- identify problems of the real “energy system” world and approximately situate potential gains
- present methods for the improvement of energy systems
- select appropriated simulation models and tools
- present examples of application of the approach

To reach these objectives, the document is divided into four main chapters:

- a description of the energy systems in the French building stock is given in the first chapter of the document completed with statements on the improvement potential of energy management and control.
- tools and methods that have been developed for the test and optimisation of the control and energy management of systems. These tools are a) numerical simulation, b) in-situ or lab evaluation and c) hardware in the loop approaches.
- modelling/simulation approaches and suggested modelling choices coherent with simulation objectives and accuracy.
- specific adaptations and implementations of these tools for different use cases, for illustration purposes.

CHAPTER I

IDENTIFICATION OF PROBLEMS AND POTENTIALS

This chapter introduces thermal energy systems for buildings and communities, typical sources of bad performances and a quantification of potential gains.

The chapter focusses on energy systems based on hydronic energy distribution, but the main conclusions are similar for air or refrigerant based distribution.

System typologies are briefly introduced as well as their approximate market share.

An overview of reasons for bad performances is given and potential improvements are introduced.

1. SYSTEM TYPOLOGIES AND ANALYSIS OF POTENTIAL IMPROVEMENTS

1.1 INTRODUCTION ON HEATING, COOLING AND DHW SYSTEMS

A generic layout of district energy systems has been developed to allow districts to be compared on a harmonised basis. This layout, presented in *Figure **1***, includes the components on the central level as well as on the building level.

Components on the central level can be:

- Heat production: Waste heat, boiler, solar thermal, combined heat and power (CHP)
- Heat storage: direct, short-term storage for heat and cold
- Seasonal storage, ambient or waste energy: thermal storage in the ground (or aquifer) or in other long-term storage, ambient air, low enthalpy waste heat, via direct use or heat pumps
- Electricity production: Solar PV, wind
- Electricity storage/consumption: vehicles, hydrothermal storages etc.

Components on the local, building level:

- Heat production: Waste heat, boiler, solar thermal, CHP, heat pumps
- Heat storage: direct, short-term storage for heat and cold
- Electricity production: Solar PV, wind
- Electricity storage/consumption: vehicles, electrical storages etc.

The fuel types for heat and power production can be fossil, waste or renewable, on a central and local level.

Any line in the layout represents a “distribution” which is also part of the global energy system.

Such a layout can be very helpful in understanding energy concepts on a district level and even more important, to show differences between different energy concepts that are typically shown in rather detailed and specific layouts.

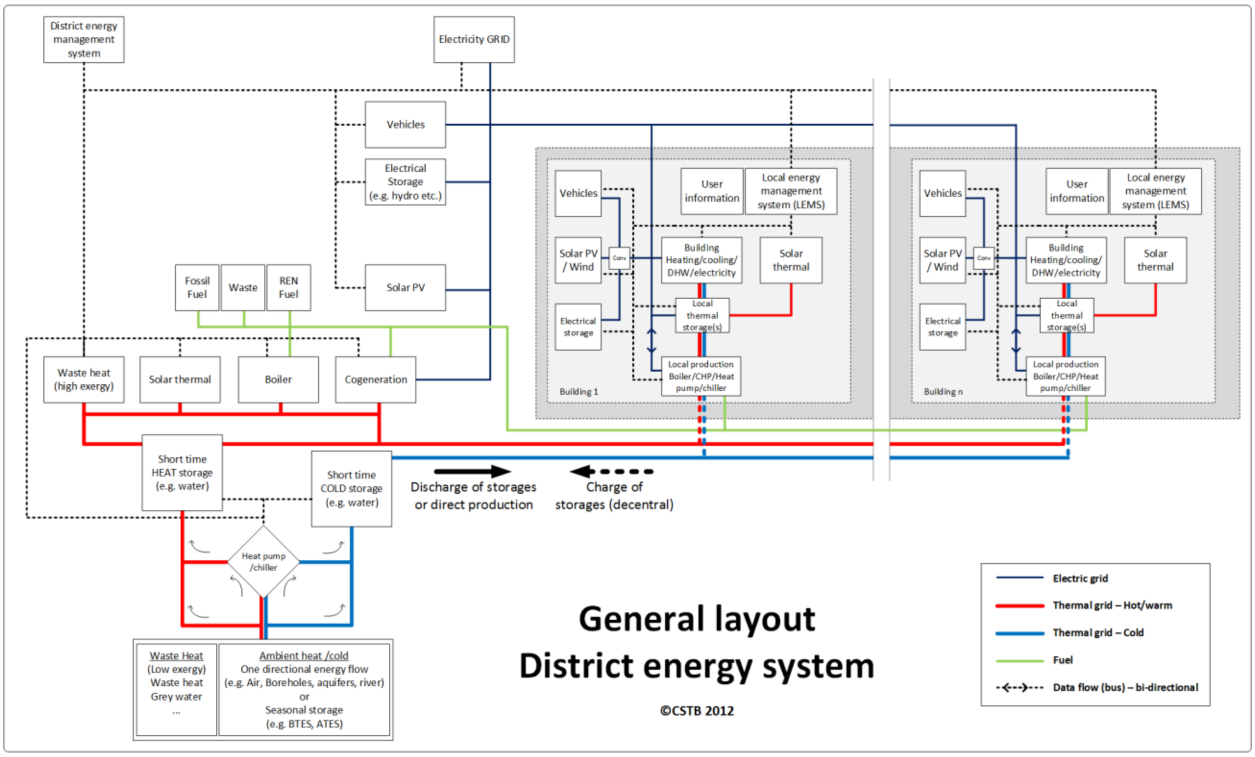


Figure 1 : Energy system at different levels (district, building, building zone)

In the following paragraphs, the most typical systems on a zone, building and district level are introduced.

On each of these different levels (zone, building and district), the energy chain can be structured as follows (*Figure* ***2***):

- **Generation** of heat, cold or electricity:

  The generation is to be understood as a transformation from the energy input (gas, fuel, electricity) to heat, cold or electricity as energy output for the connected district, building or building zone energy system.

- **Distribution**:

  The energy output from the generation will be the energy input into the distribution level. The main vectors of distribution are fuel, air, water or electricity.

- **Delivery** (Emission, or transmission to a successive element such as a substation etc.)

  In this last stage, the generated and transported energy will be delivered to the user. The user can for example be a thermal zone where heat is to be delivered.

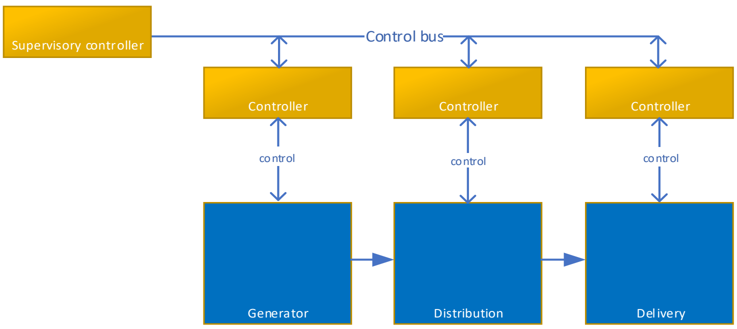


Figure 2 : General delivery chain

These 3 levels can be applied, as mentioned before, to any level of the district energy supply chain: district, building and zone. In the case of the district, for example, the delivery will be the substations on the building level (thus as a “generator” for the building).

Energy storage can be located at any of these three levels. It is sometimes automatically included in the inertia of the system (e.g., thermal hydronic network) or explicitly added for control issues or for storing fluctuating energy from renewable or heat recovery sources.

The definition of these elements is illustrated for the declinations of zone, building and district in *Figure **3*** - *Figure **6***. These definitions of borders will allow later also to define efficiencies on each level as well as to properly structure any system simulation model.

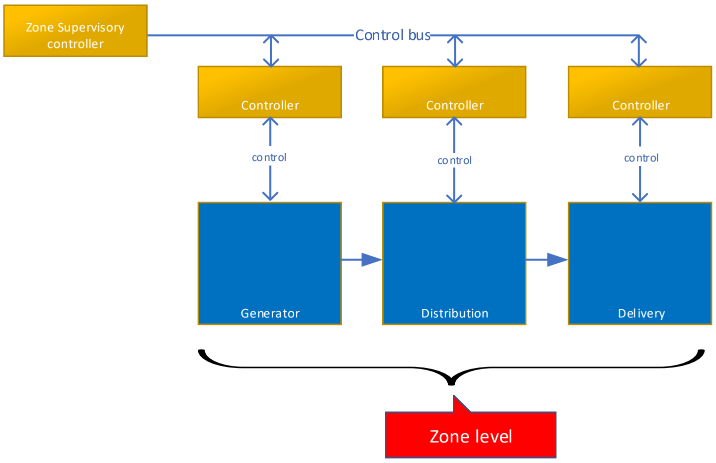


Figure 3 : Zone level delivery chain

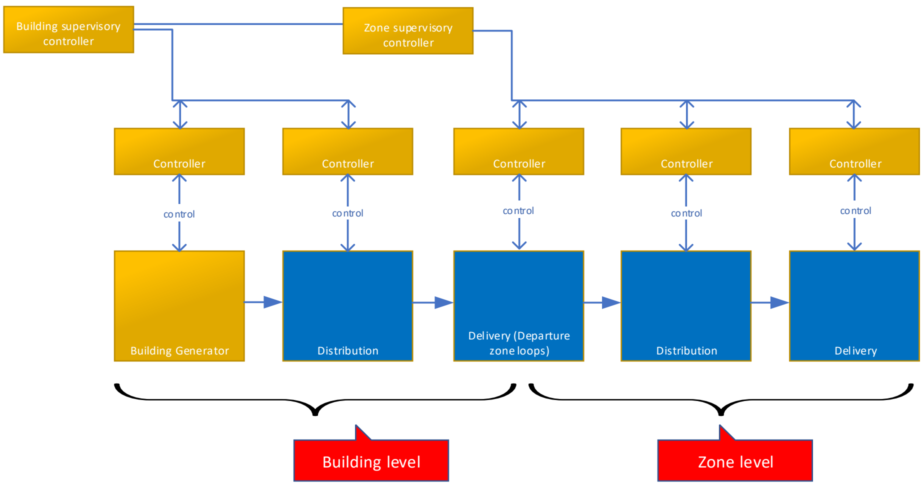


Figure 4 : Building level delivery chain

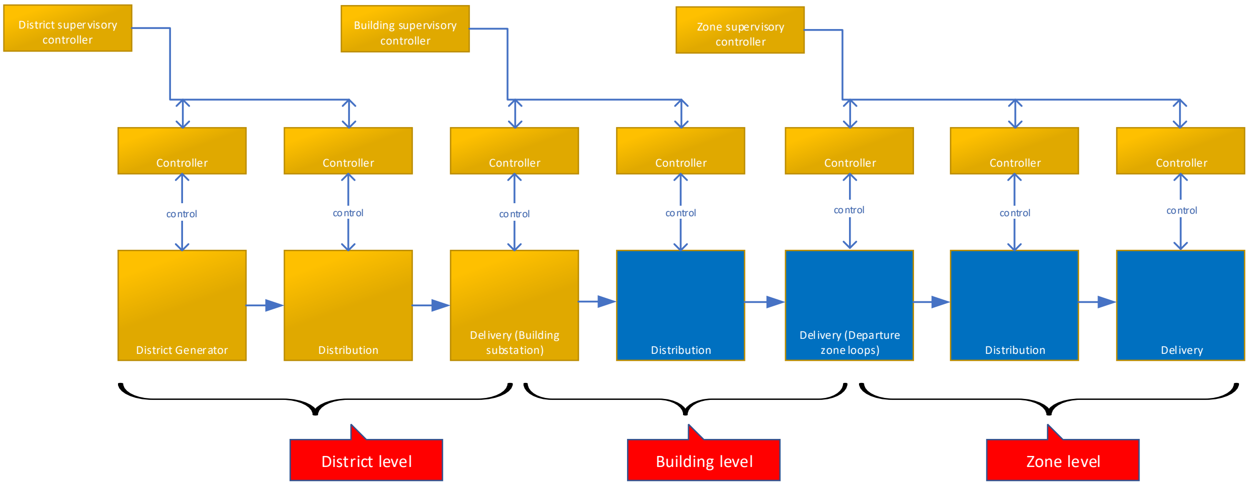


Figure 5 : District level delivery chain

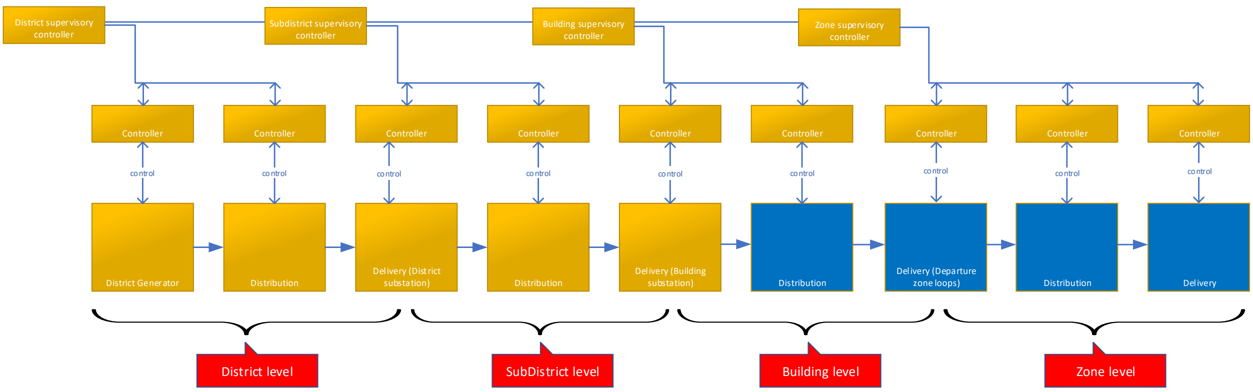


Figure 6 : District level delivery chain with subdistrict

It is important to mention here that the addition of levels in this energy chain (e.g., *Figure **6***) adds a lot of additional energy input for distribution and more complexity on the control level. From an energy performance point of view, it will, in almost all cases, be the best solution to produce energy as close as possible to the requested energy delivery. This will minimise at the same time auxiliary energy and complexity of control. With the increasing interest in what is called "smart" algorithms, which tent to optimise all control signals as a whole (either in a global optimisation or an optimisation of grouped components) and the wish to operate complex systems close to "perfection", people will be more and more push to complex energy systems. This fact is from my point of view very dangerous since one believes that for any system, smartness will render any energy system efficient, which is wrong. And with the wish of creating energy networks to share renewable or heat recovery sources, all energy systems risk to get very complex and require smartness (or better artificial intelligence). And not forget that auxiliaries for networks and control of water or air networks are not at all on the same level of performance as electricity networks.

On the other hand, it would be simple to create energy efficient systems that are only implemented on the local level, without pushing too far into smart algorithms.

1.2 ZONE AND BUILDING LEVEL ENERGY SYSTEMS

1.2.1 ZONE-LEVEL ENERGY SYSTEMS

As already introduced, the zone level energy system can be divided into production, distribution and delivery (or also emission in the case of heating or cooling).

Energy production on the zone level is mainly in one of the following categories:

- Combustion of fossil or renewable fuels (gas or oil in boilers, cogeneration units etc.)
- Thermodynamic systems
- Solar thermal and/or electrical systems (in general assisted by one of the two previous categories as backup)

All of them are used for either heating, cooling or for domestic hot water production.

Recently, other renewable energy sources or heat recovery solutions have been initiated, but these are mainly coupled as source for thermodynamic systems (e.g., geothermal energy sources) or to diminish the heating or cooling load (pre-conditioning of air for ventilation).

From the point of view of the energy distribution four main types can be distinguished:

- Hydronic distribution (this can be the distribution to hot water radiator, fan coil units or also, in case of air conditioning systems, to the coils of terminal units);
- Electric distribution with electric heat emitters (very common system in the building stock in France);
- Refrigerant distribution (this can include air conditioning systems on a local level, air conditioners as split or multi-split or monobloc consoles. In the latter case production, distribution and delivery is almost all implemented in a single unit);
- Central air conditioning systems with pre-treated air distribution.

Of course, mixtures of the above types exist e.g., pre-treated air distribution coupled with hydronic or electric distribution. An example for this is the use of a constant or variable air handling unit with terminal units (equipped with water/air or electricity/air heat exchangers).

From the point of view of the energy delivery (heat or cold emission), two main categories can be defined:

- Emitters based on a mix of radiation and natural convection (hot water radiator, convector, floor heating etc.)
- Emitters based on forced convention (fan coil units, air conditioners etc.)

Even if the market suggests products called radiation panels, this category does not really exist since they are basically included in the first category. Any hot or cold panel transferring radiation does also emit at least parts of its heat or cold by natural convection. The share between the radiative and convective part depends on many local boundary conditions (e.g., a floor heating system is often considered as a radiative emitter; but depending on the air circulation of the room, for instance generated by a cold wall or window, the convective share can be more or less important. In general, it varies between a 20% - 40% share of convective heat exchange (the linearized heat exchange coefficient by radiation can be estimated to about 5.5 $W/m^2/K$ while the convective heat exchange coefficient can vary between about 1-3 $W/m^2/K$ for floor heating).

The simplified layout of a zone level energy system is presented in *Figure 7*. It shows the three levels which are production, distribution and delivery for the example of heating and DHW delivery. In the latter case an additional distribution may exists (circulation) for a faster availability of hot water, especially in zone with larger distribution lengths. The corresponding circulation pump must then be equipped by a time-dependent program in order to keep the heat losses and auxiliary electrical energy on a reasonable level.

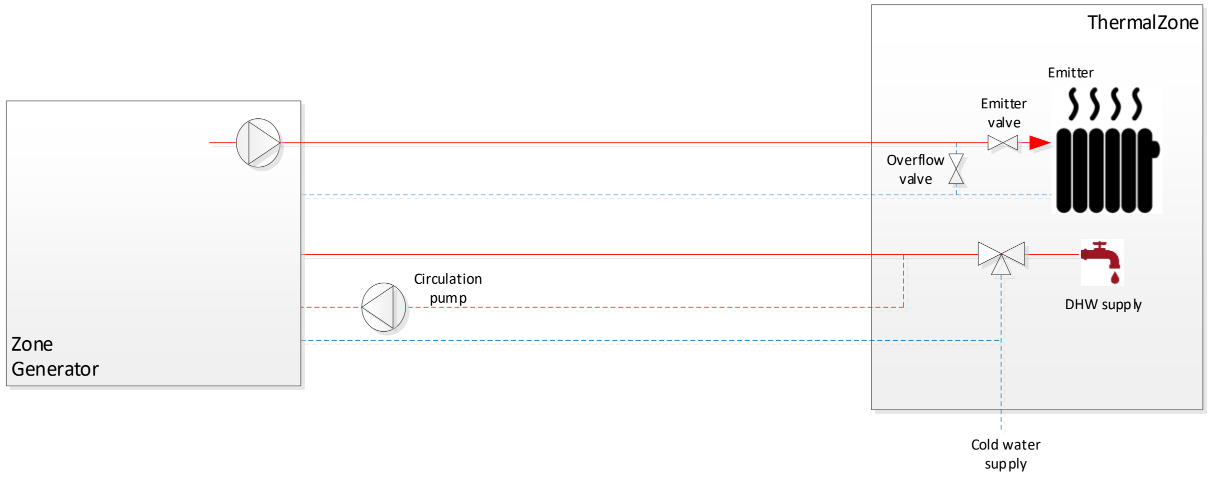


Figure 7 : Energy system at zone level (example for hydronic systems)

A more complex example of a zone system is shown in *Figure 8* for the case of a so-called heat interface unit that assumes the production at a higher or centralised level (building or district level). However, distribution and delivery remain similar to the simple case. The production will be allowed by heat exchangers or storage tanks that receive the energy from an upper level. Compared to the classic building level system, this configuration has the advantage of an independent control on the zone level.

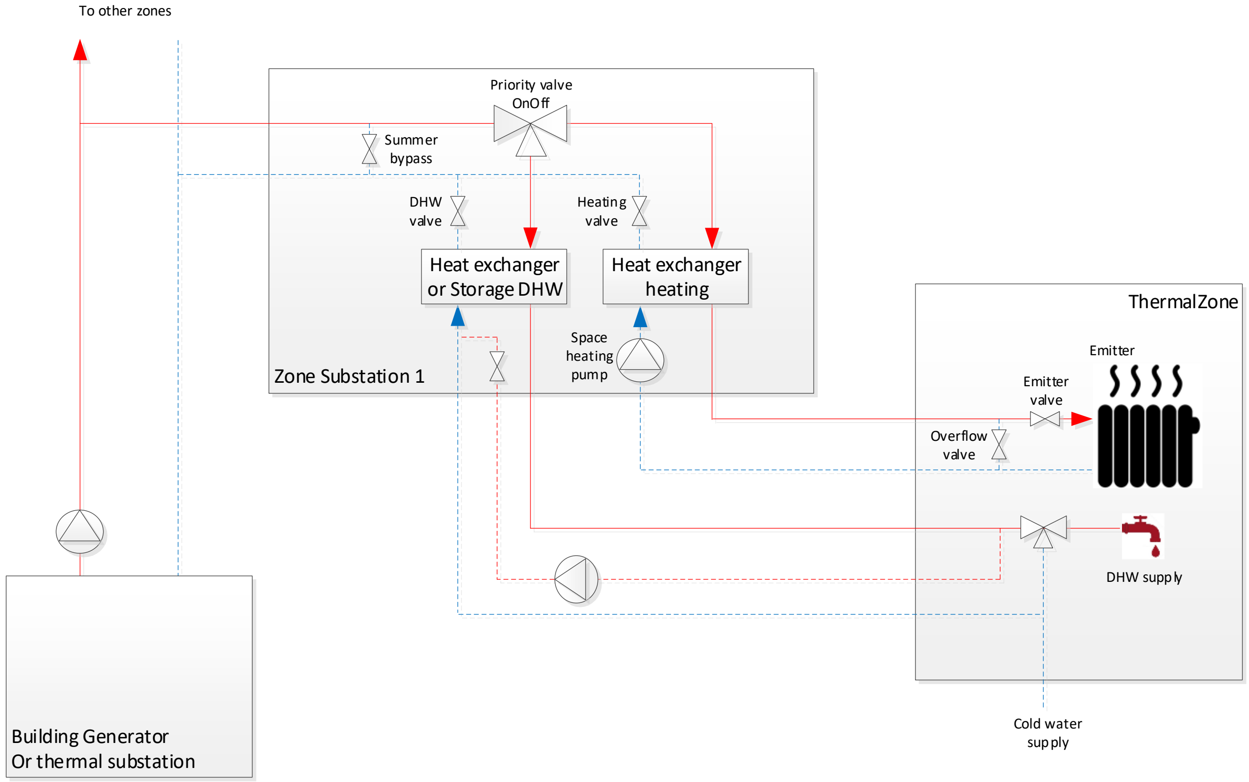


Figure 8 : Energy system at building level, substation at zone level (heat interface unit)

A last example is related to the production part. This can be of two types:

- Monovalent production (one single production unit)
- Bivalent production (two components acting as base and backup system as show in *Figure* ***9***. Remark: this example also presents the combination with a thermal energy storage which is the most representative case for bivalent systems. The base generator can for example be solar thermal panels and the backup generator a boiler).

Storages can either be used for a single purpose (heating only, cooling only, DHW only) or combined for heating and DHW as shown in *Figure* ***9***. The choice for a single purpose and combined one depends on several criteria or parameters and is in many cases chosen either by experience or using numerical simulation.

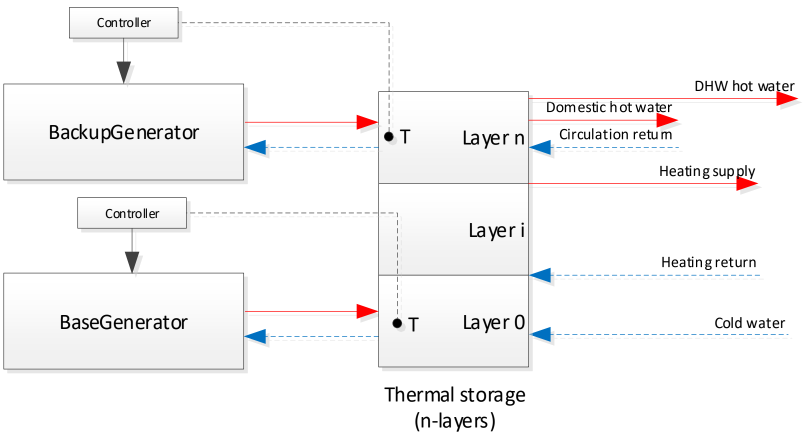


Figure 9 : Combined heating and domestic hot water production at zone or building level (idealised layout without necessary heat exchangers)

1.2.2 BUILDING-LEVEL ENERGY SYSTEMS

The case of building level energy systems is not so different from those on a zone level from the point of view of production and delivery. The main difference lies in the distribution part: additional components and controls are added in order to adjust states of the energy distribution vector (hydronic, refrigerant or air) to be distributed. For the example of a building with Northern and Southern facades and thus thermally different zones, supply temperature can be better adjusted to the zone energy demand (which might not be done in case of zone systems since they consider a zone not necessarily from a thermal point of view). Its complexity can also be simplified if heat interface units (zone substations) are used, as described previously.

In the example of *Figure **10*** the additional components are 3-way-valves and distribution pumps in order to set a heating law that allows better control and higher performances of the complete energy system. However, additional control is necessary which results in more potential errors in controls or faults and higher maintenance efforts.

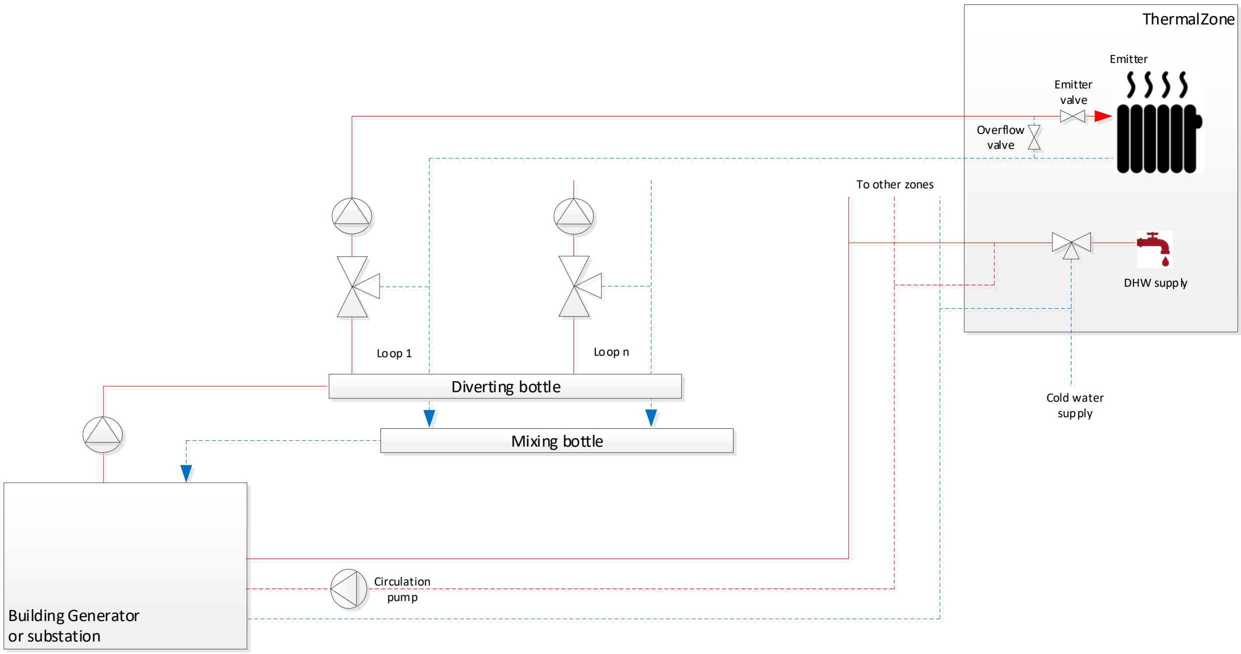


Figure 10 : Energy system at building level

A specific (and still quite rare case) for a building system is the thermo-refrigerating heat pump (*Figure **11***). The advantage of this system is that, for parallel heating (or DHW) and cooling loads, a heat pump is plugged in between these loads. The heat pump driving energy is thus used once, but for both hot and cold generation. The resulting efficiency is very attractive. The necessary heat input on heat sink or heat source side is diminished and can even be 0 in the extreme case. If not, it might be delivered from a district energy network (typically heat sharing networks with very low temperatures). Again, numerical simulation is a perfect method in this case to conceive and size such systems.

The example also shows the combination with a backup and storage for DHW production.

The building level energy system represents thus the following advantages: it allows more complex production systems that would be too complicated and expensive on a zone level, and it profits from a smoother load profile than a single zone. On the other hand, it adds additional components and controls as well as necessary energy input for the energy distribution.

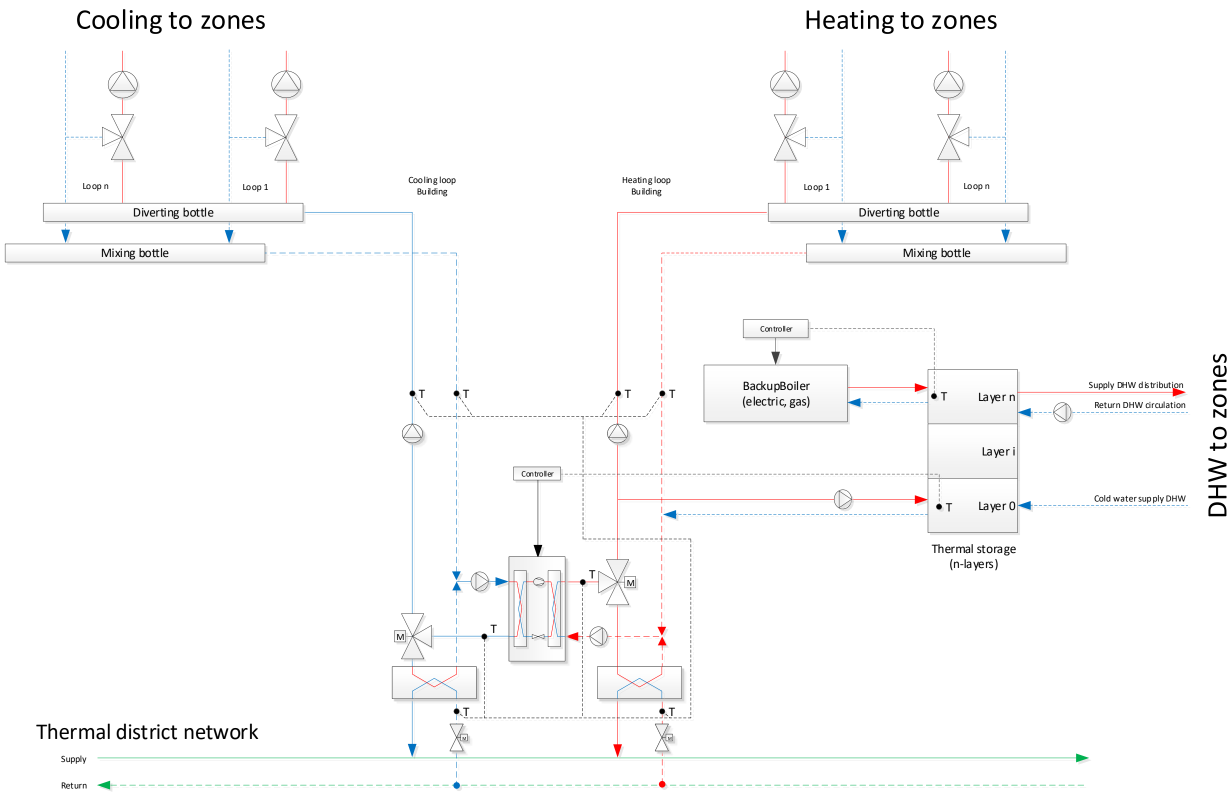


Figure 11 : Multigeneration energy system thermo-refrigerating heat pump

1.3 DISTRICT THERMAL SYSTEMS

The district thermal system is, as the other levels, composed of:

- Production: In most (hopefully) cases of a district thermal energy system, the production will be different to those on a building and zone level. Typical examples are geothermal or heat recovery sources that would be too expensive for their use in a single building. Since these sources are almost for free (except auxiliary energies to pump the working fluid), they make sense in a district energy system. Other examples are larger cogeneration units with fossil or renewable fuels.

  However, with the decreasing heating demand in the buildings (and thus lower power densities), the net advantage of a district thermal energy system has to be verified since thermal losses in the network and the necessary auxiliary energy might render such an installation les performing than a building or zone level system.

  An advantage is the relocation of the energy source on a centralised level (and so just 1 source instead of several sources) which makes this solution interesting for modern urban planning.

- Distribution: the distribution in district heating systems has the following differences to those on building and zone level:

  - The pipes are generally installed in the ground; heat losses are thus really lost, which is not always the case in buildings or zones;
  - Transportation distances are larger, i.e., auxiliary energy consumption and losses must not be neglected;
  - Piping configurations can be different with the use of specific arrangements with high, medium and low temperature tubes. Depending on the use and control, supply and return of a component can be plugged to each of these three temperature levels. Many different network structures are available with 1 or 2 level thermal networks (*Figure **12*** or *Figure **13***);
  - Since district heating is generally based on energy supply contracts, supply and return temperature levels are precisely defined in contracts to secure energy supply. However, this might not be the optimal temperature regimes for ensuring maximum performances. On the other hand, new piping concepts allow very performing concepts such as heat pumps that can be plugged to the network pipes for achieving better performances.
  - Network temperatures are more and more reduced (from 1G to 4 or 5G network concepts) in order to reduce thermal losses and increase energy performance. However, this requires the compatibility of building, zone and network temperatures and potential adaptations (building renovation etc.).

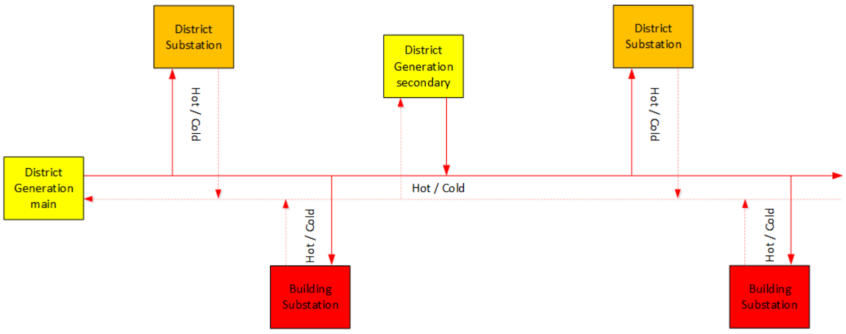


Figure 12 : District thermal network with district and building substations

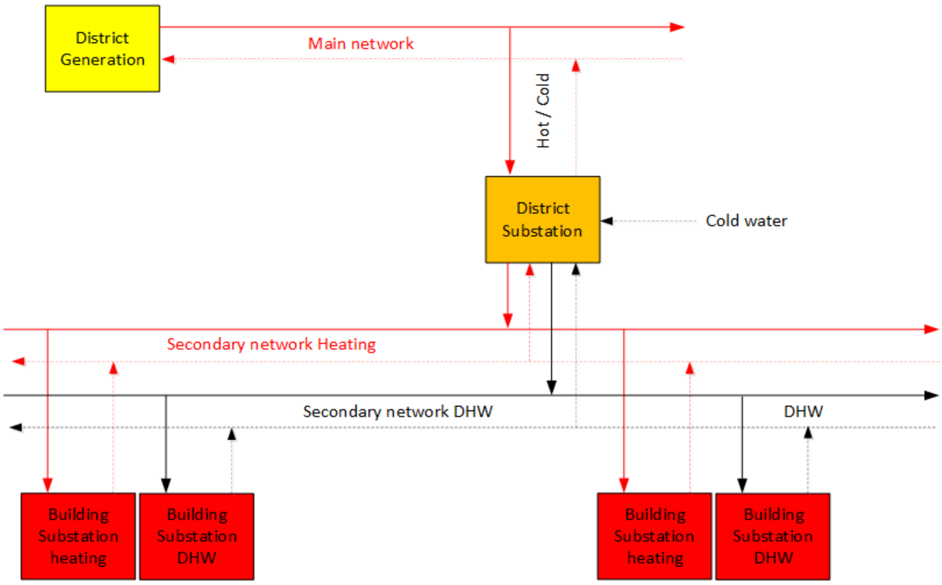


Figure 13 : District thermal network with parallel sub-networks

- Delivery:

The delivery in district thermal networks is generally ensured by a substation that transfers thermal energy to a lower-level network. This lower-level network is, in most cases, the building thermal network and the substation is thus a “building substation”. If the lower-level network is a secondary district thermal network, the substation is called (in this document) “district substation” and a secondary thermal network will transfer energy to the next level which will be on the building level. All principal substation arrangements are presented in *Figure* ***14***.

3 main types can be distinguished:

- Direct connection: the heat transfer fluid is the same in the upper and lower-level network;
- Heat exchangers for hydraulic separation of heat transfer fluid of the upper and lower-level network;
- Thermodynamic substations in which the upper and lower-level network consists in the heat source ad heat sink of a heat pump. This can also be combined with a direct heat exchanger configuration and the thermo-refrigerating heat pump principle if two lower-level networks are connected.

Apart from the components and heat exchange applied, a second factor is the use of constant or variable flow configurations. Variable flow configurations allow the reduction of auxiliary energy for pumping, especially in mid-season. The latter solution should be preferred.

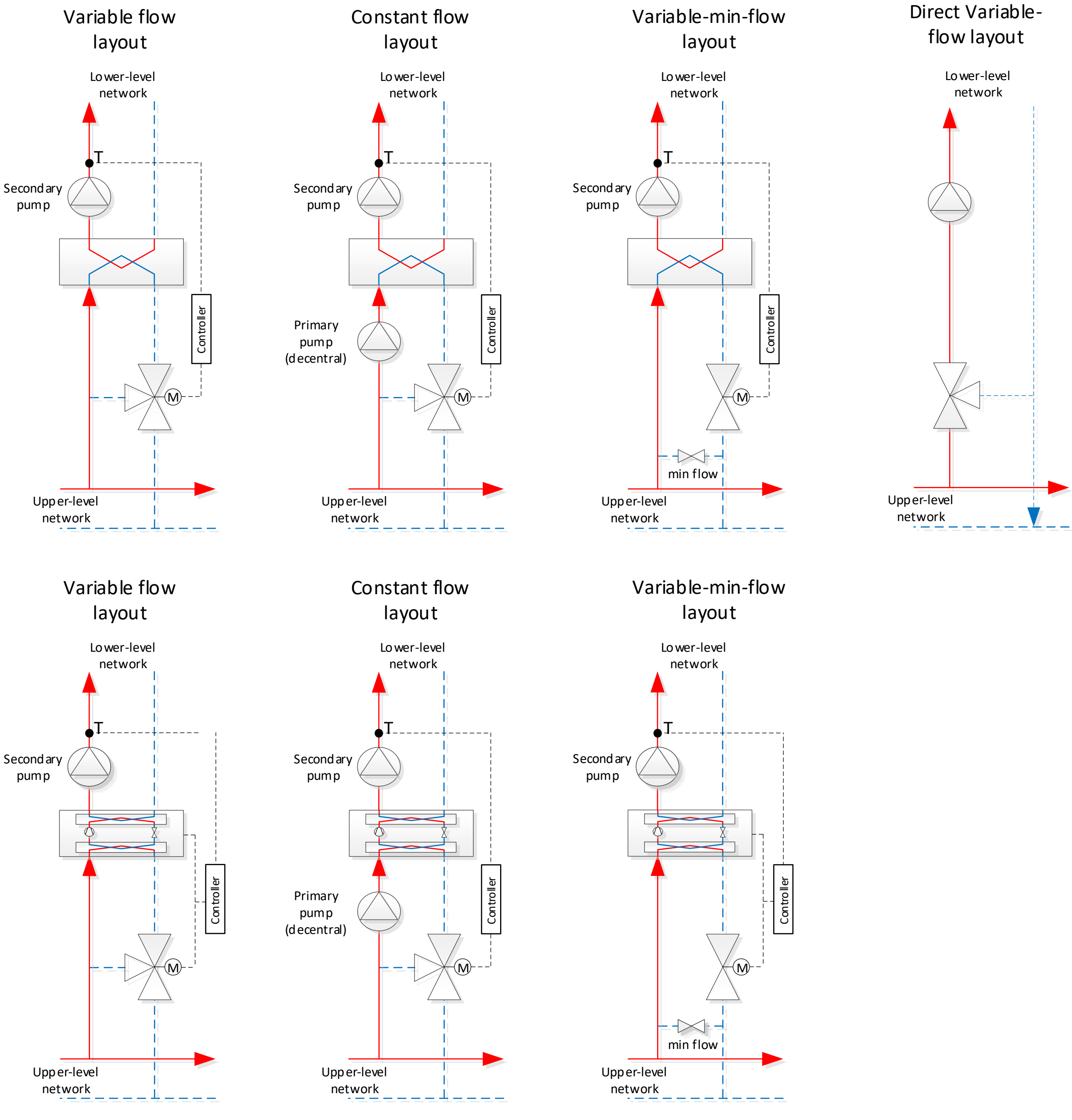


Figure 14 : Thermal substation – main configurations (simplified layout)

1.4 BUILDING CHARACTERISTICS, SYSTEM TYPOLOGIES AND MARKET SHARE IN FRANCE

This paragraph is not intended to deliver a complete analysis of the French market share of system topologies but to give some orders of magnitude of the share of typical systems.

This is necessary in order to develop tools and methods which are appropriated to the building and system sector that will have the highest impact on climate change. In the case of new constructions, it is important to follow innovative technologies on the market. But for existing buildings and their renovation, these tools and methods must be applicable to the most strategic technologies, the knowledge of the existing building parc is thus mandatory.

In France, in 2017[1], heat represented about 52% of the global energy consumption[2] (153.6 Mtep) in France, corresponding to 80 Mtep. The residential and tertiary building sectors were responsible for about 2/3 of the national heat consumption (53 Mtep or 619 TWh).

From these 619 TWh, 4% i.e. 25.4 TWh have been used for distributing heat in district heating networks. The remaining 96% were thus consumed for individual building or zone energy systems.

The following sections will give a short overview, limited to the residential sector, of the characteristics of buildings and the energy system related to heating. The data is taken from the Phébus project[3] from 2013. Even not updated, this gives an acceptable vision of buildings and system typologies.

It is not intended here to deliver a detailed analysis of the French market share of system topologies but to give some orders of magnitude of the share of typical systems.

1.5 BUILDING TYPES IN FRANCE

*Figure **15*** - *Figure **17*** show the characteristics of the French residential building park in 2013.

Besides detail on the floor area of dwellings, two very interesting facts can be highlighted:

- 80% of the building stock has been built before 1990 and is thus characterised by poor energy performances (except those that have already been renovated).
- Almost 60% of all dwellings are located in the H1 climatic zone, which is the coldest one in France. If renovation shall be done, the climate must be considered, to guarantee good performances after renovation.

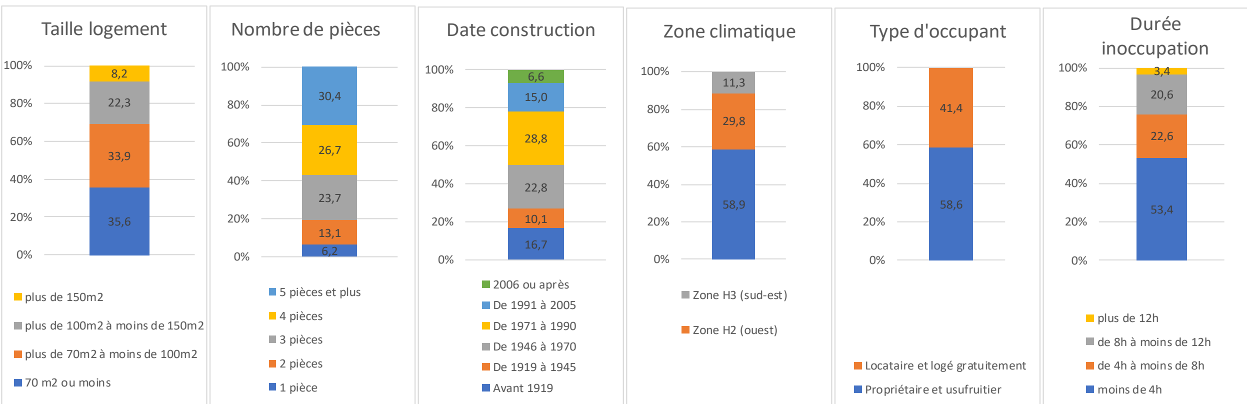


Figure 15 : All dwellings (individual and collective)

[1] http://reseaux-chaleur.cerema.fr/les-chiffres-cles-de-lenergie-edition-2018
[2] Consumption must be distinguished from production
[3] Phébus : https://www.statistiques.developpement-durable.gouv.fr/enquete-performance-de-lhabitat-equipements-besoins-et-usages-de-lenergie-phebus

The detailed data is presented hereunder for individual housing (Figure 16) and residential collective (Figure 17).

For the entire France, individual housing represents 58% of all dwellings, residential collective 42%.

The main differences between these two categories are:

- The floor area in individual housing is significantly bigger than in the collective sector
- The share of dwelling owners and landlords is almost proportionally inversed between both categories.

The age distribution of dwellings is similar in both cases.

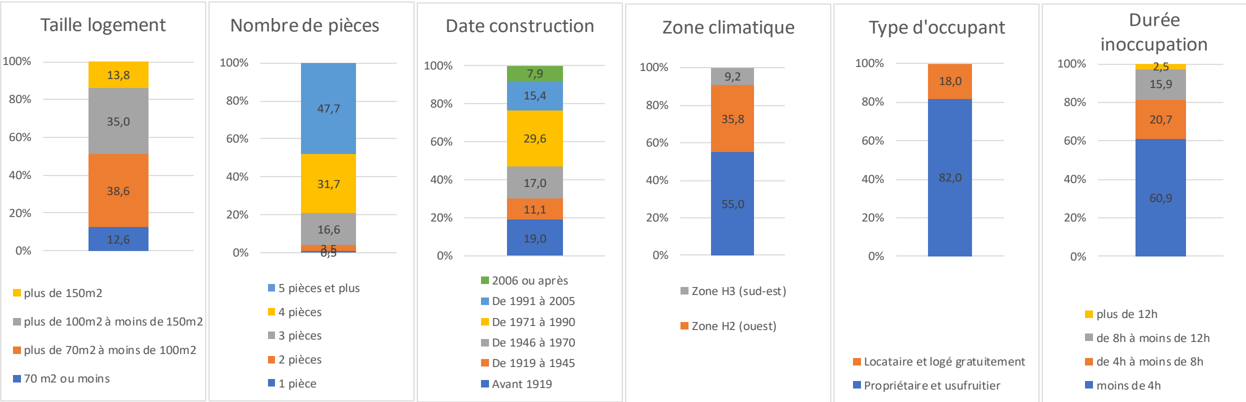


Figure 16 : Individual housing

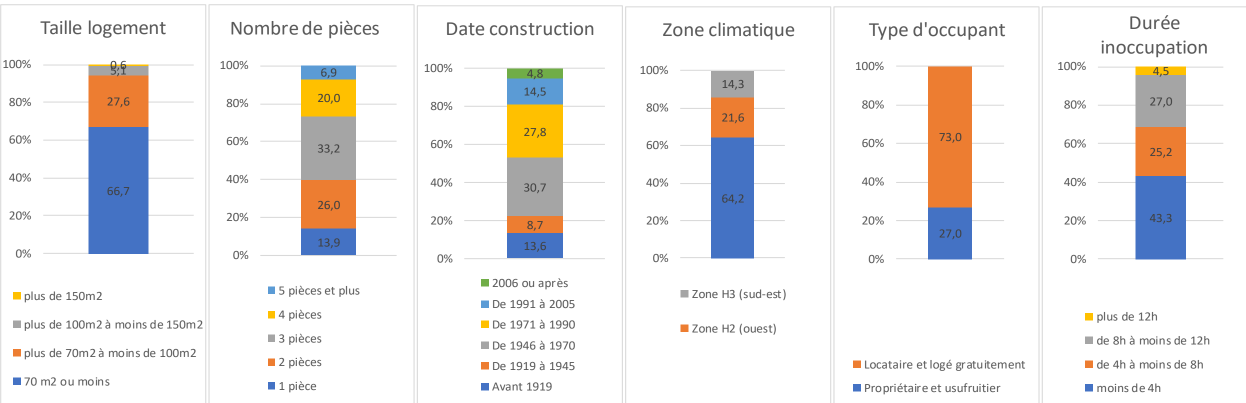
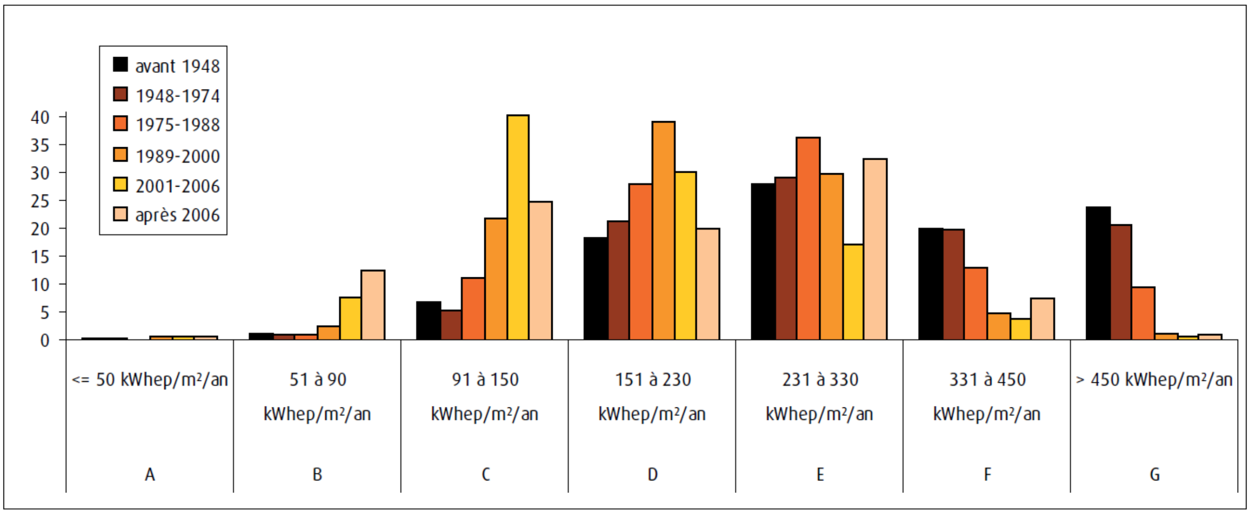


Figure 17 : Residential collective

Related to the energy performance of the French building parc, *Figure* ***18*** and *Figure* ***19*** resume the energy performance class of heating and DHW systems.

While *Figure* ***18*** allows to analyse the performance as function of the building age, *Figure* ***19*** plots, for individual and collective housing as well as for the total building stock, the cumulative curves of the share of buildings less efficient than a specific class. This way of presenting shows the poor energy performance of the French building stock: as an example, 84 % of the total residential building stock are in the classes D-G. The potential of renovation related to climate change impact is thus extremely high.



Source : SOeS, enquête Phébus 2013

Figure 18 : Energy performance of the French building park as function of building age

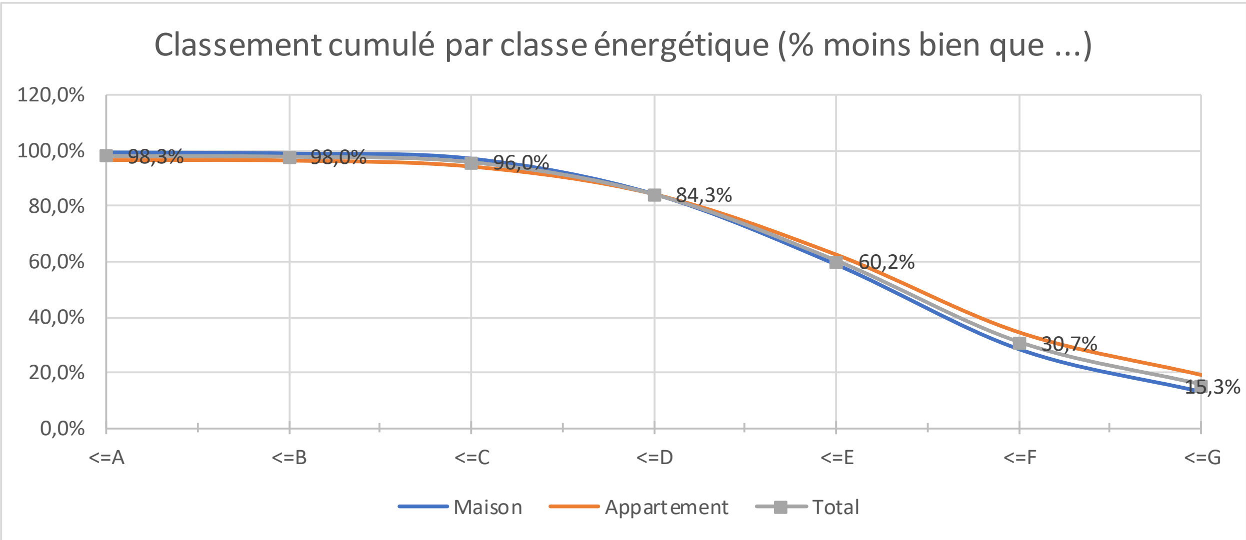


Figure 19 : Energy performance of the French building park (share of buildings worse than …)

1.6 HEATING SYSTEM TYPOLOGIES IN FRANCE

Again, this typology is important when talking about renovation issues. If simulation shall be applied to building renovation, the models must fit to the key characteristics of existing buildings. In France this means for example that the main insulation type is at the internal side of the wall, leading to a relatively high number of thermal bridges.

On the other hand, the knowledge of system typologies is necessary to correctly evaluate potential gains. The tools must be able to correctly simulate the systems typically installed in these buildings, additionally to the new system to be installed. An overview of system typologies in the French building stock is shown in *Figure **20*** and *Figure **21***.

Several key conclusions can be highlighted here:

- The share of central heating systems has diminished from the 80's, due to the development of electric heating systems.
- In small dwellings electric heating is the dominant heating system.
- *Figure **21*** highlights the development of heat pumps from 2016 with a higher share of floor heating systems as emitters and heat pumps as production unit.
- The dominant emitter type for central heating systems is the hydronic radiator (almost 90%)

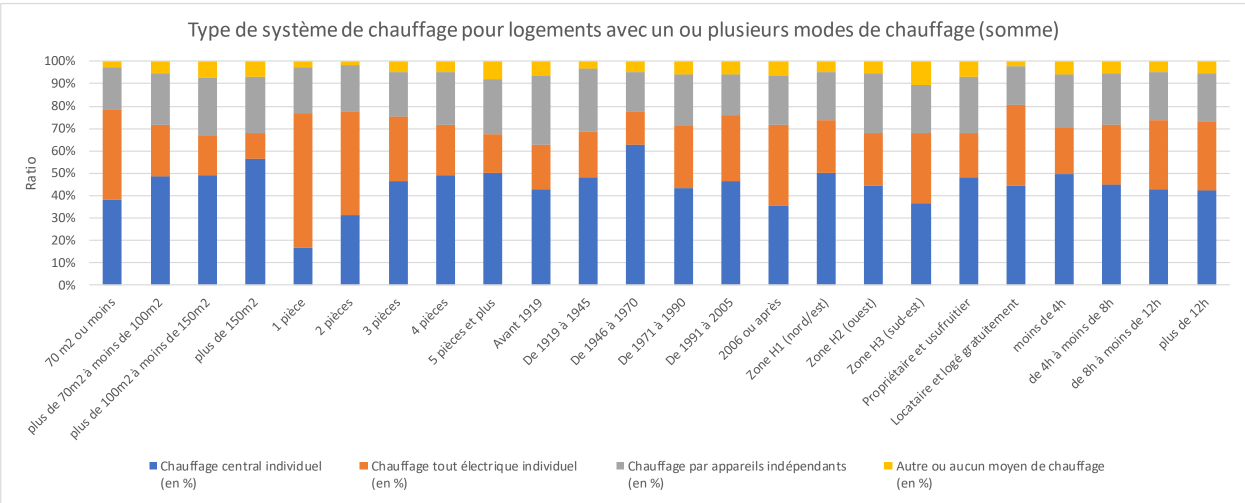


Figure 20 : Share of heating system type for all dwelling types (monovalent and multivalent systems summed)

It can clearly be stated that the share of thermodynamic systems (heat pumps) is increasing since the beginning of this century.

To get an idea on the sector of heat pumps, *Figure **22*** shows the market share of variants of heat pump systems sold in 2010. Even if the situation might have changed, it still gives a good vision on the situation.

Air/air systems are thus clearly the biggest market with more than 350000 units sold. Second place, with a huge distance from air/air numbers are air/water heat pumps with about 55000 units of several types. The decreasing tendency of air/water market has definitively changed and has become positive in the last years.

The key systems that have to be considered in detail (at least for renovation issues) are thus condensing boilers (renovation of central heating systems) and heat pumps, that are naturally, due to their favourable performances in the main part of the French territory, a solution with increasing market share.

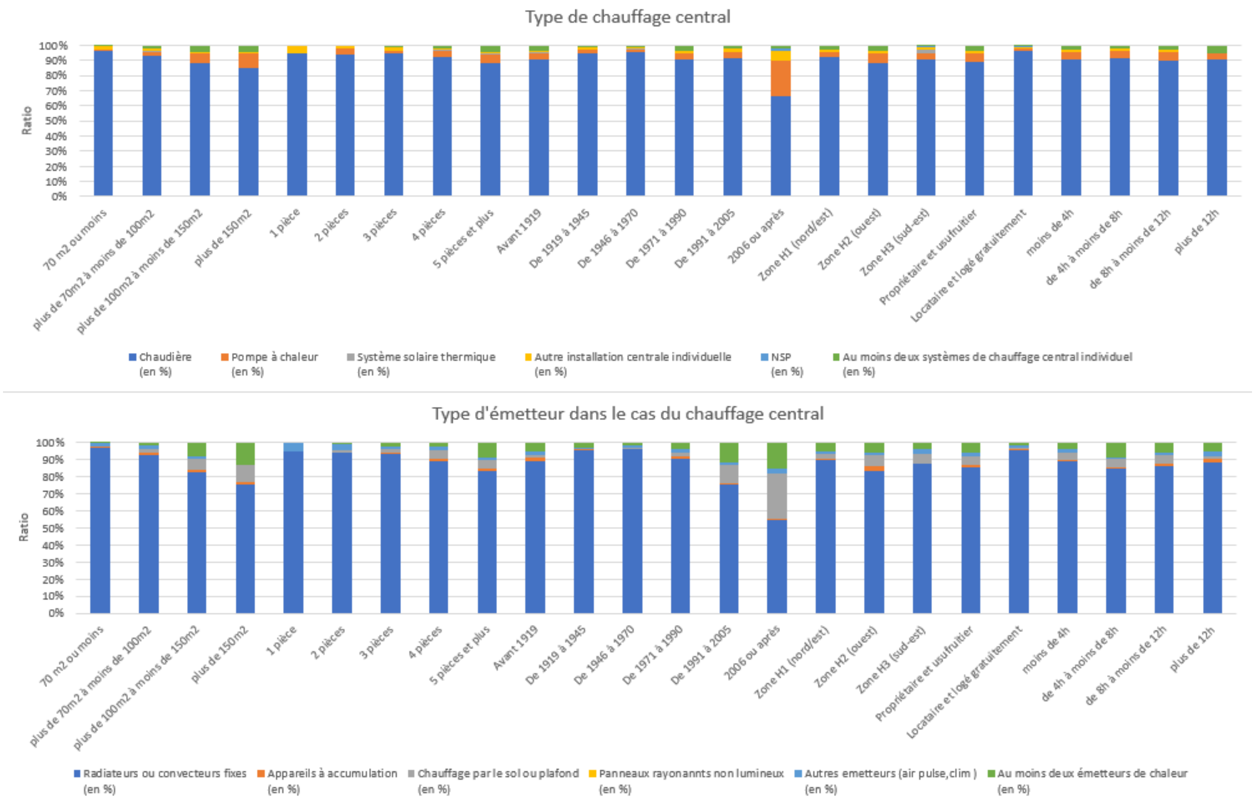


Figure 21 : Type of heating system and emitter in case of central heating systems

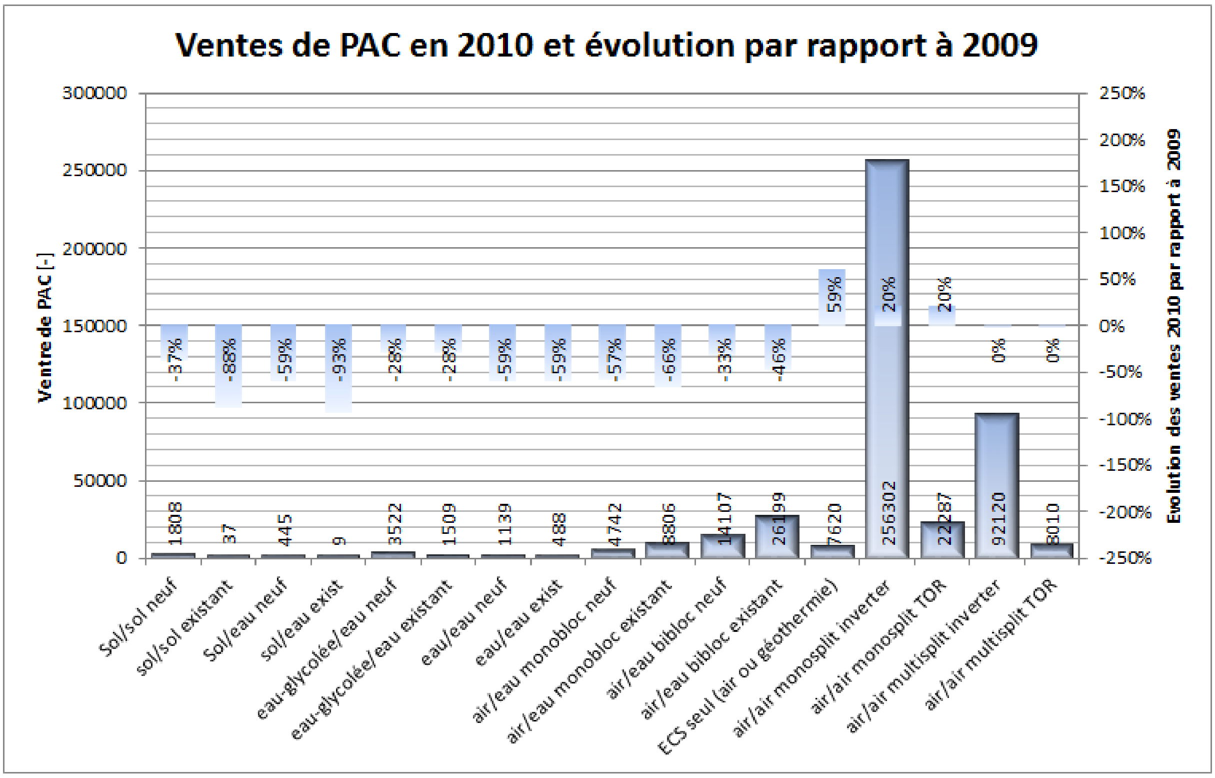


Figure 22 : Market share of heat pump types France / 2010 (sources: AFPAC[4], PAC & Clim'Info[5], Groupe Axiome[6])

[4] AFPAC: association française des Pompes à chaleur
[5] La climatisation, les pompes à chaleur. Les chiffres du marché français de janvier à décembre 2010.
[6] Le marché de la PAC air/eau et géothermie en France, 1000 entreprises ayant installées des PAC, Groupe Axiome – Etudes / Médias / Services, Septembre 2010.

2. DISCUSSION OF SYSTEM PERFORMANCES AND POTENTIAL GAINS

2.1 OVERVIEW OF PERFORMANCE CRITERIA

In this paragraph, performance is correlated to the following aspects (it will be defined more in detail in the next chapter):

- Energy consumption: The energy consumption is driven by auxiliaries and thermal losses in distribution and delivery as well as the efficiency of heat, cold and electricity generation (in case of CHP).

- Costs (operation, maintenance and investment costs): Operation costs are closely linked to energy efficiency and energy vector prices (electricity, gas, oil, biomass …) which can be fix or variable. Maintenance and investment costs are driven by the choice of the energy concept and technologies. Maintenance can also be affected by bad control behaviour reducing lifetime and maintenance or intervention intervals. The control behaviour itself is closely linked to controller tuning and oversizing of components that can convert modulating control strategies to on/off behaviour. This will definitively reduce lifetime of the controlled component (e.g. compressor of a heat pump) and thus increase investment costs.

- Comfort of the occupants:

  Comfort will be divided here into two aspects:

  - thermal comfort, which is linked to temperature (again, a mixture between air temperatures and radiant temperatures from wall and window surfaces as well as short or longwave radiation), air humidity and velocity. The clothing is of course a main parameter, but it is not directly linked to system operation.

  - Other comfort: this will be mainly acoustic (pumps, fans, compressors etc.) and visual comfort (if the system includes active blind control, visual aspects will play an important role).

While energy consumption and costs are an issue on all levels of the described energy chain (production, distribution and delivery, on district, building and zone level), comfort is linked exclusively on the zone level where the final delivery of heat, cold and DHW is carried out.

2.2 IDENTIFICATION OF MAIN REASONS FOR BAD PERFORMANCES

It is suggested here to identify the phases from conception to operation and define which phase might have an impact on bad performances in the system operation phase.

The phases from concept to operating energy system are defined here in a simplified manner:

1. Product development (factory phase): Almost all components and products are conceived, developed and manufactured by the manufacturers. Conception and development are carried out in internally by the manufacturer or can be done by subcontractors. The test of new concepts, starting from new ideas, was initially done using prototypes. With the development of simulation (numerical or prototypes with reduced size), simulation plays a more and more important role in this phase since it allows to conceive better products in less time and with less research costs. For example, the development of combustion chambers can be simulated using CFD models which will allow to test many geometrical configurations without building various prototypes and doing costly measurements or tests. This is almost true for any recent product. On the other hand, in the development or the conception and development of the control system, in various cases the related developments are still done without

simulation. The use of system simulation and emulation (explained in the next chapter) would be greatly useful since it allows to cover many boundary conditions and test cases. The control system (or also the complete product) can be tested by simulation or emulation techniques for the criteria of robustness and performance in order to develop a better product in less time and with lower costs. While many products are tested in real buildings for months, with quite high costs, they could be easily tested using emulation with lower costs and a much larger band of configurations (e.g. emulating a heat pump in a virtual building which is placed under different climates, with different occupant behaviours etc.).

2. Conception and sizing: These two aspects are closely linked. System and layout choices will be done here (e.g. the planner must choose between zone, building or district energy systems, from a large variety of system layouts, with or without storages, etc.). Once this choice done, the equipment must be sized in order to allow good performances (in case that the system operates properly). It is a very important phase since it will set the base for good performances later. Any other phase is only necessary to reach the planed performances, but they cannot render the system layout better than it is.

   Typically, this phase is done more in detail for larger buildings but from the experience of the planner for single family buildings. However, in most cases, planers tend to repeat concepts that have been judged “good” in the past, to simplify the planning process and risks for future buildings. This is on the one hand a good choice since these proofed concepts are maintained (or further improved) for future projects. On the other hand, other system layouts might perform better for local project specificities. The obligation of planers in larger projects to analyse the use of renewable sources pushes in this sense, but in case of other buildings (especially residential buildings) this is not done. Numerical simulation would be a very good option to assist in this phase, but the major problem are the costs related to these efforts. Additional (simple and quick) planning tools based on numerical simulation might thus improve this phase by “scanning” several system concepts without a large modelling effort.

   Sizing is generally carried out following normalised methods. This secures the planner who can state that he has fulfilled the official sizing procedures or standards. The bad thing of this method is that all systems are oversized. The sizing methods apply generally the worst-case scenario (that might never happen) and the planner will apply an additional oversizing coefficient to be 100% sure that the installed power will be sufficient. From the performance point of view (energy and cost performance) this is not necessarily the best choice since the systems always operates in a rather low load range. This might tend even modulating control to On-Off control since modulation is stopped below a certain load ratio. Numerical simulation, if applied more systematically, would highlight these aspects and could lead to better and more robust operation. However, this would lead to a smaller sizing and the occupants might be exposed to lower thermal comfort conditions in some hours of the year. Such a dynamic sizing method should thus be covered by additional paragraphs in the related contracts or standards.

3. Installation: the installation should carefully respect everything that has been planned, but the reality is different. Differences can be of different nature:

   - System layout is wrongly implemented: In most cases this error will probably be identified (but not necessarily) since the system operates not at all or does not satisfy completely the comfort of the occupants. However, it might take some time to identify the problem. For example, the inverse connection of a radiator to the supply and return lines might cause some thermal discomfort and eventually acoustic problems since the valve is flowed in the opposite sense, but in principal the system will operate (more or less).

- Sizing data is not respected: A typical example is the installed pipe sections and if they differ too much from the calculated ones (in case they are calculated), acoustic problems or also discomfort might occur; and in the less critical case, higher auxiliary consumptions.

  In case of the non-respect of production or storage size as well as pump or fan characteristics, the system will be undersized and thermal comfort might not be guaranteed. The typical problem might be the use of “equivalent” equipment which, in the case of pumps or fans, might not operate as it should.

In general, installation problems will either result in complete disfunction of the system or discomfort due to missing power. Simulation will only be helpful to demonstrate the effect of these problems on the operation of the system but not to prevent these errors.

4. Reception:

   Reception is interpreted here as the end of installation to ensure the accurate installation of the system and to start operation in a sense that the correct operation at the beginning of operation is ensured. This will thus include controller tuning if needed.

   The conformity of installation will mainly be verified using checklists and manual and visual verifications. Simulation is not necessarily helpful, except for analysing the consequence of errors in the installation.

   This is not completely true for the verification of correct operation. It will partly be dealt with using checklists, but it could be assisted by simulation in specific cases such as controller tuning. Some companies even emulate the controllers in order to ensure the correct operation of the global building energy management system. This allows even for pre-tuning that will then be refined in the real installation. With the development of “smart” solutions, this tuning procedure can be automated online since it is part of the smartness itself (learning algorithms).

5. Operation: The operation phase is assumed here to start from the point where the correct operation has been ensured in the reception phase. The main reasons for performance degradation in this phase are:

   - Application of non-optimal control laws: Two options occur here: either the control laws are not able to adapt to changing environmental and boundary conditions or they have been set to “standard” (or have not been set at all). The best performance will be achieved if control laws would always be assisted by expert rules or smart algorithms that allow to self-adapt control to the changing conditions. With the development of smart control algorithms this is currently changing a lot. However, with the boom of artificial intelligence, this has to be done carefully since these algorithms not necessarily verify the physical truth of the obtained results since they only allow to interpolate (and not to extrapolate) from measurements of past events. Algorithms based on physical laws do not have these problems, but their accuracy is generally lower. A combination of both shows here best results.

     In the case of fixed control laws, which is the most common case, they will do what they are supposed to do, but if they have not been adapted to the real project (and system), they might not ensure good performances. This will be shown in the next paragraph for the example of heating laws on heat pumps.

   - Faults and fault detection: In most cases, faults are detected when occupants complain. And this means that if the fault is not too obvious, the system will operate with this fault for some (or a long) time. For example, if a sensor fails that is needed for a control law, the controller might calculate a control set point value which still guarantees a minimum comfort. If the controller does not detect sensor failure, the system will continue operating. An example: in the case of a heating law, the generator might operate at the maximum supply temperature and the generator performance will be much lower than it could be. The occupants will thus still have good thermal comfort but pay additional costs without knowing about the problem. Modern controllers should alert in case of sensor failures, the installer also has to use this information to correct the failure on site. Online commissioning methods based on numerical simulation can detect failure since they verify also deviation of sensors with time.

On the other hand, if faults are obvious and more severe, occupants will probably complain immediately since their comfort is not ensured anymore.

As explained, each of these phases will or might have an impact on the operational performances of an energy system. In many cases, numerical simulation is an excellent manner to assist theses phases or at least to investigate what would typically happen if one of these phases are not properly carried out.

2.3 TYPES OF IMPROVEMENT AND QUANTIFICATION OF POTENTIAL

This section shall highlight an example for low performances and give some rough estimations on potential gains.

In general, the type of improvements can be split into 4 groups that are discussed in the next subchapters.

2.3.1 EFFICIENCY OF PRODUCTION COMPONENTS

The efficiency of production components can be maximised by reaching the best possible operating points. This is on the one hand allowed by correct conception and sizing, on the other hand by the “best” possible operation. As an example, a condensing boiler needs low water return temperatures in order to ensure condensation and thus better efficiencies. The conception / sizing procedure has to make sure that these return temperatures can be achieved. In the operation phase, the control algorithm must ensure to reach these low return temperatures, as defined in the conception phase. If only one of these two factors is done correctly, performances will rarely be close to the optimum.

The following figures illustrate potential gains in the efficiency of production for the case of heat pumps in heating mode.

The figures have been produced by simple calculations based on Carnot efficiencies with a system efficiency coefficient of 40%, thus:

$$COP_{real} = 0.4 * \frac{T_{sink}}{T_{source} + T_{source}}$$

*Figure **23*** shows the evolution of COP as function of the heat sink temperature. Three sets of curves show the COP for source temperatures of 0°C, 5°C and 10°C. Besides the conclusion that sink temperatures shall be chosen as small as possible in the conception phase (conception and sizing), it clearly shows also the impact of a high source temperature. This is the reason why ground source heat pumps perform better in cold climates.

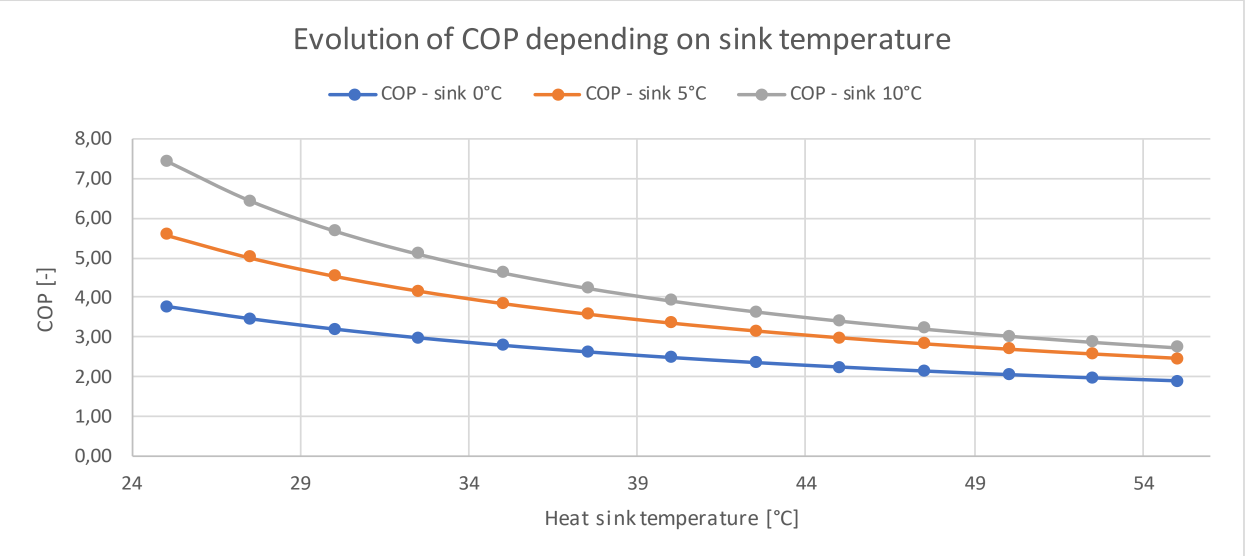


Figure 23 : Estimation of real COP as function of sink temperature

*Figure **24*** on the other hand shows the evolution of COP as function of the sink temperature. The example shows the case of an air source heat pump that needs defrosting at temperatures around the freezing point. A gaussian law has been added to illustrate this impact.

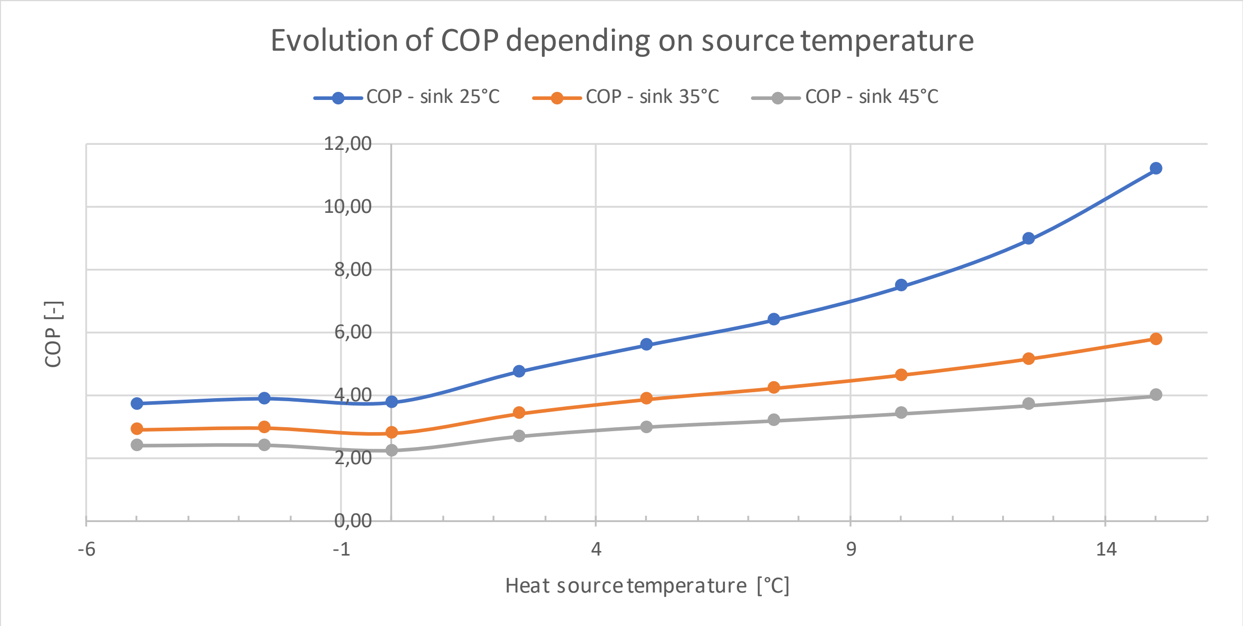


Figure 24 : Estimation of real COP as function of source temperature

*Figure **25*** show the impact on energy consumption as a gain by changing the source and sink combinations.

A reference sink temperature has been set to 55°C as a typical renovation case of a heating system with hot water radiators. On the left axis, the gain at a certain sink temperature is shown compared to the reference of 55°C. The reduction from a sink temperature of 55°C to 30°C (change from radiators to floor heating) gives thus a gain of about 45% at a source temperature of 5°C (solid lines). It can be seen that the consumption of such a heat pump is extremely sensitive to temperature levels. A bad conception, sizing or control can thus lead to significant changes in energy consumption, in the order of magnitude of insulating a building!

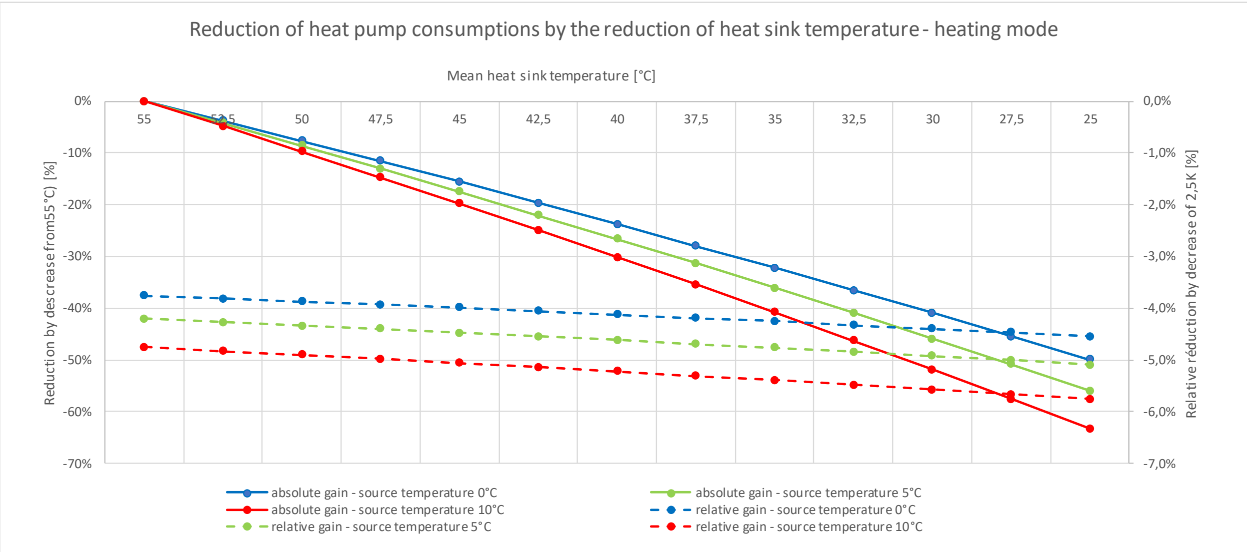


Figure 25 : Reduction of consumptions as function of sink temperature

The dotted lines (right y-axis) show the relative gain for a decrease in sink temperature of every 2.5K (from the higher source temperature to the lower one). It is thus clearly visible that each reduction of 2.5K in sink temperature brings additional 5% of energy gains, which is huge. The "optimal" choice and selection of emitters is thus extremely important. For example, if the source temperature cannot be changed (e.g. from air source to ground source heat pump), a lot of savings could be achieved by changing the emitters in the buildings or at least, to optimise heating laws for controlling supply temperature.

*Figure **24*** finally shows the same principle, but for a changing source temperature and again, for an air-source heat pump.

The impact of defrosting is clearly visible in this graph with a maximum loss of about 10% by the defrosting activation (at 2.5°C source temperature). Again, the relative gain of a 2.5K change in source temperature is about 5%, so slightly higher than for a 2.5K change in the sink temperature.

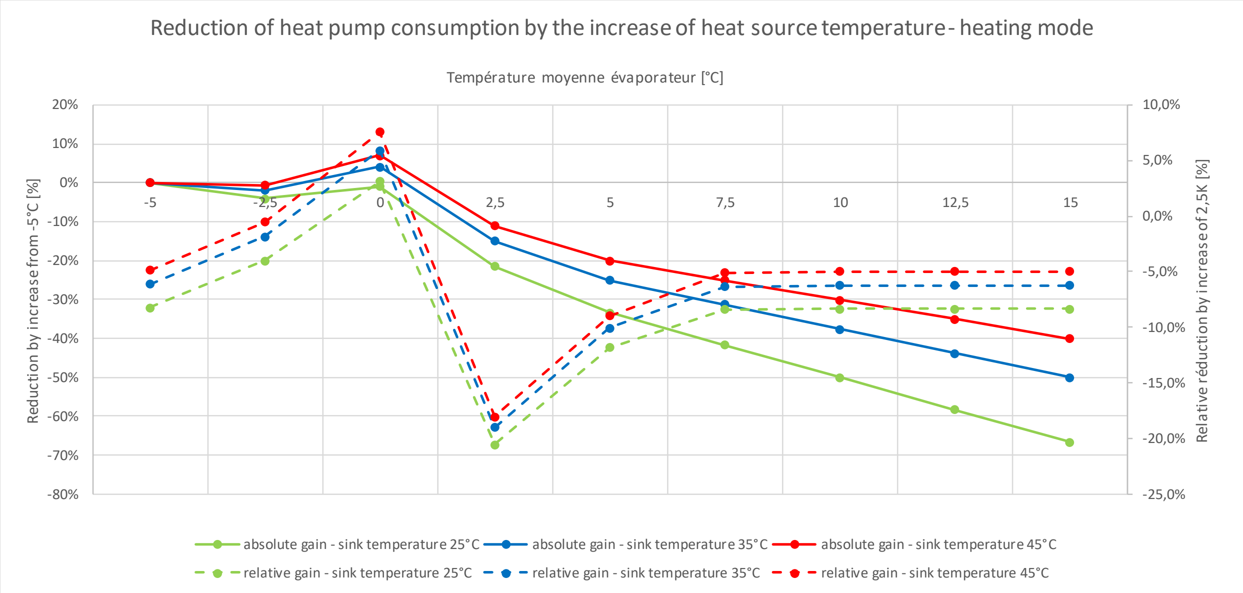


Figure 26 : Reduction of consumptions as function of source temperature

As a conclusion of this section, it can be stated that conception, sizing and operation are extremely important for obtaining best system performances. The gains can be much higher than expected (e.g. if the question is to better insulate the building envelope or to change heat emitters, the result is not as obvious as that). Numerical simulation provides here the best tool to make the correct choice.

2.3.2 ENERGY LOSSES

Besides building losses which are the main reason for thermal energy demand in buildings, losses occur in any production, distribution or storage component. In this document mainly thermal losses are addressed since they are the predominant losses in HVAC systems which is the main scope of this document. However, if for example electrical storage is part of the system, electrical, chemical or mechanical losses are not negligible.

Thermal losses mainly depend on heat loss areas and heat loss coefficients, i.e. surfaces exposed to ambiance and the insulation of this surface. The objective in reducing thermal losses is thus to minimise exposed areas and increase insulation. In the case of buildings or boilers, losses by infiltration or ventilation have also to be considered.

Thermal losses can be partially recovered if the component is an internal distribution or storage (for example losses of hydronic heating distributions inside the building in winter). On the other hand, losses over the building envelop will always be losses.

It is very difficult or better impossible to present the order of magnitude since energy losses depend on many factors. Nevertheless, especially for thermal losses they can get quite important, but again, depending on heat exchange areas, medium temperatures and ambient conditions. This is particularly the case for district heating networks. It should thus be intended to diminish network length and to properly size tube sections (compromise between pump consumptions and thermal losses). To avoid bad performing networks, minimum energy density levels (this is one example) have been defined to allow simple decision rules whether a building or group of buildings should be connected to a network or not.

2.3.3 AUXILIARY CONSUMPTIONS

Most production and distribution components need auxiliaries to satisfy their function. Very often these auxiliaries allow to transport energy from one point to another one (e.g. distribution pumps or fans for hydronic or air distribution networks). While from the production point of view a certain temperature difference between supply and return would be optimal (e.g. very small in case of heat pumps and rather big for condensing boilers), this has a negative impact on the auxiliary consumption. A compromise is thus to be found. In the case of heat pumps as an example, water supply and return temperature difference (deltaT) is often sized and controlled to about 5K.

In praxis, auxiliaries operate too much time. A typical problem is that fact that building distribution pumps run continuously in order to allow the control of the heating law, even if there is no demand. A first step towards the reduction of this unnecessary consumption is the application of variable speed pumps that reduce their flow rate in case of low demand. In case of on-off production units or mid-season operation, cycling of pumps can also be a simple solution.

One can also push this argument to the extreme: if a system without potential auxiliaries can reach the same performances (performances are here understood as multicriteria performances, not only energy performance), network-based solutions should be avoided since they will add additional consumptions that are often higher than expected.

An example on energy consumption split into auxiliaries and production is given in *Figure **27*** for heating, cooling and DHW production modes. The data has been obtained from a 2-year measurement campaign on 26 heat pumps in a power range between 8 and 150kW nominal thermal power. In the study, auxiliaries are split into the auxiliaries on the environmental side (fans or circulation pumps) and building side (building circulation pumps). Following the results of this project the auxiliaries on the environmental side represent between 10 and 18% (for heating and cooling mode respectively) and those on building-side are responsible for 33 - 44% (for heating and cooling mode respectively) of the global consumption (heat pump and auxiliaries). These values are extremely high but represent unfortunately the reality of many systems installed in the French building stock. The results are probably better for production units with modular control (this study concerns mainly geothermal heat pumps with on-off or cascade compressors), but several other monitoring studies also showed relatively high auxiliary consumptions on the building side.

Things are different for DHW production where the auxiliaries were “as it should” with a total amount of 10% of all auxiliaries (including hot water circulation pumps for faster availability of hot water).

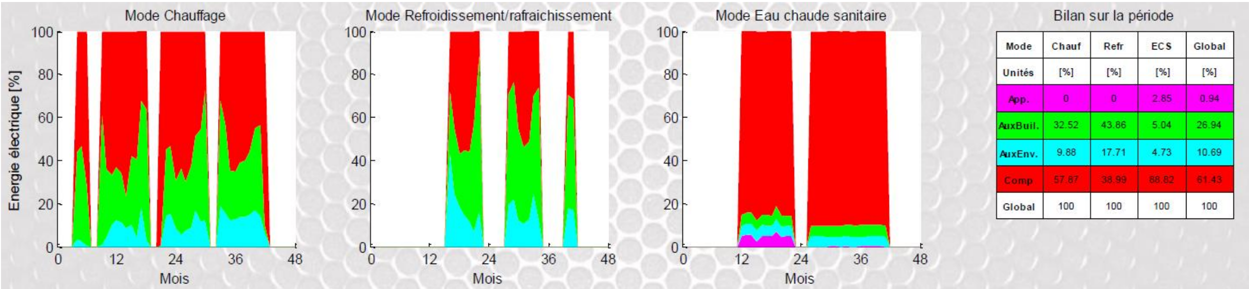


Figure 27 : Share of energy consumption of a measurement campaign on 26 heat pumps[7]

[7] Capitalisation & Valorisation des pompes à chaleur géothermiques (VALPAC), CSTB/Ademe, 2005

2.3.4 MAXIMISE RENEWABLES AND HEAT RECOVERY UTILISATION

Renewables and energy recovery sources are mostly not synchronised with the energy demand. The key point of all these sources is thus the equilibrium between source energy power and available energy storage capacities. This is valid for thermal and electrical sources (e.g. solar thermal and photovoltaics).

They key point of any conception of REN&R sources is thus to find the best compromise between recovery and costs. Note that this compromise is very subjective: for one, the best compromise will be to find the optimum between costs and recovery from an economic point of view (global costs optimisation in a certain time span). For others the best solution might be to recover as much REN&R as possible and to accept higher costs, with the wish to be green and to contribute to the fight against global warming.

2.3.5 GENERAL REMARKS AND RECOMMENDATIONS

It is important to deal with ALL of these 4 points that have presented previously. Especially during the conception phase of energy systems, it is important to choose the concept for which the global impact of all 4 points is optimal, and not only for one or several points. There are several criteria to verify, but as an example, the global primary energy consumption will be reflected by the sum of performances of these 4 points.

To reach the objective of high-performance energy systems, the key considerations will thus be:

- Send the needed energy in the state and flow that allows optimal performances and a minimum of auxiliaries
- Everything is transient and inert, so consider inertia effects (good and bad ones)
- In other words, step by step:
    - reduce loads (minimise losses) as much as possible;
    - produce only what is really needed (including predictions to avoid inertia effects);
    - produce with the maximum efficiency (also including predictions: e.g. it might be better to produce heat with a heat pump at times when the source temperature allows higher performances, even if storage losses may occur);
    - reduce auxiliary's consumption to a minimum. Whenever possible, reduce them or switch them off.

And for each of these comments and steps, numerical simulation represents an excellent way to analyse these impacts on global performances.

CHAPTER II

APPROACHES TO QUANTIFY AND IMPROVE SYSTEM ENERGY PERFORMANCES

This second chapter describes approaches to characterise and improve performances of energy systems.

In a first section, key performance indicators and relevant boundaries are presented. The second section describes measurement approaches for quantifying energy performances.

Then, the third section highlights the use of numerical simulation for the evaluation and optimisation of energy performances.

The fourth section combines measurement and simulation in an emulation or "hardware-in-the-loop" approach, combining the key advantages of both, measurement and simulation.

Finally, the last section briefly presents optimisation and prediction methods for improving performances of energy systems.

1. ANALYSIS OF THE PERFORMANCES OF ENERGY SYSTEMS

If system performances shall be analysed in detail, it is suitable to split the complete system into subsystems in order to identify potential gains in different parts of the system.

A proposal of sub-division has been presented in the RESILIENT[8] project and is summarised in the following paragraphs.

1.1 SYSTEM BORDERS FOR PERFORMANCE ANALYSIS

The definition of boundaries in the energy system of a district can be divided into three main parts:

- Centralised energy production (EHUB)
- Distribution of energy from central to local (building) level
- Local energy system (Buildings)

The building level can also be divided up to the zone level, but this is not done here for reasons of simplicity. However, the same concept as for the district level can be applied in that case.

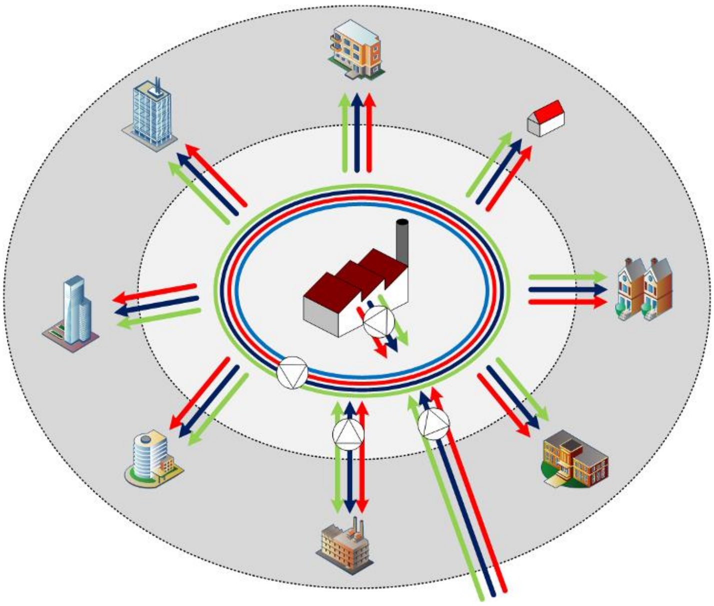


Figure 28 : District energy system with central, distribution and building level

Finally, a generic (or transversal) level can be defined which is the component level. This level is the boundary around a production unit (e.g. boiler) that can be on a central or local level.

1.1.1 CENTRAL ENERGY HUB LEVEL

In the Energy HUB, heat, cold and electricity is delivered to the distribution network, produced by components which are described in the next sections. The energy HUB may need sources as fuel or electricity.

Only auxiliaries for the internal energy distribution in the Energy HUB are included in this balance. Auxiliaries for energy distribution to the local levels (buildings) are accounted for on the district distribution level as shown in *Figure* ***29***.

[8]Coupling renewable, storage and ICTs, for low carbon Intelligent energy management at district level (Resilient) – European project, agreement n° 314671

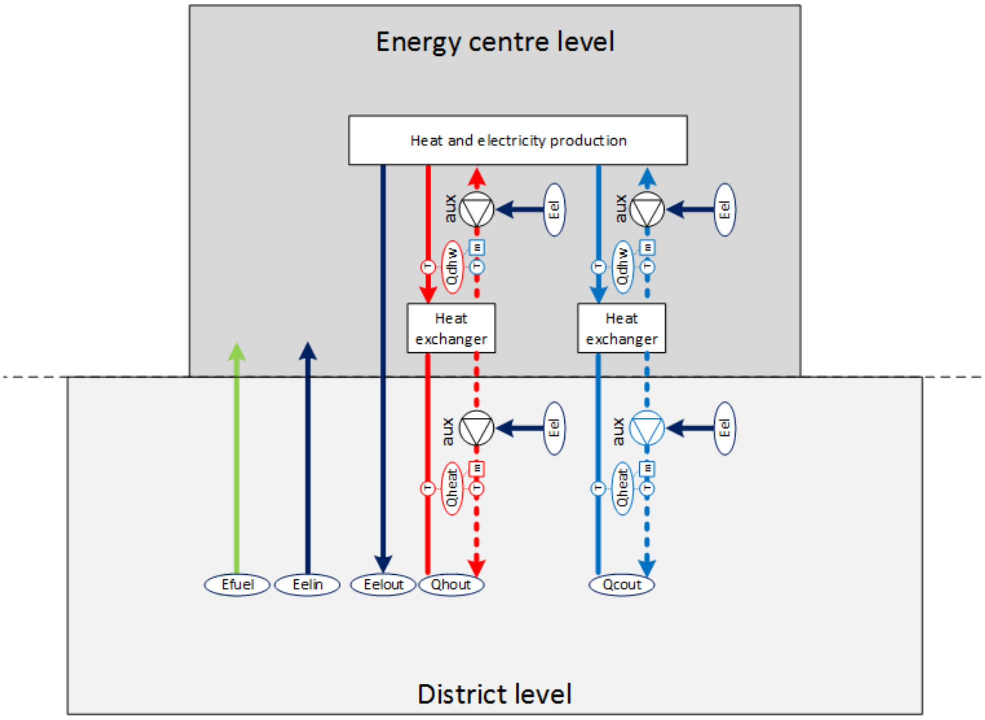


Figure 29 : Inputs and outputs of energy centre of a district energy system

1.1.2 BUILDING LEVEL

On the local or building level, the definition is similar to that on the component level.

*Figure **30*** shows in a simplified (right) and detailed (left) layout the inputs and outputs of energy to and from the building.

- Inputs:
  - Thermal input for Heating, Cooling and DHW
  - Driving input for building services (local heating, cooling and DHW production)
  - Electricity input for Heating, Cooling, DHW, ventilation, Lighting, charge of electrical storages (batteries, vehicles etc.), divers specific electricity consumption.
- Outputs:
  - Heat output (local production components)
  - Electricity output (local production components)

In order to be able to characterise efficiencies or detailed energy flows on the building level, any auxiliary used for delivering energy to the building should be excluded from the building level and included on the upper level, the district network or grid. Heat and electricity should thus be evaluated “inside” the building without the part of delivery. The latter should be considered in the distribution part. This is also valid for a local heat or electricity production: any auxiliary for deserving the district network (e.g. circulation pumps providing heat to the district) should be accounted for outside the building level since it allows the use on the district level (e.g. in other buildings).

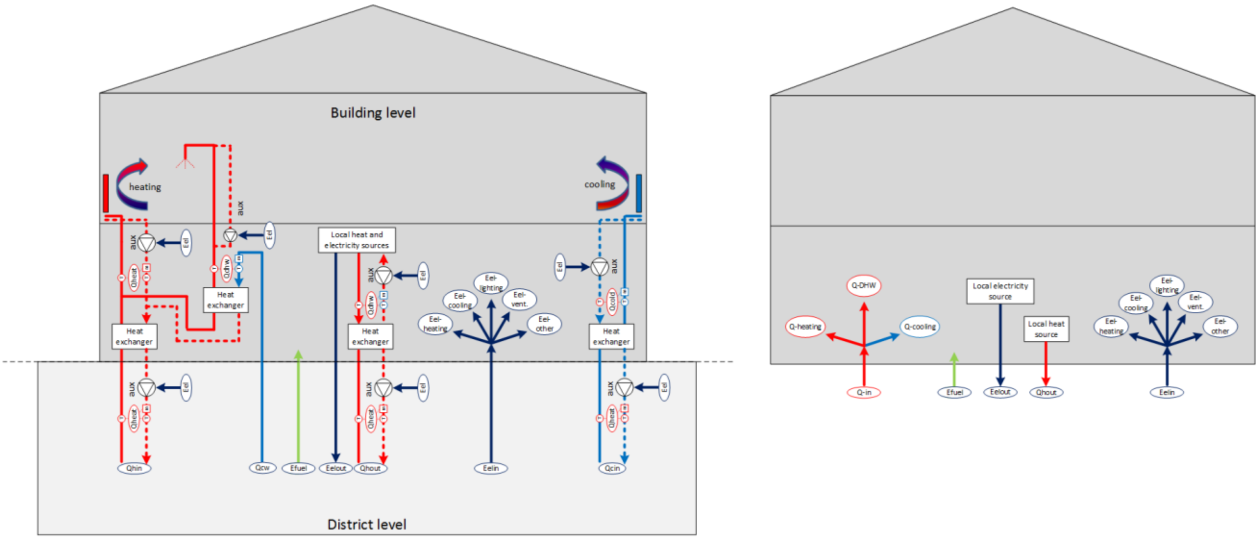


Figure 30 : Building energy inputs and outputs (left: detailed, right: simplified)

1.1.3 DISTRIBUTION LEVEL

The distribution level corresponds to supply/return pipes in the case of thermal networks and to the electric grid for the electric case.

The energy flows on the distribution level are incoming and outgoing energy flows (thermal or electric) and the auxiliary consumption (pumps etc.) necessary to deliver energy (via mass flow) from the Energy HUB level to the building level or vice versa.

As for the component level (§1.1.4), intrinsic and global performances can be calculated while “intrinsic” corresponds to the performance/energy balance without auxiliaries and “global” to the balance including all necessary auxiliaries.

The auxiliaries that must be considered on this level are all those that will allow to receive the energy on the opposite level (local for the central production case and central for the local production case). I.e. any hydronic pump in a district heating network that is on the primary side of a local thermal substation is considered as auxiliary of the distribution system, the pumps on the secondary side of the substation are considered on the local (building) level.

1.1.4 ENERGY PRODUCTION UNIT

In this section, the boundaries of a generation/storage system are defined using an approach on two levels:

- Intrinsic: the boundary is such as consumption/efficiency will be calculated for the intrinsic performance of the component, without considering auxiliaries for the connection to other components (without energy delivery)

- Global: the boundary is such as consumption/efficiency will be calculated for the global performance of the component by considering auxiliaries for the connection to other components (with energy delivery)

*Figure **31*** shows the boundaries for the production and storage components in any district energy system.

Thermal energy is measurement using thermal energy meters with flow meter as well as supply and return temperature. By convention, heat transfer is considered positive for heating and negative for cooling.

In the figure, E_{el} stands for electrical energy, E_{fuel} for fuel energy and Q_{heat} for thermal energy.

Any thermal/electrical energy system is characterised by:

- A driving energy input ("driving source") which can be in form of electric, gas or fuel (E_{aux}) or thermal energy
- Auxiliary energy input E_{aux} (auxiliaries require in almost any case electrical input)
- "Heat" / "Cold" output, the useful energy as well as $E_{prod\text{-}el}$ (electricity production)

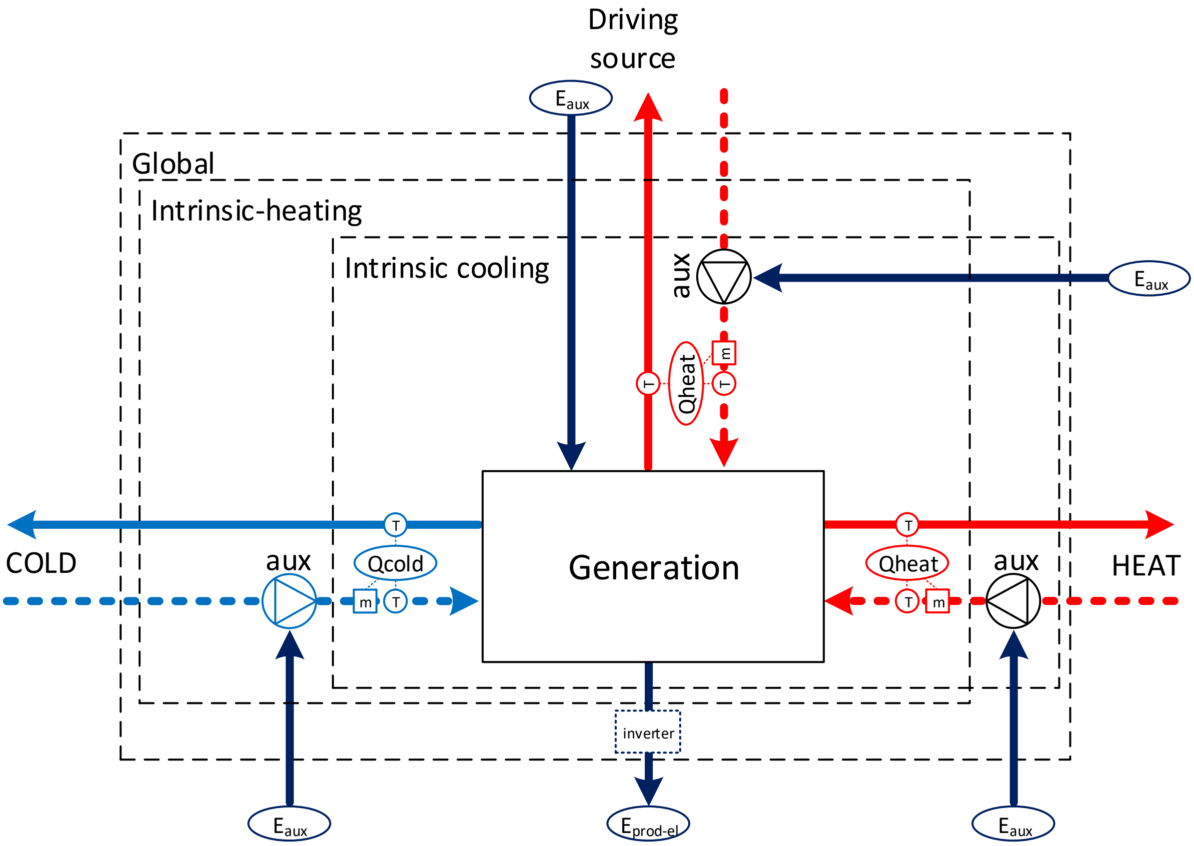


Figure 31 : General system layout for performance evaluation

Remark:

A more detailed layout has been defined in the European Sepemo-Build project[9] which has delivered the reference method for heat pumps. However, in this more global context, a simple hybrid way with two levels has been presented in Resilient allowing to analyse performances with and without auxiliaries.

[9] SEasonal PErformance factor and MOnitoring for heat pump systems in the building sector (SEPEMO), CIP-IEE-2008 - IEE/08/776/S12.529222

1.2 DEFINITION OF PERFORMANCE CALCULATION

The following definitions allow the measurement and/or calculation of efficiencies of all components (generation, building, distribution etc.) or a global system. Efficiency is here defined as the ratio of useful energy to the energy necessary for the operation i.e. the value can be higher than unity, e.g. for solar systems or heat pumps.

Although efficiencies can be calculated on an instantaneous basis (power ratio), it is here defined as the ratio of energies (i.e. integrated power values), allowing the evaluation of components and systems for a given period that can be day, week, month, season or year.

The definition of efficiency in general for any level (electricity and heat):

- without auxiliaries for energy distribution: $\eta_{intrinsic} = \frac{E_{out}}{E_{in}}$

- with auxiliaries for energy distribution/connection: $\eta_{global} = \frac{E_{out}}{E_{in} + E_{aux-connection}}$

Applied to a thermal component or system (heating, cooling or DHW etc.) it follows:

$$\eta_{intrinsic} = \frac{E_{out}}{E_{in}} = \frac{Q_{useful}}{E_{fuel} + E_{elec-process} + Q_{auxheat-in}}$$

$$\eta_{global} = \frac{E_{out}}{E_{in} + E_{aux-connection}} = \frac{Q_{useful}}{E_{fuel} + E_{elec-process} + Q_{auxheat-in} + E_{aux-connection}}$$

For electrical systems or components:

$$\eta_{intrinsic} = \frac{E_{out}}{E_{in}} = \frac{E_{useful}}{E_{fuel} + E_{elec-process} + Q_{auxheat-in}}$$

$$\eta_{global} = \frac{E_{out}}{E_{in} + E_{aux-connection}} = \frac{E_{useful}}{E_{fuel} + E_{elec-process} + Q_{auxheat-in} + E_{aux-connection}}$$

And for hybrid systems or components:

$$\eta_{intrinsic} = \frac{E_{out}}{E_{in}} = \frac{Q_{useful} + E_{useful}}{E_{fuel} + E_{elec-process} + Q_{auxheat-in}}$$

$$\eta_{global} = \frac{E_{out}}{E_{in} + E_{aux-connection}} = \frac{Q_{useful} + E_{useful}}{E_{fuel} + E_{elec-process} + Q_{auxheat-in} + E_{aux-connection}}$$

1.3 PERFORMANCE INDICATORS

1.3.1 ENERGY CONSUMPTION

Final energy consumption

Final energy is the energy that is consumed at a certain place, for example by « end users » (e.g. household, industry etc.). Final energy is measured as the quantity of energy in kWh that passes the energy meter (in kWh of heat, electricity, gas, oil etc.) without considering neither the quantity of energy that has been used to produce nor that to transport it.

In the case of on-site production, using any combustible, the final energy can be calculated from the volume of fuel that was burned and the energetic value of the fuel. Here a distinction is made between the higher heating value (HHV) and lower heating value (LHV). The HHV (also gross energy or higher caloric value) is the amount of energy that can be used after the combustion of one mass unit of primary fuel and bringing back all the combustion products to the initial temperature (25 °C as standard reference). This includes recovery of condensation energy from vapors that are formed during the combustion (e.g.) water vapor. LHV on the other hand does not include the condensation of vapors in the calculation.

Primary energy consumption

Primary energy consumption, on an end user level, means that the whole energy supply chain is considered. This corresponds to the amount of final energy delivered plus the additional energy that has been consumed to produce this amount of final electricity.

It is very difficult to calculate primary energy since the energy supply chain is very long. To deliver electricity in a buildings, the whole energy supply chain has to include in theory even the energy (primary) that has for example been used to produce the concrete of the foundations of a wind turbine (including transport and energy of ciment etc.) as well as to deliver it at the place of the wind turbine (any kind of transport). This chain is extremely complex which makes it impossible to have an exact value. Many assumptions have to be made in oder to simplify the problem.

Table ***1*** gives an overview on the range of primary energy factors calculated for the different EU member states as well as suggested values used in the fraame of the EPBD context as an average.

Table 1 : Intervals of primary energy factors for fossil energy carriers[10]

Countries	Mains gas	LPG	Oil - general	Diesel or heating oil	Fuel oil	Coal - general	Biomass - general	Wood - general	Wood pellets	Grid Electri-city	District heating - general
EU countries in average	1.00-1.26	1.00-1.20	1.00-1.23	1.00-1.14	1.00-1.20	1.00-1.46	0.01-1.10	0.01-1.20	0.01-1.26	1.5-3.45	0.15-1.50
CEN (non-renewable) defaults	1.1	1.1	1.1	1.1	1.1	1.1	0.2	0.2	0.2	2.3	1.3

While primary energy factors for fossil fuels are almost constant, they vary a lot in time and space for electricity, depending on the mix of power plants that are based on the following primary energy resources:

- Nuclear,
- gas, oil and coal,
- biomass,

[10] Primary energy factors and EPBD: https://epbd-ca.eu/wp-content/uploads/2018/04/05-CCT1-Factsheet-PEF.pdf

* hydroenergy,
* solar and wind energy etc.

The primary energy factor of the production of electricity is thus the mix of primary energy factors weighted by the part of each producer of the total energy output. This mix depends on many factors such as the availability of renewable energy sources (wind, solar etc.) as well as the current mix of power plants and possible storages to complete the missing electricity (which is exposed to the variation of consumption).

This analysis can be done for one power plant, on a regional, national or international level, but a correct balance is more or less impossible since the mix is a function of time and usage.

To give an example for one reason of the variability of the primary energy factor as a function of time, *Figure* ***32*** shows, for the period between 2007 and 2012, the renewable part of energy production as function of time of day (y-axis) and day of year (x-axis) for France (average national data). The source of data is RTE (http://www.rte-france.com), responsible for the transport of electricity (high voltage distribution) and does thus not consider the whole electricity production (i.e. local photovoltaic productions are not included).

A detailed analysis of primary energy or even worse primary energy reduction is thus not as obvious as it might seem. If energy reduction measures are applied on a larger level as only one building or a small district, at least regional primary energy factors might change as well.

The same phenomenon will be the analysis of emissions which is closely linked to the primary energy analysis.

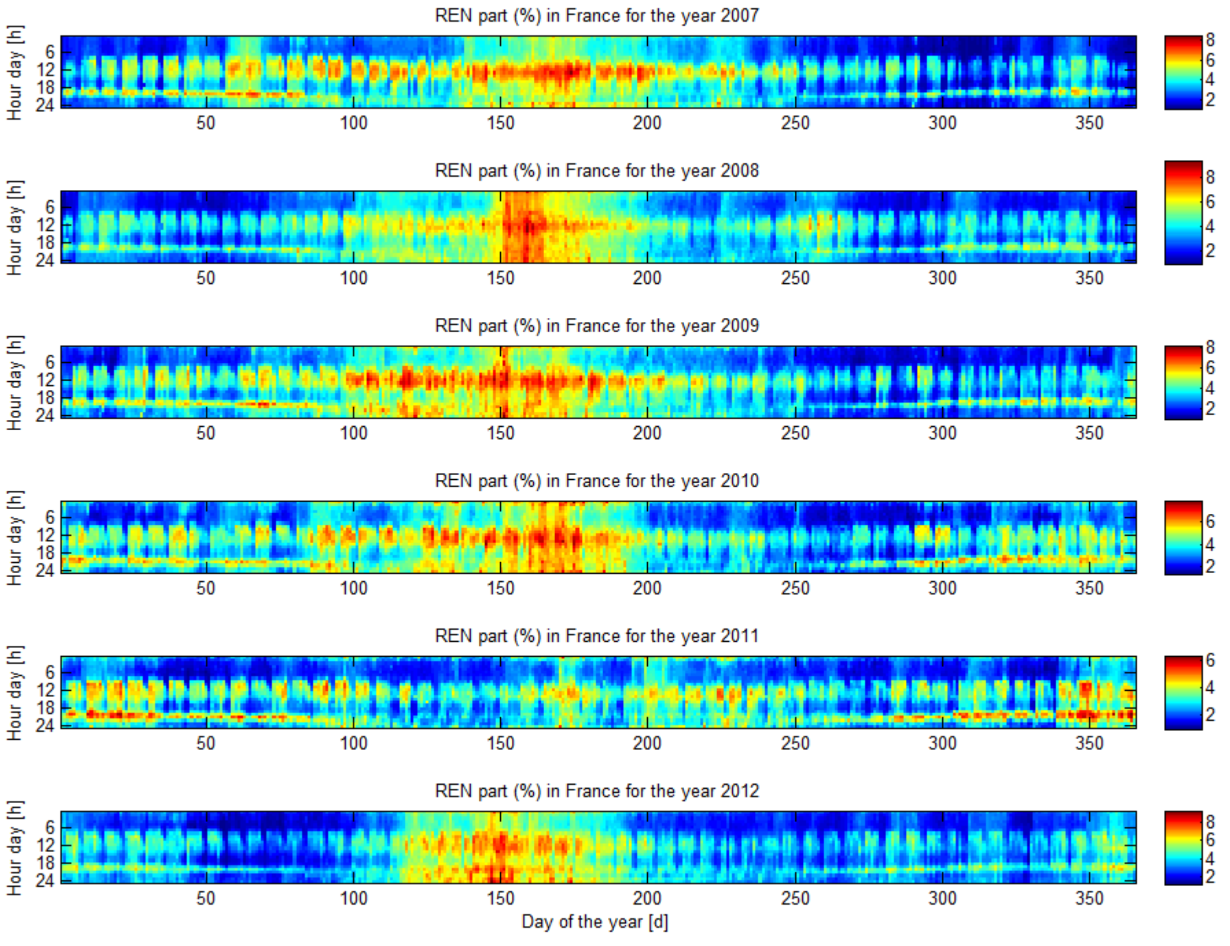


Figure 32 : Renewable part of electricity generation in France

1.3.2 EMISSIONS

Definitions

The term 'greenhouse gases' (GHG) refers to CO2 equivalent (CO2-eq) which includes the six greenhouse gases included in the Kyoto Protocol: carbon dioxide (CO2), methane (CH4), nitrous oxide (N2O), hydrofluorocarbons (HFC), perfluorocarbons (PFC), and sulphur hexafluoride (SF6).

The term carbon footprint is also applied to products, in which case the estimation methodologies are based on life-cycle analysis.

The two most important characteristics of a Greenhouse Gas (GHG) in terms of climate impact are (a) how well the gas absorbs energy (preventing it from immediately escaping to Space) and (b) how long the gas stays in the atmosphere.

Carbon Dioxide has by far the highest percentage contribution to GHG emissions with the other gases. An example of the contribution of the four most important gases in the US is[11]:

Carbon Dioxide	82%
Methane	10%
Nitrous Oxide	6%
Fluorinated Gases	3%

The Global Warming Potential (GWP) is a measure of the total energy that a gas absorbs over a particular period of time (usually 100 years), compared to Carbon Dioxide. The larger the GWP, the more warming the gas causes. Carbon Dioxide (CO2) has a GWP of 1, Methane (CH4) has a GWP of 21 and Nitrous Oxide (N2O) 310 i.e. 310 times the effect of the same volume of CO2.

Emission of electricity supply

To calculate the associated emissions, it is important to apply a CO2 emission factor that can be attributed to electricity supply - also called the electricity mix (g CO2/kWh) - to represent emissions associated with electricity generation (this has already been introduced in the previous paragraph on primary energy consumption).

This CO2 emission factor varies since the activation and power output of individual production units are constantly adapted to the current electricity consumption.

An example of CO2 emission factors for France is shown in *Figure* ***33*** for the years 2007-2012.

The figure illustrates that these profiles vary significantly from one year to another, with strong variations on a seasonal, daily and hourly basis.

However, in most simulation studies for energy systems and concepts, typical year are used. This adds an additional complexity since it is thus necessary to develop, on the same basis as for typical weather file for a year, a typical CO2 emission profile.

[11] For the example of the US : https://www.epa.gov/ghgemissions/overview-greenhouse-gases

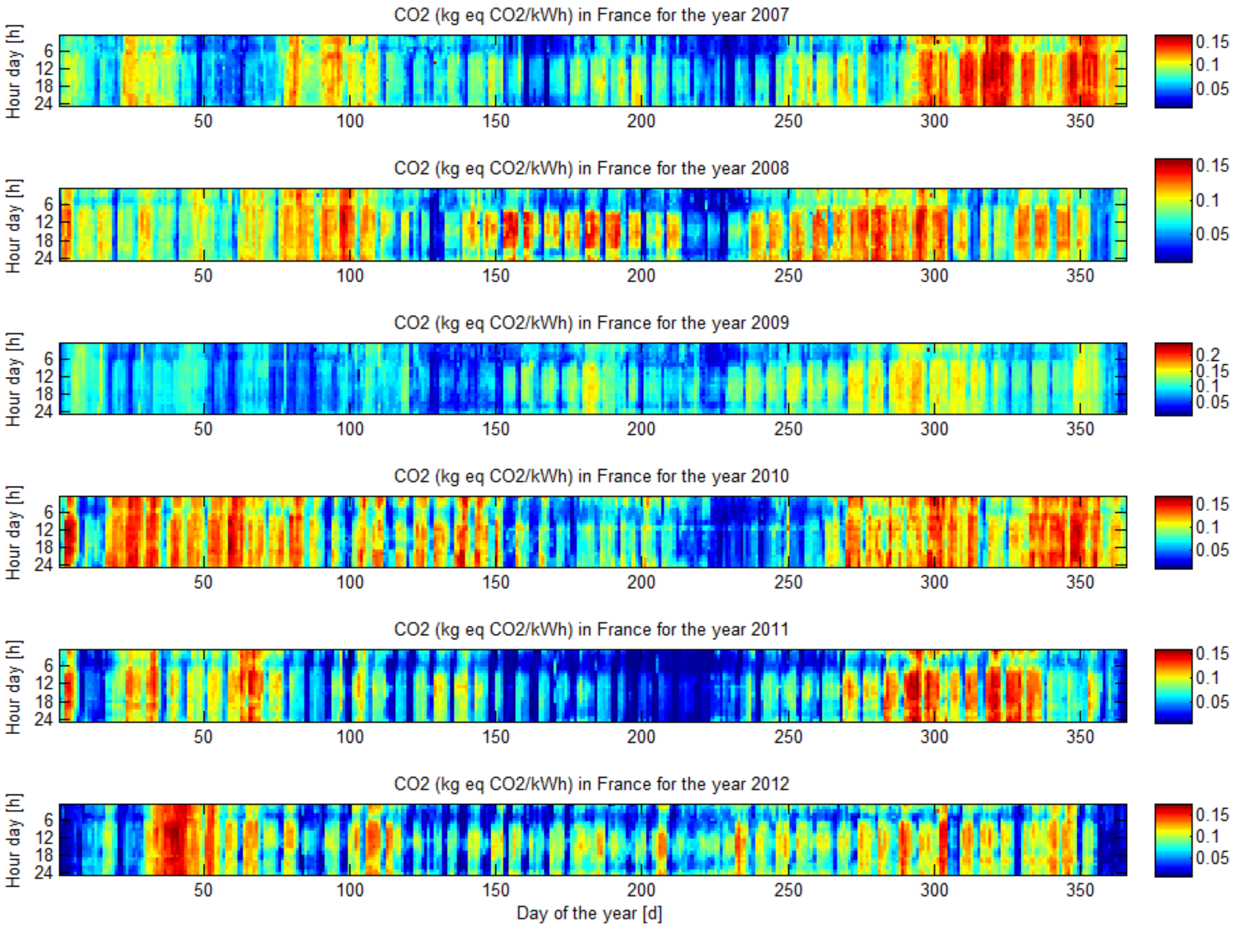


Figure 33 : CO2 emissions from electricity generation in France

In the Resilient project, emission factors for electricity generation have been defined for the 5 participating countries. These values are shown in *Figure* ***34***. The example hereunder is based on the IPCC and LCA methods. As can be send, the LCA method which considers the whole lifecycle will lead to higher values.

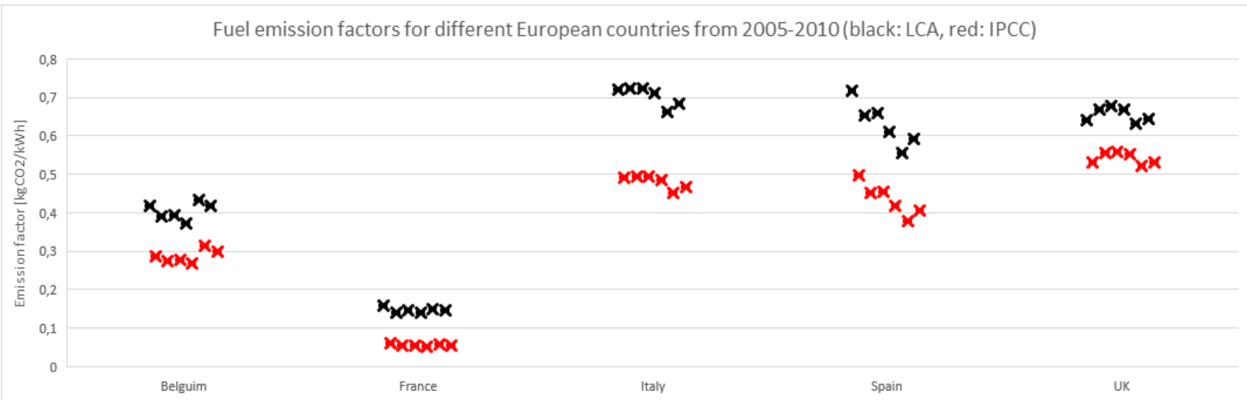


Figure 34 : Average fuel emission factors (IPCC and LCA methods) from 2005–2010 [12]

[12] Convenant of mayors : https://www.covenantofmayors.eu/IMG/pdf/Covenant_ReportingGuidelines.pdf

Emissions from fossil fuel or gas

These emissions can be calculated as follows:

- Calculate or measure the energy consumption [kWh] or its volume [m3] (plus temperature and pressure in case of gases)
- Convert this amount into a normalized volume of fossil fuel [Nm3 = kWh / (kWh/Nm3)]
- Apply the emission coefficients to the consumed volume [CO2 = Nm3 x (CO2/Nm3)]

Conversion factors to change mass or volume units into energy units, according to fuel type, representing the calorific value of fuels can easily be found in the literature.

Table 2 : Fuel conversion factor for several fossil fuels

FUEL	CONVERSION FACTOR
Natural Gas (m^3)	10,70 kWh/Nm^3 of natural gas
Butane Gas (kg)	12,44 kWh/kg of butane gas
Propane gas (kg)	12,83 kWh/kg of propane gas
Gas Oil (kg)	11,78 kWh/kg of gas oil
Fuel Oil (kg)	11,16 kWh/kg of fuel oil
Generic LPG (kg)	12,64 kWh/kg of generic LPG
National Coal (kg)	6,42 kWh/kg of national coal
Imported Coal (kg)	7,09 kWh/kg of imported coal
Petroleum Coke (kg)	9,03 kWh/kg of petroleum coke

To calculate the associated emissions, the corresponding emission factor can be found in the literature:

Table 3 : Fuel emission factors for different fossil fuels

FUEL	EMISSION FACTOR
Natural Gas (m^3)	2,15 kg CO_2/Nm^3 natural gas
Butane Gas (kg)	2,96 kg CO_2/Nm^3 butane gas
Propane gas (kg)	2,94 kg CO_2/Nm^3 propane gas
Gas Oil (litres)	2,79 kg CO_2/Nm^3 gas oil
Fuel Oil (kg)	3,05 kg CO_2/Nm^3 fuel oil
Generic LPG (kg)	2,96 kg CO_2/Nm^3 generic LPG
National Coal (kg)	2,30 kg CO_2/Nm^3 national coal
Imported Coal (kg)	2,58 kg CO_2/Nm^3 imported coal

Emissions generated by biomass

The use of pure biomass as a fuel leads to what are considered neutral emissions, as the CO2 emitted during combustion had been previously absorbed from the atmosphere. Therefore, the emission factor applied to pure biomass is zero (t CO2/TJ or t or Nm3).

'Biomass' means non-fossilised and biodegradable organic material originating from plants, animals and micro-organisms, including products, by-products, residues and waste from agriculture, forestry and related industries as well as the non-fossilised and biodegradable organic fractions of industrial and municipal wastes, including gases and liquids recovered from the decomposition of non-fossilised and biodegradable organic material[13].

[13] http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2007:229:0001:0085:EN:PDF

It must be remembered that, when referring to biofuels, this emissions calculation method does not include associated emissions that may arise from its life cycle.
Fuel or material shall qualify as pure biomass if the non-biomass content accounts for no more than 3% of the total quantity of the fuel or material concerned.

Emissions saved by Renewable energy

- Renewable energy for self-consumption of the district

  The use of renewable energy only for self-consumption results directly in a reduction of energy consumption (from the electricity grid and/or fossil fuels) and thus of the corresponding emissions of backup fossil fuels or electricity.

- Renewable energy connected to the grid (export from a district)

  Producing renewable energy (e.g. a solar or wind power installation) that is connected to the grid translates into a reduction of emissions for the total amount of electricity generated in that country, that is, the electricity mix decreases proportionally (in theory). However, the impact of that change is very small and is for the moment not considered in the suggested methods.

1.3.3 COSTS

From a business point of view and as in many areas, the main driving forces behind the choice of an energy solution are the investment, operation costs, maintenance costs and eventually associated incomes (generated from electricity selling for example). Furthermore, a same solution in terms of technical specifications and even in terms of capex can be more or less cost effective from a country to another, because of the great versatility of the energy prices (gas, fuel, electricity). Finally, the time constant for such analysis applied to certain energy systems (geothermal energy, districts energy systems etc.) is far beyond the minimal cost escalation time, up to 30 years or even more, that leads also to consider prediction of the future trends of the global energy market. The calculation methodology presented hereafter tends to address as much as possible these parameters, with the objective to determine at the end of the day a payback period.

Investment costs

Investment can be determined with a bottom-up approach, using a cost database for every elementary component influencing the total balance of the energy system. That includes systems, building envelope, windows and distribution on a district level in the case of district energy networks. For each unitary investment, unit lifetime has to be defined which leads to the case that during the time span of analyses, several units might have been changed once or several times and others not.

The principle remains the same for other components such as the envelope, using a surface unit, or the piping network using a length unit. Finally, for each cost function, particular attention is to be paid to ensure boundary range values (minimal and maximal) to avoid any dangerous extrapolation.

Maintenance costs

Maintenance cost can directly be estimated from the elementary investments, with a user-defined percentage. The calculated values are then taken into account for each year, assuming a fixed price (once determined from the initial investment, the cost is kept constant and inserted every year in the cash flow calculation).

Operation cost/income

Operation cost is deducted from the annual consumptions and productions on the following energy carriers: gas, fuel and electricity. Regarding the business model for energy production (only electricity) that can be generated either from fossil energy (combined heat power) or from renewables (photovoltaics) a choice has to be made on how to consider the strategy: either all electricity can be sold to the network or a self-consumption maximisation approach is used. The tendency in most countries is to push self-consumption strategies (which can be combined with on-site storage via batteries or electric cars) since this will, in most cases, reduce peak loads on the electrical grid.

In the Resilient project, it has been tried to build a generic model for electricity feed-in tariffs. This would have been good for evaluating the rentability of self-consumption and storage strategies. However, the tariff models are very different since they vary from country to country and even in different regions of a country as well on the connected client (individual or business) and nominal power of the energy contract.

<u>Discounted Payback Period – Net Present Value</u>

Once all the annual net cash inflows/outflows calculated over the user-defined timespan, the so-called discount rate is applied. This crucial value, having the potential to make big differences in decision making by varying of just one or two percentage points, is also defined by the user, whatever the methodology is used to figure it out. Whether the user wants to get a non-discounted analysis he only has to set this value to zero.

The total cumulative cash flow can then be calculated (containing as many values as the number of years defined in the time-span) and payback period is typically deducted as the year corresponding to the break-even point of the cumulative cash flow curve, and the net present value as the cumulative cash flow value itself for the final year.

1.3.4 User acceptance

This section is focused on the assessment of other factors related to the interaction of the users with the energy systems and their level of acceptance which is an important factor and must be guaranteed.

In terms of quantification of this acceptance, there are different factors to be considered, the three most important ones:

- Occupant/user satisfaction with the buildings and energy system in place
- Occupant health
- Comfort (mainly thermal)

<u>Occupant/user satisfaction</u>

The quantification of this factor of acceptance can be analysed based on user enquiries in real buildings and is not dealt with in this report. Numerical simulation will not have a significant contribution, except modelling of user satisfaction, which is out of the scope.

<u>Occupant health</u>

Occupant health is mainly related to pollutant emissions and thermal conditions outside the critical comfort range. Typical pollutants analysed in simulation studies, especially on ventilation of buildings are CO2 or radon. They will not be further developed in this report.

<u>Thermal comfort</u>

Thermal comfort is defined in the Standard ISO 7730 as “that condition of mind which expresses satisfaction with the thermal environment”, that is, satisfaction with the hydro-thermal condition to which a person is exposed to.

According to that statement, the term “thermal comfort” describes a person’s psychological state of mind and is usually referred to in terms of whether someone is feeling too hot or too cold. Thus, the thermal (or hygro-thermal) comfort is an indicator of satisfaction with the environment or the absence of thermal discomfort.

Definition of thermal comfort is not an easy task due to the fact that a range of environmental and personal factors must be taken into account when deciding what will make people feel comfortable. These factors make up what is known as the “human thermal environment”.

The best achievement that can be expected in a building, as a thermal environment, is to reach the “reasonable comfort” that is the thermal environment which satisfies the majority of the people (usually 80-90% of the occupants for indoor/outdoor). It can be said that thermal comfort is not usually measured by sensors, but by the number of people complaining of thermal discomfort.

The most commonly used indicator of thermal comfort is temperature (air or operative). It is easy to use, and most people can relate to it. But although it is an important indicator to take into account, temperature alone is neither a valid nor an accurate indicator of thermal comfort or thermal stress. The temperature should always be considered in relation to other environmental and personal factors.

The six factors affecting thermal comfort are both environmental and personal. These factors may be independent of each other, but together contribute to user’s thermal comfort.

Environmental factors:

- Air temperature: Average temperature of the air surrounding the occupant, also known as dry-bulb temperature. Note that in most cases, temperature varies in space and time. Especially thermal stratification will expose a human body not only to one single temperature, but a field of temperatures.

- Mean Radiant temperature and radiation: Thermal radiation is the amount of radiant heat transferred from a surface, and it depends on the material’s ability to absorb or emit heat. The mean radiant temperature depends on the temperatures and emissivity of the surrounding surfaces as well as the view factor, or the amount of the surface that is “seen” by other objects. So, the mean radiant temperature experienced by a person in a room with the sunlight streaming in varies based on how much of her body is in the sun. Radiant temperature has a greater influence than air temperature on how we lose or gain heat to the environment.

- Air speed (draught): Air speed is defined as the rate of air movement at a point, without regard to direction. According to ASHRAE Standard 55, it is the average speed of the air to which the body is exposed, with respect to location and time. The temporal average is the same as the air temperature, while the spatial average is based on the assumption that the body is exposed to a uniform air speed, according to the thermo-physiological model used. However, some spaces might provide strongly non uniform air velocity fields and consequent skin heat losses that cannot be considered uniform. Therefore, the designer shall decide the proper averaging, especially including air speeds incident on unclothed body parts that have greater cooling effect and potential for local discomfort.

- Humidity: Relative humidity is the ratio between the actual amount of water vapour in the air and the maximum amount of water vapour that the air can hold at that air temperature, while absolute humidity gives the absolute value of this amount. However, since thermal comfort is closely linked to the couple of temperature and humidity, relative humidity is a more generic way to analyse and understand comfort and is thus widely used in this context.

Personal factors:

- Clothing insulation: The heat loss of a human body is influenced by the clothing as insulation worn by a person, having a substantial impact on thermal comfort due to the modification of thermal balance. Clothing is both a potential cause of thermal discomfort as well as a control for it as we adapt to climate which we live and play. People can add layers of clothing if they feel cold or remove layers of clothing if they feel warm.

- Metabolic rate: The ASHRAE 55-2010 Standard defines metabolic rate as the level of transformation of chemical energy into heat and mechanical work by metabolic activities within an organism, usually expressed in terms of unit area of the total body surface. Metabolic rate is expressed in met units (1 met = 58.2 W/m2, which is equal to the energy produced per unit surface area of an average person seated at rest). People have different metabolic rate that can fluctuate due to activity level and environmental conditions.

Thermal comfort assessment includes a part of unambiguously defined performance indicators based on the notion of objectively quantifiable performance measures. The set of indicators is founded on existing knowledge in biophysics and physiology. Several researchers discussed the theoretical derivation of the indicators for the normative assessment of thermal comfort in buildings and their relevance in building design.

According to the factors which are involved in thermal comfort and that have been described before, some classical sub-indicators of thermal comfort combining several states or conditions are:

- PMV (Predicted Mean Vote)
- PPD (Percentage of People Dissatisfied)

Or, in certain studies, only individual states or conditions might be used such as:

- Air and/or operative temperature
- Relative humidity
- Air velocity (Draught)
- Vertical air temperature differences
- Radiant asymmetry

Each performance indicator is dependent of specific indicators or parameters.

The observation of these indicators leads to different qualitative and quantitative assessment methods for both design and operation phases.

Assessment methods for thermal comfort are described more in detail in the Resilient D5.2 deliverable[14].

Since many studies related mainly concern the performance and consumption of energy systems, the Resilient project has used the operative temperature for all evaluations. The use of more detailed methods (e.g. PMV/PPD) would need the estimation or measurement of very detailed states and parameters which are not available in many simulation tools that fit to this purpose.

[14] Coupling renewable, storage and ICTs, for low carbon Intelligent energy management at district level (Resilient) – European project, agreement n° 314671

2. EXPERIMENTAL MEASUREMENT OF ENERGY PERFORMANCES

2.1 MEASUREMENTS APPROACHES

Two main types of measurement approaches exist:

- Test of products in a laboratory with standardised or custom test scenarios
- Evaluation of systems as a complete installation in real buildings

Both approaches have their advantages and disadvantages. They will be presented and discussed in the next paragraphs.

2.1.1 LABORATORY TESTS

Laboratory tests are used since the first steps in research, of course also in the field of energy systems.

The tests can be grouped by the scale of the experiment into:

- real scale experiments: this group is generally used to test energy systems as a whole or partly. An example is the test of a heat pump on a test rig.
- reduced order model experiments: reduced order models can be seen with some kind of similarity to numerical simulation. While numerical simulation requests a modelling effort in order to properly build the model of the system or concept to be simulated, reduced order simulation requires a complete analysis of similarity in order to proof that the reduced order model will be exposed to the same phenomena (e.g. Reynold numbers etc. in case of fluid mechanics).

A variant of real scale and reduced order model experiments would be to test a real system, but with a smaller nominal power. This might also make sense of controller shall be evaluated which are identical for a range of products (e.g. heat pump with 5, 7 and 10kW nominal thermal output).

Laboratory tests can then be divided in two other categories:

- steady state tests: steady state tests are used to evaluate performances at one or several given operating points. For each operating point to be determined, steady state conditions will be controlled in order to make sure the validity of the data point (e.g. COP of a heat pump for a given set of heat source and sink temperatures).
- transient tests: transient tests can have different motivations. Either they are carried out to determine performances related to different control signals (e.g. part load with OnOff cycles), or they shall serve to evaluate for example the robustness of control algorithms (e.g. stability of output for proportional-integral controllers), or the component are exposed to variable boundary conditions (e.g. system testing for solar hot water heaters with imposed hot water draw profiles).

In a last step, laboratory experiments can be divided into two other categories:

- standardised tests: these tests are mainly used in official assessment or certification programmes. A standard defines exactly all test conditions and the laboratory must be accredited in order to ne authorised to carry out the certification tests.
- custom tests: custom tests are mainly used for prototypes or research on improvements of products or components.

Of course, combinations of these three mentioned groups or categories are possible.

2.1.2 IN-SITU MEASUREMENT

In situ measurements are considered by many people as the most realistic way to assess performances of energy measures and/or systems in a real context.

The idea is to measure real energy performances or characteristics directly in a building with real characteristics, real equipment and real occupants. The building is thus considered as “reality” since it is just one in the building stock picked up to allow monitoring.

Depending on what is to be analysed, sensors and meters will be added on site in order to allow measurement and then, the analysis of the behaviour in the “real” world.

While the idea is of course good in general, there are many aspects that should not be neglected. Some key aspects are listed hereunder for discussion:

- Even if the building is a real one, does it really represent “reality”? Reality means that by testing the product, one can make sure that the performance will be at least similar or can be extrapolated to other buildings. This is rarely the case since occupant behaviour, building characteristics and specificities are very different from case to case.

- In order to allow any extrapolation, a larger set of experiments has to be carried out. This is generally called “monitoring campaign”. To ensure that this campaign covers statistically all specificities on terms of building, equipment, sizing, occupant behaviour and many other aspects, this is an extremely complex and critical issue.

- Even considering that the previous question marks are managed, the question is if occupants do really behave as usual while being “observed”? Especially in energy performance questions, will they change their behaviour in order to show a better picture of themselves (who will appear as an energy harvester), even if they are supposed to be anonymous? The same is true for the installer or the company ensuring the maintenance of the system. Will they do the same job as for any other building? Or do they want to seem better as they are and fine-tune the energy system?

- Identification of sites for a monitoring campaign is very often complex and time consuming. The search of sites can either pass by the installer networks (who are not so much familiar with the objectives of the monitoring), by official announcements or by social connections, relations or networks. But who will accept the offer and constraints of the campaign? Will these people be the “typical” people with “typical” behaviour? This is not sure at all.

- Is the combination of selected building (geometry, orientation, isolation, type, etc.), climate and occupants statistically the right one to cover a large range of other cases? How to ensure this coherence? This is a again very difficult issue.

All these aspects are generally known, but monitoring campaigns are still considered to be obligatory to demonstrate real performances (this is good). But if budget is limited, and only one or “some” samples can be picked up, particular attention has to be paid on the representativity of the outcomes.

2.2 MEASUREMENT DEVICES

In-situ measurements are generally time and cost expensive. To reduce costs, a compromise between accuracy and budget is often researched.

*Table **4*** lists typical recommendations on measurement types and recommended accuracies for measurements in monitoring campaigns. These have been defined based on available technologies with acceptable costs.

More details on the definition of these accuracies and the types of sensors or equipment that can be used to match these recommendations are specified in RESILIENT[15] D5.2 deliverable. It details specifications for the different measurement types with, for each variable, the suggested accuracy. This accuracy has been defined on the basis of previous experiences in monitoring projects (Sepemo[16] project) and will allow to calculate efficiencies with a global accuracy of lower than 4 %.

The suggested time step for monitoring is 1 minute in the specifications from Resilient. This time step has been chosen mainly for capturing phenomena on the building level (local production and electricity consumptions). It can be higher for central and distribution level, since control actions of components on this level are generally of lower frequency. But it can also be lower, if high frequency data has to be measured. For example, to correctly measure DHW draw profiles with flow rate and temperatures, it is important to reduce significantly the time resolution. In this case, the order of magnitude of the time step is from 1 to several seconds.

Temperature measurements that are not directly linked to performance calculation can have lower accuracy since they are only used as supplementary indicators. Also, wireless sensors can be applied in this case.

Table 4 : Recommended measurement accuracy for in-situ energy system monitoring

Type	Index	Name	Variable name	Variable type	SI Unit	Comments	Accuracy
Thermal energy metering	Q	Heat meter	T1	Temperature	°C	The meter has to deliver temperatures, flow rate and energy	+/- 0,1K
			T2	Temperature	°C		+/- 0,1K
			m	Flow rate	m3/h		+/- 1.5% of measurement
			Q	Energy	Wh		+/- 3.5% of measurement
Electricity metering	Eel	Electricity consumption	Cel	Active power	W	the meter has to deliver the instantaneous power or fine pulses	+/- 0.5% of measurement
		power factor	cos-phi	power factor	-	optional but recommended	+/- 0.5% of measurement
Fuel metering	Fuel	Gas meter for gas consumption	Vgas	flow	m3/h	gas meter is combined with température and pressure measurement. Specific heat value can be taken from provider or by measurement	+/- 1% of measurement
		Flow meter for fuel consumption	Vfuel	flow	m3/h	Specific heat (LHV/HHV) value can be taken from provider or by measurement	+/- 1% of measurement
			Msol-fuel	quantity	kg	Solid fuel consumption is measurement by max balance or delivery. Specific heat (LHV/HHV) value can be taken from provider or by measurement	+/- 1% of measurement
other measurements	Tamb	Room temperature sensor	Tamb	Temperature	°C	average of representative zones	+/- 0,5K
	Tsurf	Surface temperature sensor	Tsurf	Temperature	°C	average of representative zones (floor heating)	+/- 0,5K
	Text	External temperature sensor	Text	Temperature	°C		+/- 0,5K
	P	Pressure sensor	p	Pressure	Pa		+/- 1% of measurement
	HR	Humidity sensor	HR	Humidity	%		+/- 2% of measurement
	Irr	Solar irradiation	SR	irradiation	kWh/m²	direct, diffuse (or global)	+/- 5%
	Move	Movement detection	Move	occupancy	-	average of representative zones?	
	Luminance	luminance in buildings	lum	lumen	lux	average of representative zones	
						Time step of measurement	**60 sec**
						Time step for data acquisition	**60 sec**

Also, besides the accuracy specifications, it has been underlined that sensors and meters have to be calibrated/certified before and after their use in order to ensure the correct outcomes. In

[15] Coupling renewable, storage and ICTs, for low carbon Intelligent energy management at district level (Resilient), Europe (EeB.NMP.2012-1), Grant Agreement No.: 314671
[16] SEasonal PErformance factor and MOnitoring for heat pump systems in the building sector (SEPEMO), CIP-IEE-2008 - IEE/08/776/S12.529222

in-situ campaigns, this will drastically increase the budget. Different approaches exist there: a manufacturer calibration, in-house calibration or the calibration by a recognised third-party company or institution. As mentioned before, the calibration should theoretically be done before installation of the equipment, and after removal on site. If the final verification is not coherent, the total measurement period might be invalid.

For the measurement in laboratory tests, requirements are much higher in terms of accuracy. This can easily be explained with the fact, that only 1 set of sensors and meters has to be purchased and maintained (including calibration). The costs are then divided by the number of tests and can be covered much easier than for monitoring campaigns.

In these cases, the types of sensors will also be different. As an example, while monitoring campaigns will mainly use energy meters using ultrasonic flowmeters which are a very good compromise between costs and accuracy, laboratory equipment will either be electromagnetic or Coriolis flow meters which increase accuracy by almost a factor of 2-3 for the flow measurement.

2.3 DISCUSSION OF MEASUREMENT ADVANTAGES AND DISADVANTAGES

There is generally no competition between laboratory and in-situ measurement. Both techniques have their well-defined field of application.

While laboratory tests cover principally research and certification aspects, in-situ campaigns have the role to demonstrate in a real case, that the concept or system operates as planned. Even with the critical points identified in the corresponding paragraphs, it is very important to convince people of the performances of the system. And this is important in any case, even if the performance cannot be guaranteed on a larger variety of buildings. To cover this last question, several proposals will be listed at the end of this chapter, by combining approaches of measurement, simulation and emulation in order to guarantee performances while managing the necessary budget to do that.

3. SIMULATION FOR THE ANALYSIS OF ENERGY PERFORMANCES

3.1 MODELLING AND SIMULATION

3.1.1 HISTORY OF NUMERICAL SIMULATION AND USAGE

On the field of research on energy systems or concepts (as on many other fields), numerical modelling and simulation is an essential instrument because it responds to the incessant need to improve knowledge and provide solutions to almost any problem.

The study of heat and mass transfer in buildings dates back almost a century now with the models developed having become more complex and refined over the decades. From the 1970s, numerous thermal building simulation software programs have been developed. Over the years, the monolithic architectures that characterized the first developments have given way to much more flexible and modular approaches: description of the problem, identification of phenomena and their links, assignment of models, resolution and analysis become separate worlds.

These evolutions were strongly inspired by concepts borrowed from systemic and computer science (e.g. objects, hierarchy, inheritance, etc.) and they were accompanied by several efforts to define semantics of transversal modelling on different fields. However, the needs of research and a profession that requires increasingly global and transversal evaluation approaches have not been met yet.

Today, developments are marked by the concept of interoperability and by the appearance of digital platforms grouping dedicated codes (thermal, acoustic, lighting, life cycle analysis, etc.) capable of sharing information, to interact with each other and to provide more global design solutions.

To provide some examples, the use of simulation will help for:

- the innovation and the creation of new ideas on various problems or concepts related to energy performance: the integration of renewable and heat recovery solutions, energy management systems, energy production in various forms, storage and distribution or production in networks, new envelope concepts etc. They need to be tested and evaluated and, as such, computer simulation of the operation of the devices imagined by the researchers allows to provide rapid answers and at lower cost as by experiment. And partly also results with higher quality.

- interdisciplinary exchange, through a network containing at the same time thermal engineers, electricians, automation engineers and socio-economic and building stakeholders (architects, design offices, managers, etc.)

- the development of a global evaluation and design approach integrating energy, air quality and comfort, environmental, socio-economic aspects, etc. with the ambition to meet objectives of a diverse nature (certification, design, management, diagnosis, etc.) and which involve different skills and spatiotemporal scales of analysis.

- the generation of dedicated tools according to needs (energy certification, design, monitoring and operation, regulation, energy diagnosis, etc.) and the questions asked by building stakeholders is a key point for efficient transfer of innovative technologies and scientific knowledge to practice.

3.1.2 STRUCTURE OF A NUMERICAL MODEL

Computer simulation can be defined as the process of mathematical modelling that allows to predict the behaviour of a physical system. The process of simulation can be divided into the following chain of three actions: Modelling, Simulation, Analysis. It has to be highlighted that a model, by definition, is in fact only an approximation of the "real" component which is modelled.

Modelling is the activity of writing algorithms and equations that allow to rebuild the real system as a computer model. It needs parameters and inputs for producing its outputs. The simulation corresponds to run the complete model in order to solve all equations in the model.

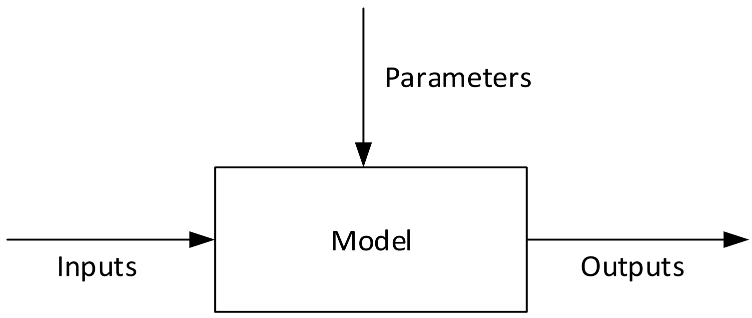


Figure 35 : Definition of numerical simulation using models

Each model needs **inputs** and **parameters** in order to calculate **outputs** (*Figure* ***35***). In this report, *the definition of* ***parameter*** *is defined as any type of data input* (strings and/or numerical values in scalar or matrix format) necessary in the model that is *constant throughout all iterations* (in case of the simulation of a single operating point) *and the complete simulation time* (in case of a time dependent simulation). Contrarily to parameters, **inputs** are defined as any data input into the model that might vary during iterations or time.

Based on these parameters and inputs, the outputs can be calculated and then analysed. The analysis will either use directly simulation outputs (e.g. time series with thermal power of a heat pump, temperatures etc.) or calculate additional information in postprocessors.

The model can also be split into several unitary models (*Figure* ***36***), each of them interconnected and dependent on outputs of other models. This is the case in case of subdivision of a complex into smaller sub-algorithms or in system simulations where each component is represented as a unitary model (e.g. a central heating system with production, supply network, hot water radiator, return network and a controller). In this case, in order to ensure the correct result, the model must be run in an iterative process in order to guarantee "convergence" for each calculation step.

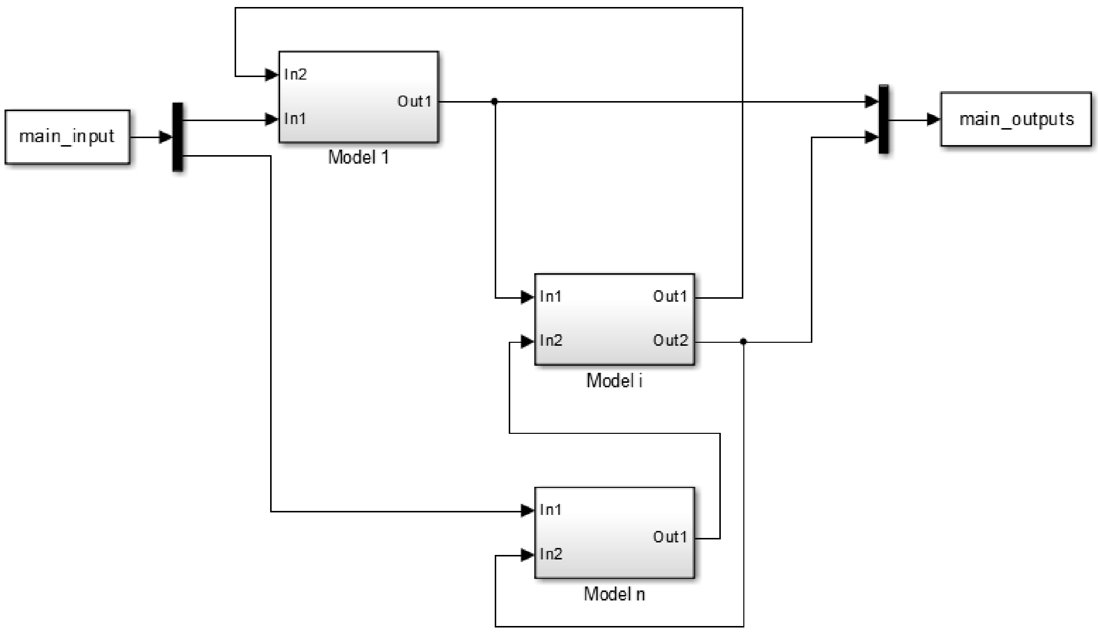


Figure 36 : Simple example of a global model with subsystems

3.2 MODEL TYPES AND CHOICE

Models are built for many different applications and components or systems. In the scope of this report on building and district energy performance evaluation, models are mainly related to:

- Thermal zones: these zones, depending on the simulation objectives can be single rooms, groups of rooms or a complete building. The definition of a thermal zone will allow to group several parts of a building to thermally similar zones. The objective is to simplify as much the model in order to allow lower modelling efforts, lower complexity and faster simulation time. Multi-zone building models will thus contain several thermal zones that are either linked thermally or assumed as adiabatic between themselves.

  Mainly in case of single rooms, several approaches exist on how to model the internal air of this room: so-called "well-mixed" models assuming one uniform air temperature, zonal models in which several air nodes are distinguished or computational fluid dynamics (CFD) models that try to model detailed phenomena in the zone, even natural convention effects. The choice of the appropriate approach is also linked to the modelling choice on the building envelope which will be thermally linked to the air model. Making a very detailed model for the air with a very fine mesh and linking these mesh nodes to one internal surface temperature calculated by a single, lumped wall model will not necessarily improve the quality of results.

- Thermal systems: As already shown in chapter I, the following distinction of system parts is made in this report:

  - Production: fossil and renewable; controllable and non-controllable
  - Storage: sensible, latent, thermochemical
  - Distribution: air, water (and glycol mixtures), refrigerant
  - Usage/emission

  System models are typically composed of different subsystems in a modular approach. It would be possible to build a model of a global system with a unique software algorithm, but this would restrict its application to a very small range of applications. Modular simulation libraries for systems have thus been developed since the early beginning of building modelling and simulation (SIMBAD[17] and Carnot[18] Toolboxes in Simulink[19], TRNSYS, and more recently Modelica[20]).

  As for the thermal zone model, system models vary in level of detail. Starting from simple and steady state efficiency parameter models, the system parts can also be modelled as very detailed component models including various transient phenomena. The appropriate choice will depend on the simulation objectives. A typical example is the model of a water pipe in a heating system. The pipe model can have two different objectives (or both at once):

  - Represent correctly thermal losses in the pipe (purely energy related simulation)
  - Represent correctly the dynamics in the pipe (simulation related to control)

  The choice of model type will thus be different in these both cases. Typical approaches of modelling will thus be either a steady-state model derived from the analytical solution, a simple transient nodal model or even up to a plug-flow model where as much as detail is represented as far as the time step of the simulations allows for.

  For the modelling choice it has also to be defined, especially for production and storage modules, if a white, black or black-box approach is applied (cf. next section).

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[17] A. Husaunndee, et al., Building Simulation, 5, 1997, Prague, Czech Republic, p. 269-276
[18] CARNOT Toolbox Ver. 6.3, 10/2018 for Matlab/Simulink R2016b, © Solar-Institut Juelich
[19] https://fr.mathworks.com/products/simulink.html
[20] https://github.com/ibpsa/modelica-ibpsa

- External environment: The external environment is typically the choice of weather files and radiation processor modules. Weather files generally contain at least the following information:
    - External states: dry and wet bulb temperature, absolute and/or relative humidity, air pressure, ground temperature, etc.
    - Solar radiation: e.g. direct normal and diffuse horizontal radiation
    - Information related to clouds: cloud cover, rain or snow, etc.
    - Wind velocity and direction

  Weather data is stored in several file formats. Most of them have been the initial choices related to a simulation program (e.g. .epw for energy plus, .tmy or .tm2 for TRNSYS).

  Although any weather data set is generated from real measurement in weather stations, simulation weather data is in many cases based on typical weather files. Software such as Meteonorm[21] allow to generate weather data that corresponds to average weather data for a 20-year period. The methods behind the data generation will not be detailed and discussed in this report since this is considered as input data. The advantage of this data is that is represents a typical behaviour of a site. However, with measurement data being more and more complete and detailed, real weather data can be used for simulations. Especially with the trend of performance guarantee for energy systems, to run a simulation for several years with real weather data will allow to analyse the realistic behaviour of the system and its yearly variations of efficiencies and consumptions and thus to ensure the service provider on the range of possible results.

  In recent work, especially when districts or cities are modelled, UHI and micro-climate models have been added to building simulation in order to better represent real external conditions around the building. This means that the impact of building arrangement, short and long wave radiation, vegetation on buildings etc. can be considered in building or district simulation. In the opposite sense, building conditions and consumptions will have an impact on micro-climate, it is thus a coupled phenomenon[22].

- Equipment and user behaviour:

  One of the most complex parts in energy system simulation is the modelling of behaviour and actions of occupants. And not surprisingly, it is at the same time the modelling where mostly simplified approaches are applied. In many cases, occupants and equipment are associated with sensible and latent heat gains in the building zone. Either these gains are assumed constant throughout the simulation, or hourly schedules might be applied (distinguishing weekdays, weekends, holiday periods etc.). This is probably sufficient for estimating the impact of these gains on heating or cooling loads in the thermal zone. The same approach can be applied for domestic hot water draw profiles.

  But on the other hand, actions and behaviour of occupants are still completely simplified while the impact on results in a single building (but also on a district level) is significant:

    - Which set point(s) (mainly temperature) do the occupants fix? Which value(s) in case of several occupants in one zone? Is there a negotiation on these values?
    - What is the reaction of the occupant(s) if the temperature is higher or lower than the set point? Do they open a window (to warm), dress more (to cold) or change set point (either)?
    - What are the actions of occupants? Occupants do many choices and actions. They switch on or off equipment, which has an impact on the behaviour of the building energy system.

[21] https://meteonorm.com/
[22] G. Kyriakodis, E. Bozonnet, P. Riederer. Minimizing the inconsistencies of urban building energy simulations through strong microclimate coupling, Proceedings of the 5th International conference on countermeasures to urban heat islands conference, Hyderabad, India, 2019

- What is the reaction of the occupants on disturbances? Reactions might be on thermal or visual discomfort, for example in case of incoming solar radiation. If the occupants close the blinds, solar heat gains are highly affected. This has a substantial impact on the heat load in the thermal zone.

All these phenomena which are not predictable using standard models will render completely impossible to exactly predict what will happen in one particular building with particular occupants. This must be considered in order to prepare the appropriate simulation approach for a specific objective. If, for example, the typical or reference energy consumption shall be calculated for the building, the applied models using internal heat gains will be sufficient. On the other hand, if the robustness of control of the energy system shall be analysed, the model of occupants and actions should be different.

Recent work has been carried out in the last decade in determining occupant behaviour (Croniq[23], Labeeuw[24] etc.). The developed models are mainly used for the simulation of energy performances of districts. In this case of simulation, average and simple models would affect errors less than for single building simulation since errors of individual buildings will tend to diminish the error for the complete district.

- How to model phenomena:

A key question in modelling energy related phenomena is the level of detail and type of models. A large variety of choices exist with white, grey and black box modelling choices and mixtures between them.

A black box model does not describe any physical phenomena in the model, it does only evaluate an abstract mathematical function without any physical laws behind, in order to calculate the output as function of all parameters or inputs. This approach depends totally on the amount and range of available data that will allow to identify the mathematical function. Different types of black box models exist: They reach from simple polynomial functions, armax methods to neural networks (Bloem[25]) or other approaches. In many cases, if enough (and appropriate) data is available, these models fit very well with the real behaviour of the object to be represented. However, and this is the main reason why these models can be judged non appropriate in some cases, they can give completely wrong output if they are used to predict results outside of the training (or identification) data range or time resolution. In the recent trend with IoT and "smart" sensors[26], black box models have reached an excellent position since the massive deployment of measurement devices allows to cover a broad operation range and thus to minimise extrapolation risks.

On the other hand, white box models represent almost all physical phenomena behind a component[27]. It will mathematically describe dominant physical phenomena in order to characterise how the component will react, exposed to boundary conditions and inputs. Contrarily to black box models, if the model is built with an appropriated level of detail, extrapolation outside the range of validation is possible with acceptable accuracy since the model relies on physical laws and not only abstract mathematical equations. This gives the white box modelling approach an advantage over the black box modelling. However, in order to be able to represent the dominant phenomena, many parameters might be necessary to set up all parameters of this model. Larger calculation time can be the main reason why such a model might be inappropriate in certain cases.

[23] C. Gay and P. Schetelat, "Low carbon district - Energy and behaviour modelling," in Proceedings of the 4th Workshop organised by the EEB Data Models Community ICT for Sustainable Places, Nice, France, 2013

[24] Labeeuw, W. & Deconinck, G., 2013. Residential Electrical Load Model based on Mixture Model Clustering and Markov Models. IEEE Transactions on Industrial Electronics, PP(99), pp.:0–9.

[25] J.J. Bloem, « Application of system identification for thermal characterisation of building components », IFAC Symposium, System Identification (SYSIS'94), Copenhagen, Denmark, pp. 115-27, 1994.

[26] From y point of view a sensor cannot be smart, only measure what it is supposed to measure. Smartness is embedded in other components but the sensor.

[27] « almost » means dominant phenomena. In fact, no white box model will be able to represent all physical phenomena behind since this will go until atomic scale and below.

A grey box model lies in between both first approaches. It will combine abstract mathematical functions with a minimum level of physical behaviour implemented in the model. Built in an intelligent way (depending of course of the simulation objectives) it will add physics into a model that allow extrapolation while minimising the necessary number of parameters to operate it.

The model of a heating or cooling coil can be cited as an example: while the white box model would need the detailed description of coil geometry, the black box model would only be a fit of function parameters to measurement or catalogue data. A grey box model would in many cases be the most suitable since it would, by using heat exchanger efficiency or NUT data, base its calculation on simplified physical behaviour and thus be operational with only 1 needed parameter which can be determined easily (Husaunndee et al[28]).

3.3 ITERATION AND CONVERGENCE

In case of models composed of several subsystems, functions or modules, it must be ensured that results converge to the right solution for one operating point or at each time step for transient simulations.

An example of a composed model with different modules and the reciprocal interactions is shown in *Figure **37***. It clearly demonstrates the necessity of iteration between the different models in order to converge to the correct solution. While some interactions are one-directional, other are multi-directional and the lack of iteration would lead to wrong results.

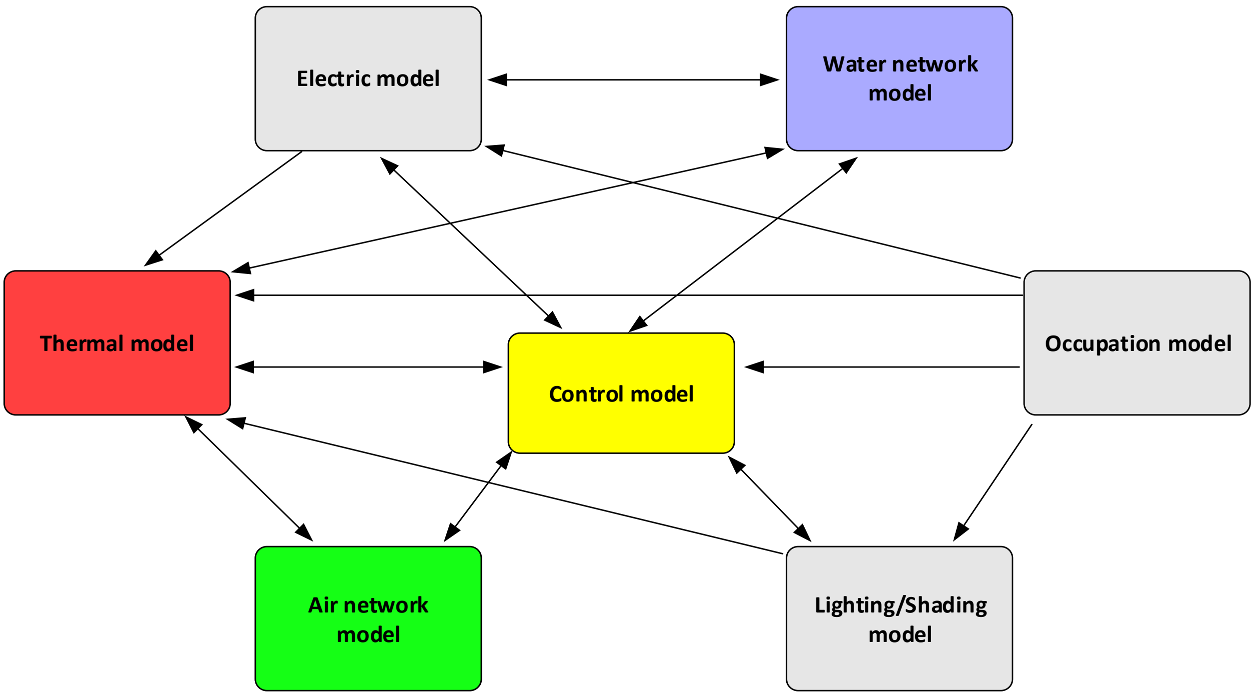

Figure 37 : Modular structure of a building model where iteration is mandatory

Two key approaches exist to handle iteration between several modules: the ping pong and the onion method (*Figure **38***). The figure easily explains both methods with a model composed of two modules “flow” and “thermal” (the author has presented a case study on the coupling of flow and thermal related phenomena). The ping pong method is based on the fact that the input state of the flow module will use results of the “thermal” module from the previous time step. Once the flow calculated, the thermal model is run and calculates its outputs. In many cases,

[28] A. Husaunndee, P. Riederer, J.C. Visier, Coil modelling in the SIMBAD Toolbox - Numerical and experimental validation of the cooling coil model, System Simulation in Buildings - SSB 1998, Liège, Belgium, 1998

this ping-pong method can work if the time step is small enough related to the variation of input values and/or system transients. Once the time step to large, this model will not give satisfactory results.

On the other hand, for the onion method, flow and thermal modules will iterate in order to converge to the correct (correct being the best result with a given error tolerance) solution at the current time step.

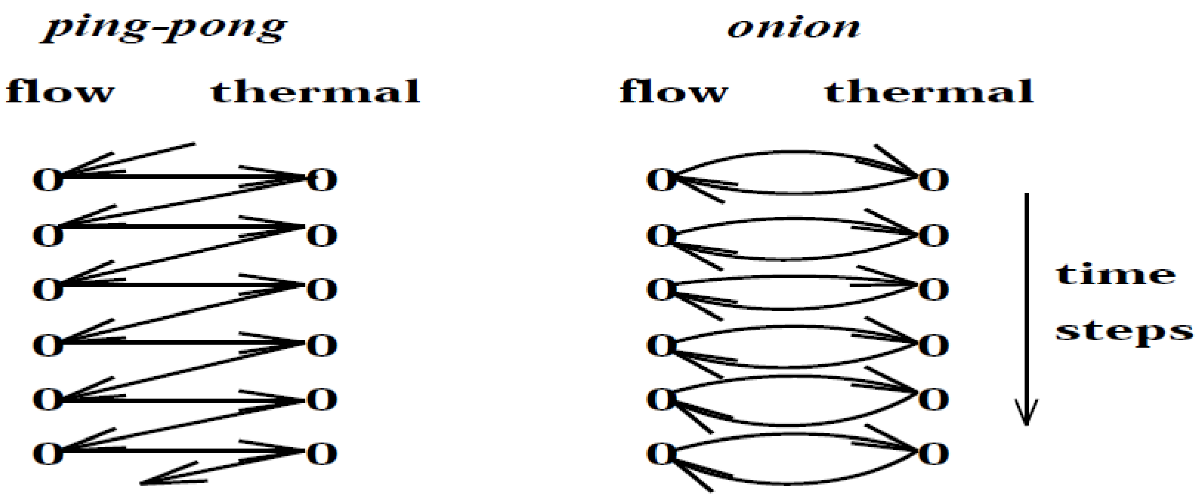

Figure 38 : Ping pong and onion calculation method (Hensen[29])

The onion method will thus give more accurate results, but with the handicap of larger calculation time. In case of doubt on the risk of the ping-pong methods, the onion method will provide a trustful solution.

In some cases, models are built in matrix format in order to implement all phenomena in one single module. This will sure calculate following the onion method and thus give best results. And at the same time with rather good calculation speed since matrix calculation methods are optimised for their resolution. In the presented problem between flow and thermal phenomena, this would give the best resolution with probably acceptable simulation speed. However, for reasons of modularity and interoperability of code, this is not necessarily the best solution.

[29] https://www.researchgate.net/publication/250898695_MODELLING_COUPLED_HEAT_AND_AIR_FLOW_PING-PONG_VS_ONIONS

3.4 CO-SIMULATION APPROACHES

3.4.1 CO-SIMULATION BETWEEN INDEPENDENT SIMULATION ENVIRONMENTS

A large variety of simulation environments exists for thermal building, district and system simulation. Collaborative work is sometimes time-consuming since, in the different steps of building and system conception and optimization, different tools have to be used, each of them specifically dedicated to a particular problem: for example the overall conception of a building can be done using the TRNSYS[30] simulation environment, while optimization of control strategies is likely to be done using the Matlab/Simulink simulation environment[31]. The same system and building are thus modelled several times in order to be able to simulate in the different environments.

A method that reduces modelling time, coherence between different phases in the deployment of an energy concept on a real building or district and a powerful combination of strengths of different tools is "co-simulation".

Two main types of co-simulation can be mentioned:

- Co-simulation of simulation tools by online coupling (example: the coupling of an energy simulation tool with an air flow calculation tool[32])
- Export of models or model assemblies from one or several environments to another one which will profit of these new models (example: export of TRNSYS models into Simulink[33]):

This second type of co-simulation can again be divided into 2 groups:

- the export of a dll or any executable code to allow running only a specific model to be called in the other environment
- the export of the required model, called within the complete simulation kernel which might be required to run the model. This second option has been implemented at CSTB and is described briefly. In fact, this export is in fact a real co-simulation, without the necessity of the user to handle both simulation tools.

Related to these both types of coupling, a methodology to export the models contained in the TRNSYS model library as well as non-standard models (called "types" in TRNSYS terminology) into the Simulink environment, and to use them in a Simulink model assembly, has been developed. Almost any TRNSYS model can be used in the Simulink environment in this way. Unfortunately, this functionality has been maintained only until version 17 of TRNSYS. The cited paper describes the methodology that has been implemented for calling TRNSYS types within Matlab or Simulink and gives advices for integrating those models into existing model assemblies. An automatic routine for exporting TRNSYS types from the TRNSYS Simulation Studio has been implemented.

Components are typically defined by an interface (Application Programming Interface, API) and an implementation (algorithm, set of equations, rules, charts, etc.).

The component interface defines the way the component will communicate with the rest of the system: it enumerates the variables used by the component (component inputs) and the values computed by the component (component outputs) which can potentially be passed on to other components. The component implementation defines the algorithm which allows computing output values from input values.

Both the syntax and the semantics of these component definitions vary between different simulation environments. However, different environments often use the same underlying

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[30] Klein SA, Duffie JA, Mitchell JC, et al. TRNSYS – a Transient Simulation Program user's manual. Madison, University of Wisconsin, 1994

[31] MATLAB. Version 7.0.1, (R14SP1). Mathworks Inc., Ma., USA, http://www.mathworks.com

[32] Weber, A., Koschenz, M., Holst, S., Hiller, M. and Welfonder, T (2002). TRNFLOW:Integration of COMIS into TRNSYS TYPE 56, Proceedings of AIVC 23rd conference - EPIC 2002 AIVC, Vol. 3, Lyon, France.

[33] P. Riederer, W. Keilholz, V. Ducreux (2009). Coupling of TRNSYS with Simulink - a method to automatically export and use TRNSYS models within Simulink and vice versa, Building Simulation Conference 2009, Glasgow, Scotland

operating system technology to implement these concepts. Under the WINDOWS operating system, the Dynamic Link Library (DLL) technology is a commonly used approach for implementing components.

It is usually possible to convert component models from one environment to another (using the same underlying technology) by adapting an existing DLL for a new simulation environment using a traditional programming design pattern known as “Adapter”.

In computer programming, the adapter design pattern (often referred to as the wrapper pattern or simply a wrapper) translates one interface into a compatible interface.

An adapter allows modules to work together that normally could not because their interfaces are incompatible, by providing its interface to clients while using the original interface. The adapter translates calls to its interface into calls to the original interface. The amount of code necessary to do this is typically small. The adapter is also responsible for transforming data into appropriate forms.

As both TRNSYS and Matlab components can reside in WINDOWS DLLs, it is easy to adapt an existing TRNSYS component for use with Matlab and/or Simulink: we simply need to encapsulate the TRNSYS component using the Matlab API, applying the ‘adaptor’ design pattern. This can be done using in a Matlab script or in SIMULINK using the “embedded function”, which will pass its input values (which are passed through Matlab data structures defined in the Matlab API) to the TRNSYS component (using TRNSYS data structures and calling the TRNSYS component’s function), recover the values computed by the component, and return them to Matlab, again using Matlab data structures.

In the embedded Matlab function, the TRNSYS function’s arguments concerning control information about the current state of the simulation must be filled correctly, based on the current state of the Matlab or Simulink simulation.

This first approach will work for very simple components, which only contain basic computation. Complications occur if the component to be used makes use of TRNSYS kernel functions – which is probably the case for more than 99% of all existing components. To be able to handle these cases, it is important that the TRNSYS kernel is initialized when the TRNSYS DLL is called by Matlab. In other words, TRNSYS kernel functions allowing to query values like simulation start and stop time, etc., must return coherent values during this process. The initialization is done by functions added to the TRNSYS kernel for this purpose. (They should be standard functions in TRNSYS 17). They are called during simulation startup in the StartFcn callback of the Matlab embedded function.

The initialization of the TRNSYS kernel also includes opening so-called ‘external files’, if the component uses this concept. External files contain configuration parameters for a given component. Unfortunately, they are opened by the TRNSYS kernel, not the component itself. We therefore must open these files this during the initialization of the Matlab simulation.

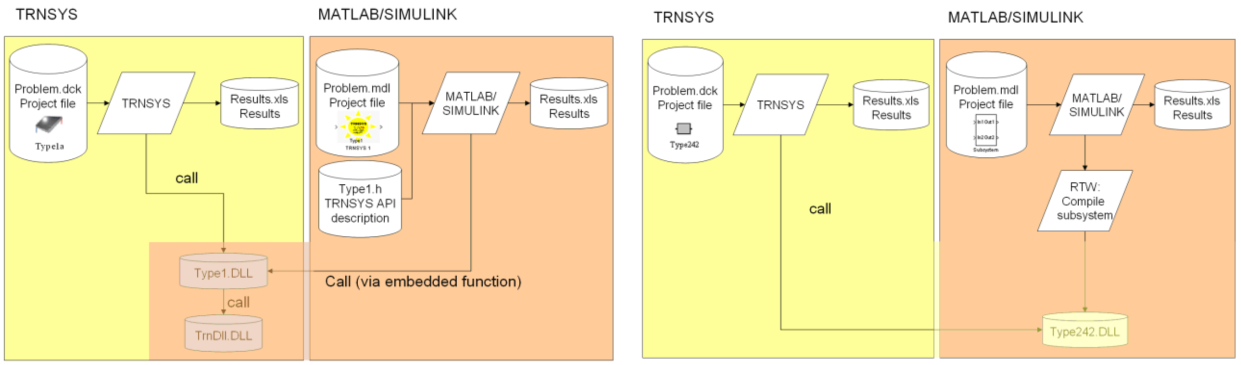

Figure 39 : Coupling between TRNSYS and Matlab/Simulink in both directions

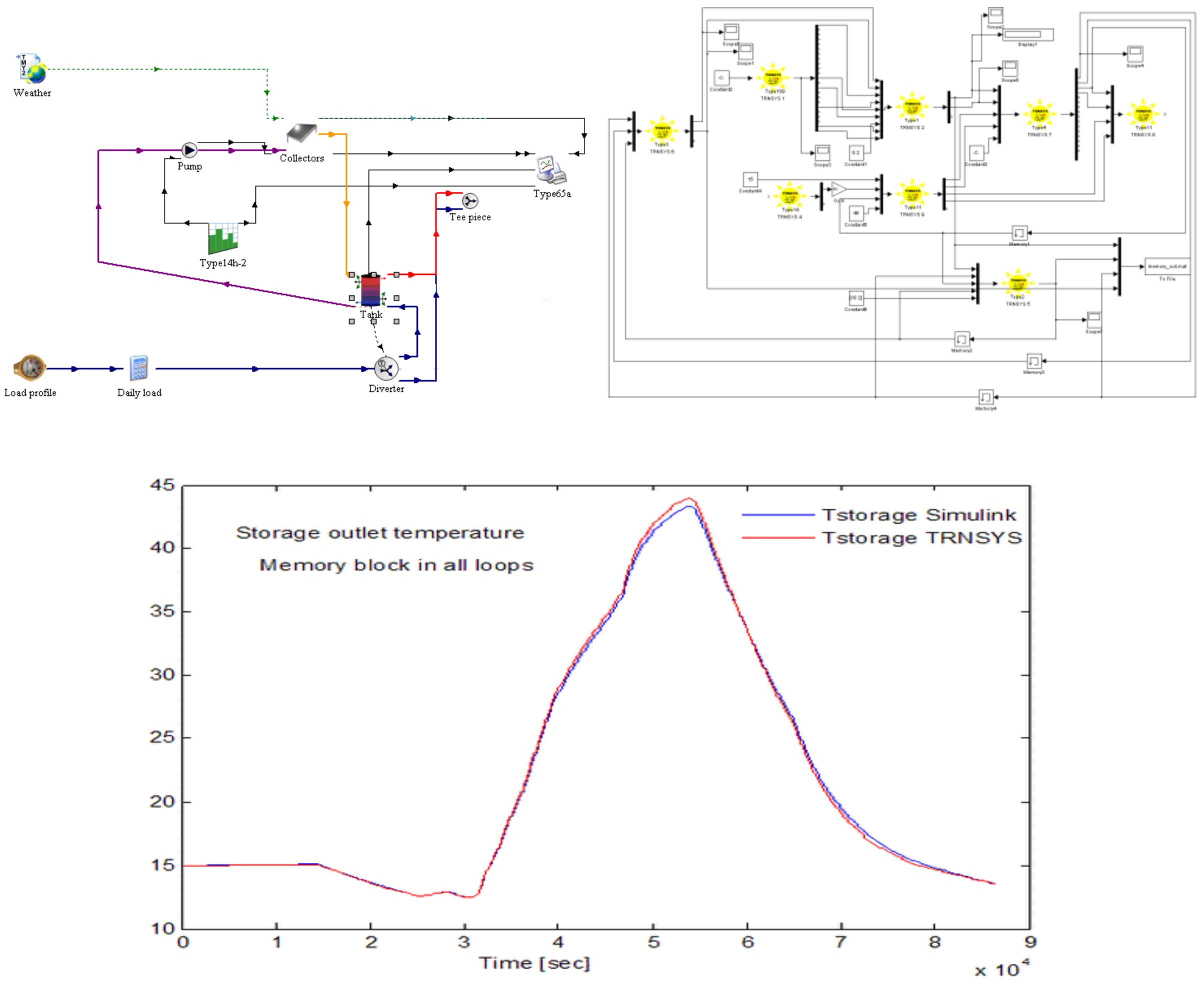

Figure 40 : Demonstration of export of TRNSYS types to Matlab/Simulink environment and comparison of results

The concept has been illustrated by automating the adaption of TRNSYS components to Matlab/SIMULINK and vice versa. The resulting components can be distributed and used without access to the source code.

The validation component per component showed identical results, the coupling is thus valid if only one component is used in the other environment. However, if an assembly of models is exported and “re-assembled” in the other environment, the validity has to be verified case by case: in the example of the solar hot water heater, algebraic loops had to be broken manually by the memory block in Simulink environment. The results showed good agreement, but they were not identical, the energy balance is thus slightly affected (*Figure* ***40***).

3.4.2 GENERIC CO-SIMULATION BETWEEN DIFFERENT SIMULATION PLATFORMS

A second coupling of simulation tools can be realised in a way that both simulations include a module for data transfer at each time step. This means that once the initialisation is done, both tools (or even more) will call, at each iteration and time step, one or several data exchange modules which respect a common data exchange mechanism and protocol (specific API).

In the framework of the Thermoss[34] project, this type of co-simulation module has been implemented into the district simulation tool DIMOSIM to allow the test of optimization modules for the management of district energy systems. The data exchange has been realised based on a socket communication which exists for any operation system and which can be easily applied to any simulation tool. A ready to use package exists in most programming environments that allows socket communication. In Python, the programming environment of DIMOSIM, it is called sockets and is a very simple tool for data exchange.

[34] Building and district thermal retrofit and management solutions (Thermoss), Horizon 2020 research and innovation programme, Grant Agreement 723562

This external control object allows thus to connect an external control algorithm (software or real product) to a simulation in Dimosim. In the following, in the case of a software the coupling will be called co-simulation, in the case of a real product it will be called emulation. Since real products might depend on real time functions, the simulation is then slowed down to real time.

The technical base of the emulation principle will be presented in §3.5 of this chapter.

As an example, the instantiation of a socket class object in DIMOSIM (Python language) is:

```
my_plugin_controller = Thermoss_control('my_plugin_controller')

my_plugin_controller.set_parameters(HOST='', PORT=50004,
        # configuring controller inputs list:
        ctrl_objects={'object_type1': {'instance_1': ['variable1, variable2']},      # object1: set variables 1 and 2 from external control module for instance 1
                      'object_type2': {'instance_1': ['variable1'],
                                       'instance_2': ['variable1']},                  # object2: set variable 1 from external control module for instances 1 and 2

        # configuring measurement list:
        meas_objects={'object_type1': {'*': ['variable1', 'variable2', 'variable3'],  # object1: get variables 1 – 3 for all instances (by definition in the API: '*')
                      'object_type2': {'instance_1': ['variable1']}}                  # object2: get variable 1 for instance 1
        )
```

where PORT is the port number of socket exchange and ctrl_objects and meas_objects are the definitions of data exchange respectively for the control inputs and measurement signal output. Once the definition set up, the communication follows the process shown in *Figure **41***.

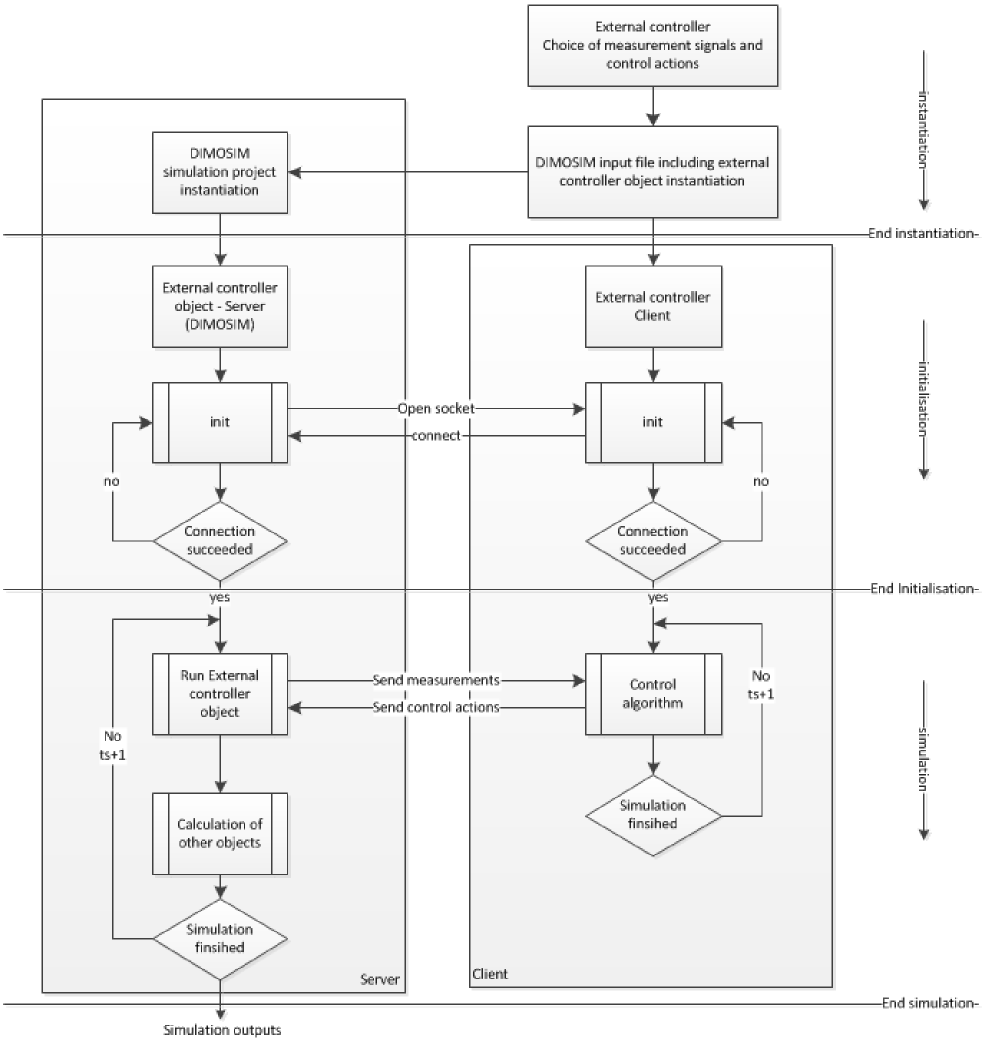

Figure 41 : Co-simulation flow-chart using socket communication

In this implementation, for the initialisation, and later any communication, a json protocol has been chosen. The data exchange has been defined in the dedicated API document.

An example of the communication message at each time step.:

```
to_send =       {"header": {"step": step, "converged": True},
                 "payload": {"ThermalZoneSetPointManager": {"THZONE1": {"current_set_point": 20.15},
                                                            "THZONE2": {"current_set_point": 17.48}}
                            }
                }
```

3.5 MODEL VALIDATION

3.5.1 VALIDATION ON COMPONENT AND BUILDING LEVEL

On the building level, several methodologies for model validation have been suggested in the literature.

Strachan[35] and Witte et al.[36] have listed several validation approaches which can be grouped into:

- Analytical tests that compare software or models against mathematical solutions,
- Comparative tests which compare against other software or models,
- Sensitivity tests which compare small input changes versus a baseline run,
- Range tests which exercise the program over wide ranges of input values,
- Empirical tests which compare against experimental data.

Many research projects and activities in which models are or have been developed often use experimental data as validation approach. This is, assuming the type of data fits with the model to be validated (range of experimental data points, steady state or transients etc.), the best way to validate the developed model. However, it has not to be forgotten that experimental data is also source of uncertainty, the experiments have thus to be carefully apprehended. Strachan[35], in the frame of the PASSYS project, has defined a methodology for empirical validation of models (*Figure **42***).

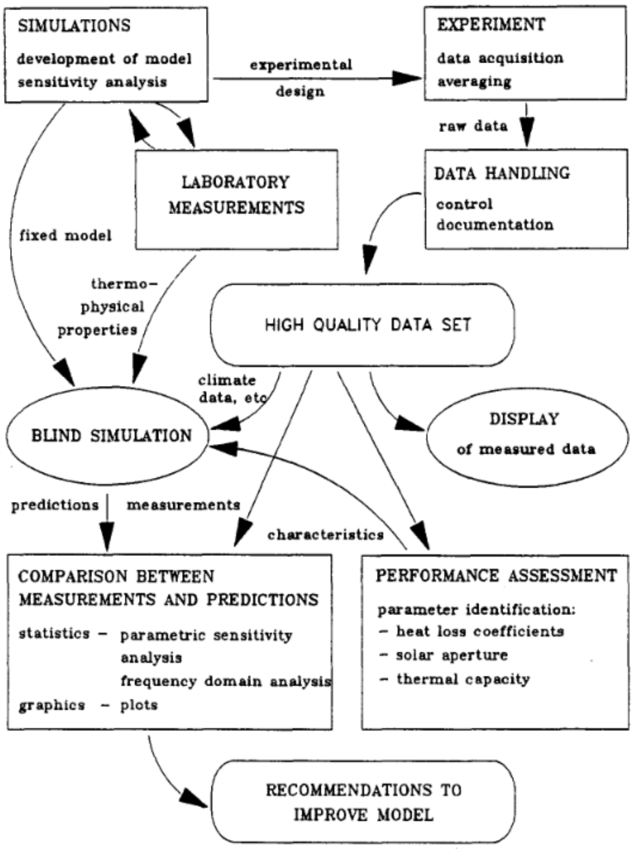

Figure 42 : Methodology of empirical model validation in PASSIS (source: Strachan[35])

[35] P. Strachan, Model validation using the Passys test cells, Building and Environment, Vol. 28, No. 2, pp. 153-165, 1993

[36] M. J. Witte, R. H. Henninger and J. Glazer, 2001, Testing and validation of a new building energy simulation program, Seventh International IBPSA Conference, Rio de Janeiro, Brazil, August 13-15, 2001

If validation data and methods shall not be generated specifically in the frame of projects but be available continuously for a broad research community, several approaches can be listed:

- Creation of a data base with test cases of experimental results: this was the idea in the Passys project;

- Creation of a data base with test cases of virtual test cases.

The ASHRAE BESTEST[37] is probably the most known initiative for the second approach for the validation of models based on virtual examples. It mainly based on comparative tests and covers quite a large field of phenomena inside and outside buildings. All the standard ASHRAE cases are related to the building envelope and do not include systems.

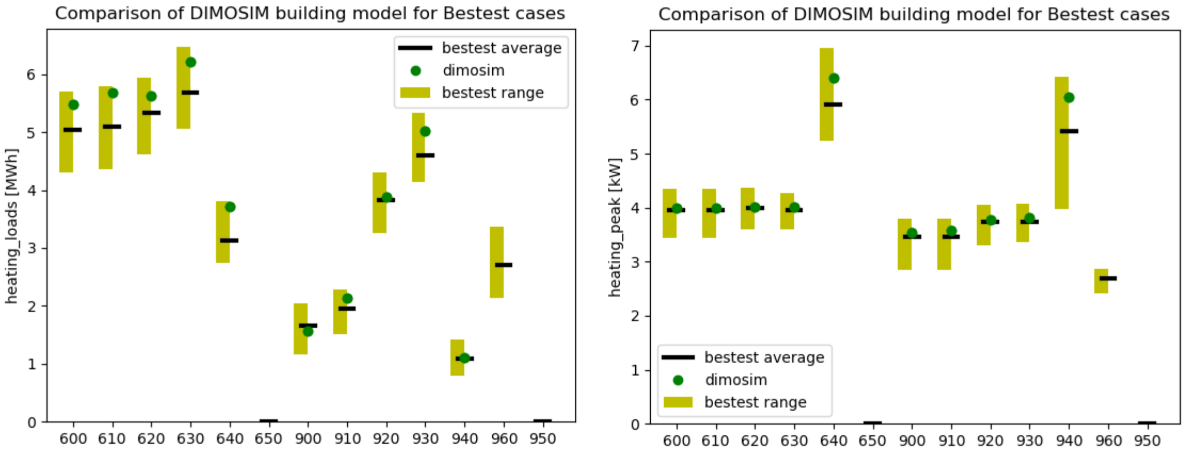

Figure 43 : Example of validation based on BESTEST test cases (left: heating loads, right: peak loads)

To add also test cases related to energy systems, these approaches have been completed later in the HVAC Bestest program[38]. The tests include only partly transients (mainly related to the building structure and envelope). HVAC systems and their control are considered based on ideal control laws which do not require transient modelling of the components.

The previously presented validation approaches allow thus the validation of models and energy simulation programs as a whole with some kind of a catalogue of test cases. However, if the simulation model or simulation platform is used for controller studies, or, as presented in §4, for emulation, the model must consider transient effects of the building and the installed energy system. This energy system is affected by transients related to energy production (e.g. boiler as generator), distribution (e.g. piping) and emission (emitter and control mechanism such as hydronic valve etc.). The validation methodologies including BESTEST and PASSYS will thus not allow to ensure neither the validity of a specific numerical model nor a global model of several specific models in a global simulation project.

In these cases, the available data bases with test cases or experimental results are not suitable. It could be an added value to report and add sources for composing a data base related to transient models. However, the effort in the collection and reporting of these test cases would require a large effort in standardisation and harmonisation of the approach.

Examples of validation of transient models are shown below. *Figure **44*** shows an example of the experimental validation of a transient cooling coil model (two options: detailed and simplified). The model has been validated for temperature and humidity transients.

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[37] IEA 1995. Building Energy Simulation Test (BESTEST) and Diagnostic Method, National Renewable Energy Laboratory, Golden, Colorado,February 1995.

[38] J. Neymark, R. Judkoff, G. Knabe, H.T. Le, M. Dürig, A. Glass, G. Zweifel, 2001, HVAC Bestest : A procedure for testing the ability of whole building energy simulation programs to model space conditioning equipment, Seventh International IBPSA Conference, Rio de Janeiro, Brazil, August 13-15, 2001.

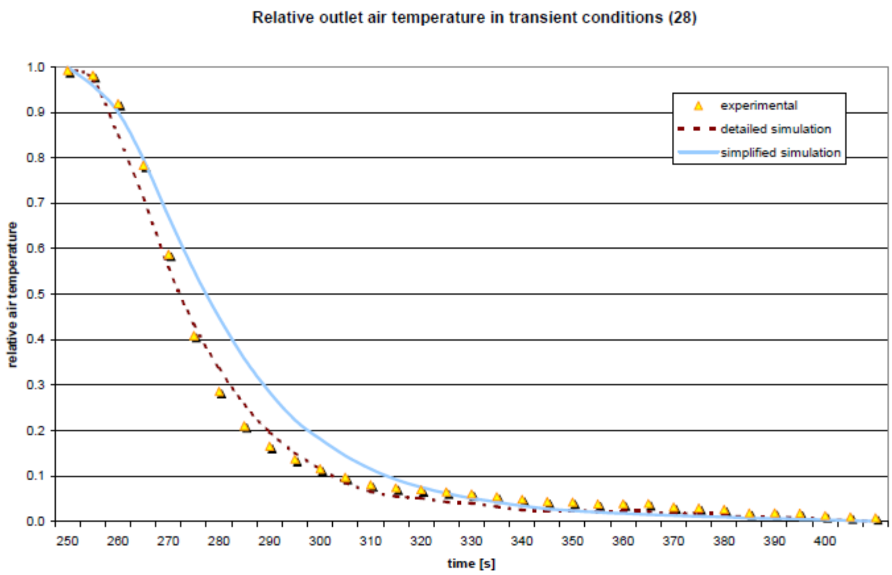

Figure 44 : Validation of transient response of a cooling coil in dry conditions[39]

Figure 45 shows another experimental validation example for a zonal room model developed for controller tests via emulation (Riederer40). This model has been developed to allow the test of room terminal controllers of different heating and cooling emitters such as convector, hot water radiator, fan coil, floor and ceiling heating or cooling. The model calculates thus the temperature at possible locations of the controller sensor (Figure 46).

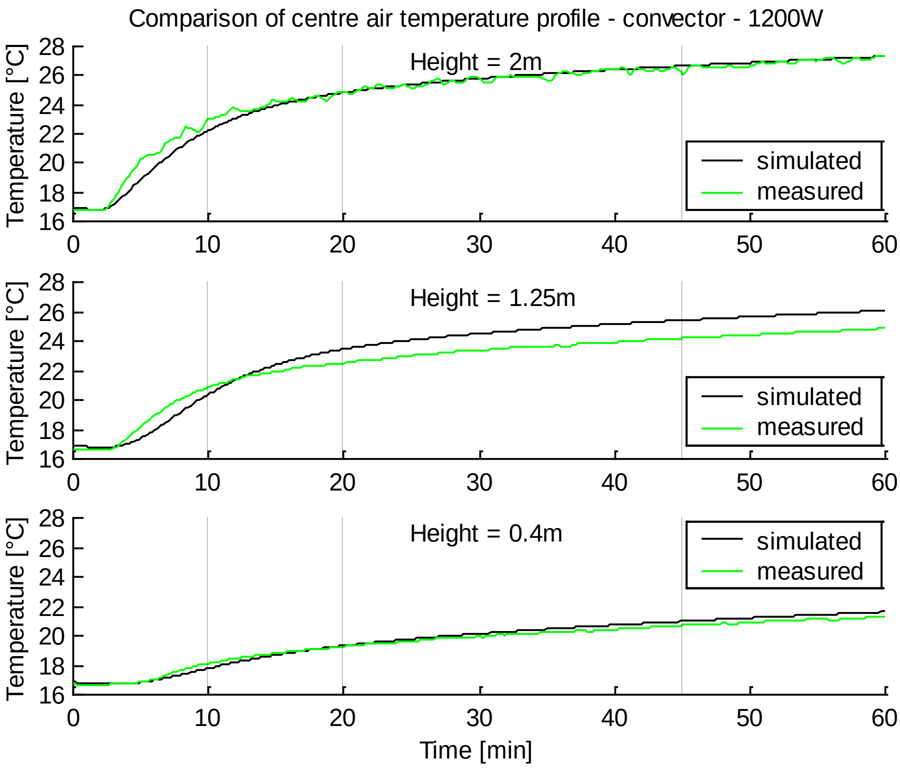

Figure 45 : Validation of transient response of room temperature (emitter: electric convector 1200W)

[39] Husaunndee A., Riederer P., Visier J.C., Coil modelling in the SIMBAD Toolbox - Numerical and experimental validation of the cooling coil model, System Simulation in Buildings SSB, Liège, 1998

[40] Peter Riederer. Thermal room modelling adapted to the test of hvac control systems. Engineering Sciences [physics]. École Nationale Supérieure des Mines de Paris, 2002. English. ⟨pastel-00000632⟩

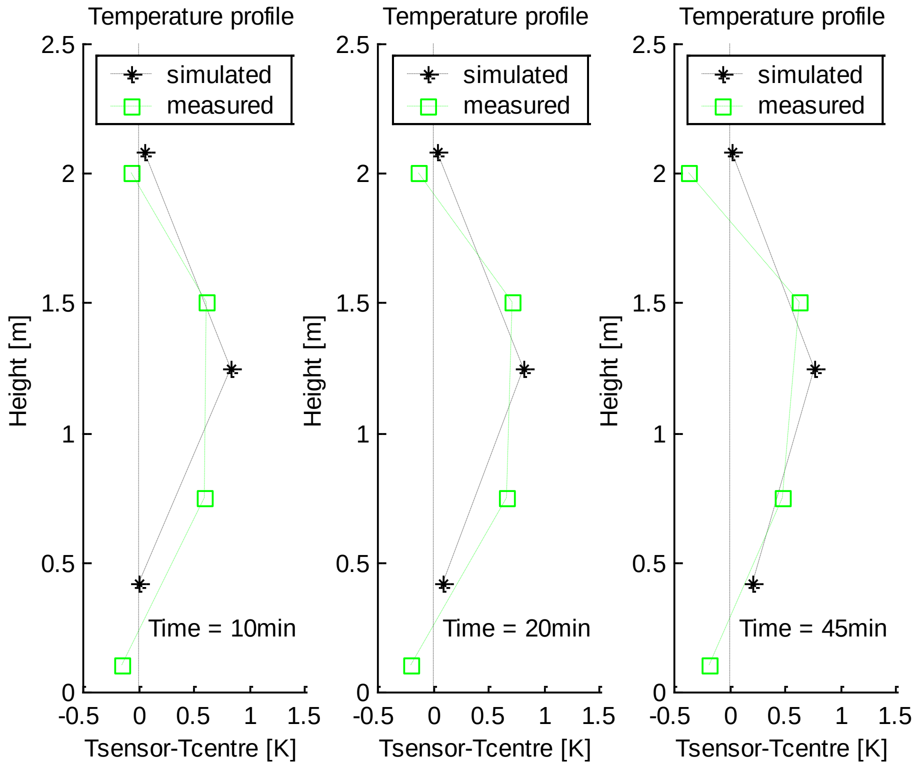

Figure 46 : Validation of temperature stratification at different sensor locations (emitter: electric convector 1200W)

It has to be highlighted that all these examples of validation show the validation of one individual component (coil, then room model).

Two main questions arise from these validations:

- How to define indicators and related threshold that allow to decide whether a model is "valid" or not. While it is relatively simple to define indicators, it is very difficult to fix corresponding thresholds. The thresholds of validity are, in theory, related to the simulation objectives and also the fact to which other models an individual model is connected to.
- Is the global model, built from several, interconnected and individually validated models, still valid (individual model validation is not equal to simulation project validation)?

Both above-mentioned points are linked. Two main options exist that allow to ensure the user about the validity of the global simulation model:

- Validation of the composed model in the same context of the simulation objective(s);
- Sensitivity analysis of the model on key parameters.

While the first option will give an answer on the validity of the composed model, it will definitively not ensure completely any extrapolation of the model to other simulation cases. But the use of numerical simulation is, in most cases, to analyse an energy system or concept exposed to other boundary conditions or inputs. The validation for any operating point that could happen is thus again very difficult, but possible. This would however be at high efforts (and costs). An example of such a validation is shown by Lahrech et al.[41].

The second option, the sensitivity analysis is to date the most used option to limit the risk of conclusions from simulation studies. It includes the risk of uncertain boundary conditions or parameters and can thus indicate a range of results in which the "real" solution should be placed. If this range is acceptable small, this option is definitively the most elegant option. An example is shown in §3.8.

[41] R. Lahrech, P. Gruber, P. Riederer, P. Tessier and J. C. Visier, (2002). Development of a testing method for control HVAC systems by emulation, Energy and Buildings, Volume 34, Issue 9, October 2002, Pages 909-916

3.5.2 VALIDATION OF MODELLING ON NEIGHBOURHOOD, DISTRICT OR CITY LEVEL

Simulation tools for studying energy flows in districts or cities are currently being developed in various research institutes and laboratories. The two main principles for the development are bottom-up and top-down approaches. This paragraph is oriented mainly to tools that follow a bottom-up approach.

The starting point for the development of many of those tools has been the simulation of single buildings including their energy systems. Most single building simulation tools are quite detailed for the building itself, but include very few phenomena around them, not negligible on a district scale, such as solar masks due to other buildings, radiative heat exchange between buildings, the diversity of occupant behaviour etc. Moreover, contrarily to single building simulation, the available input data is often quite poor on a higher scale than the single building. This can even conduct to the fact that, using too detailed models, the simulation results might in some cases even be less accurate than those obtained using simplified models.

This paragraph provides a starting point of a method on how to validate district energy simulation tools and how the research community could work together in order to guarantee accurate simulation results for specific simulation objectives.

The ideal tool for districts (and for others) should follow the law of parsimony i.e. the adequate tool for a given level of detail of input parameters and the objective of the simulation (e.g. energy demand, control studies etc.).

Main challenges in the context of the simulation of district energy flows

District energy simulation might seem only an extension of single building simulation to “many” buildings. But in fact, district simulation can be a rather complex problem since it collects a large list of constraints and phenomena that are not necessarily important (or available) if only single buildings are simulated. Furthermore, to simulate a district, energy networks will have to be considered in the simulation, principally thermal and electrical networks, but also water or gas networks might become important for certain simulation objectives.

The main questions in district simulation can be grouped in 4 parts that are closely linked:

- data availability: how to gather the necessary input data and what to do if these data are not available?

- level of detail: what phenomena and which level of detail is needed for properly considering the phenomena, especially considering available data (mostly in between very poor and average)?

- diversity: how to handle the diversity of building and system parameters as well as user behaviour?

- aggregation: is it possible to simulate energy flows in districts (or cities) by a reduced number of representative elements (households, dwellings, systems)?

A list of important points related to these questions is listed below:

- Issue 1: Availability of input data:

  The listed input data below is not always or partly available. Other approaches based on statistics and stochastic are needed to fill in blank spots in the available data.

  - Geometrical data for buildings (footprints and heights or detailed geometry, different LOD’s; window positions and area, building related masks such as balconies etc.)

    - Energy-related properties of the building envelopes (material layers and energy related properties, simplified data (U-values etc.), age and type of buildings (for a typology-based approach)
    - Zoning inside buildings (flats, offices, commercial etc.) and detail on zone usages
    - Data related to occupants (number, type etc.) and to the zone equipment (types and energy classes)
    - Information on installed energy systems in the buildings (HVAC, DHW production)

- Issue 2: Multiple phenomena on a district level

    - Solar masks (close masks from a building itself, masks from other buildings or trees, masks from ground topography) and radiative calculation (short and long wave)
    - Building envelopes (convective and radiative heat exchange through opaque and transparent envelope including eventual shading devices)
    - Building multi-zone issues (single zone, multi-zone with similar or different usage), adjacencies of zones and buildings
    - A large variety of energy systems (HVAC) that might be on a zone, building or district level
    - Diverse energy networks (electrical, thermal, water, gas) and connectivity to the buildings
    - Bi-directional link between buildings and microclimate (urban heat island)
    - Number, activity and actions of occupants as well as linked equipment (TV, dishwasher …)
    - Air change rates of buildings depending on external/internal pressure differences and distributions as well as eventually installed ventilation systems

- Issue 3: Different simulation objectives and necessary simulation outputs

    - Exploitation – District energy management
        - Analysis of peak powers
        - Study of “optimal” energy management of districts
        - Fault detection methods on district level
    - Conception/refurbishment of districts:
        - Analysis of loads and consumptions
        - Costs and CO_2 emissions
    - Urban planning and energy management on territory level
        - Prediction of consumptions and peak loads on a territory level
        - Analysis of the impacts of political actions (tax incentives, subsidies etc.)
    - Microclimate and urban heat island:
        - Analysis of the impact of building conception and operation, traffic measures etc. on the urban climate and vice-versa.

Each of these objectives might need different modelling approaches in order to guarantee a good fit between available input data, the level of detail of preponderant phenomena and simulation outputs.

Besides a different modelling approach, all these simulation objectives require potentially a specific method for validation or, at least, different criteria and thresholds for validation.

Process of building a simulation model for districts

To understand the development of an appropriate validation methodology for district simulation models, the process of building a simulation model is as presented in *Figure **47*** with the following steps[42]:

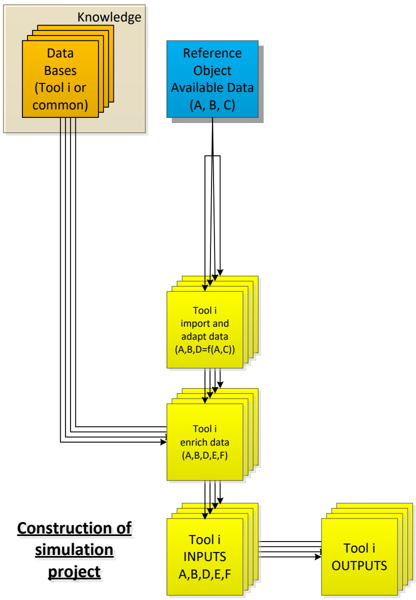

Figure 47 : District simulation modelling workflow

- Starting from the known object parameters ("reference object") the parameters A, B and C are known (e.g. geometry, window area etc.)

- Each tool imports the parameters and instantiates the model(s). It might be necessary to derive a parameter D from the available parameters and others (C) might be unused.

- Since several parameters are not available (E and F), they have to be completed using expert knowledge. For single building simulation this is typically done by the modelling person that will set all needed parameters as good as he can. On a district level this is not possible anymore (missing information combined with diversity etc.), the tool has thus to enrich the data in order to set all necessary parameters E and F (e.g. U-values depending on building age, type …) that might be available on one or several data bases or equivalent.

- When all model parameters are set in the simulation project, the simulation can start, generating the tool outputs.

Contrarily to building simulation, district simulation requires the enrichment of data since not all parameters are available. The validation methodology has thus to consider this aspect.

Methodologies for verifying the quality of simulation results ("validation")

As also presented in the previous paragraph on validation, three main methods exist to verify or guarantee the quality of the results of simulation tool(s):

- Experimental verification (often called "validation", *Figure **48***)

  The tool(s) outputs are compared to data that has been measured on the reference object (e.g. a building that has been monitored). This is definitively the best choice for the verification of component models such as boilers, heat pumps etc.

- Inter-model comparison (*Figure **49***)

  If a large panel of scenarios shall be verified, the current solution is the inter-model comparison. It allows to compare a large variety of scenarios between a set of simulation tools and thus to debug and refine specific modelling errors in the tools by comparing them to the results of the other tools. The objective is thus to be "in the range" of all other tools. The generation of scenarios covering as much phenomena as possible (and even isolated phenomena) allows to verify quite a lot of phenomena that are implemented. The most known example of this type is the ASHRAE Bestest which is still widely used.

- Tool calibration (or fitting – *Figure **50***)

  In this case the model is tuned on measured results in order to dispose of the best model of the object. This might be necessary in different cases, for example to compare

[42] P. Riederer, P. Bonneau, D. Marchio, T. Berthou, R. Bonabe de Rougé, 2017. District energy simulation tools – Validation methodology, Methopdology paper, Efficacity Institute

a baseline of the current situation and then to play alternative scenarios for refurbishment in order to compare the before/after situation. This procedure is necessary to neutralize weather and occupancy dependencies and to be able to do a fair comparison of scenarios.

The “convergence criterion” is the quality of the fit between simulated and measured results while adapting input parameters.

Figure ***51*** finally shows a global picture of all verification methods merged into one.

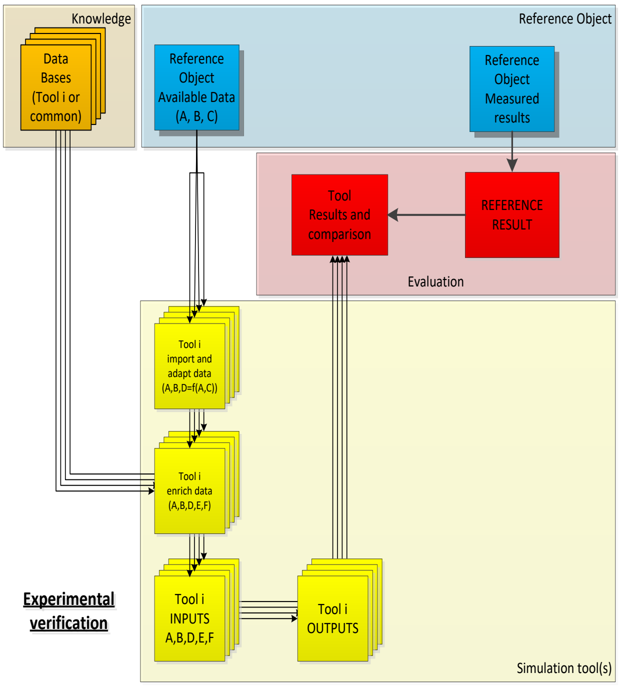

Figure 48 : Experimental verification

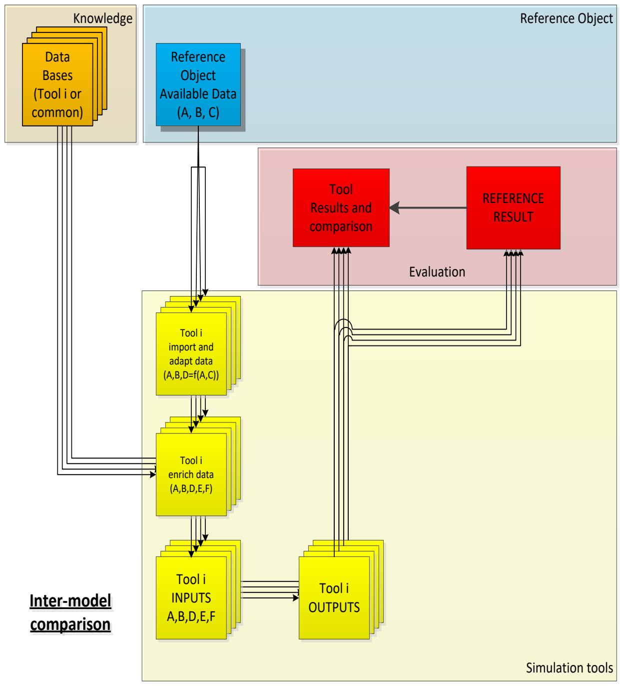

Figure 49 : Inter-model comparison

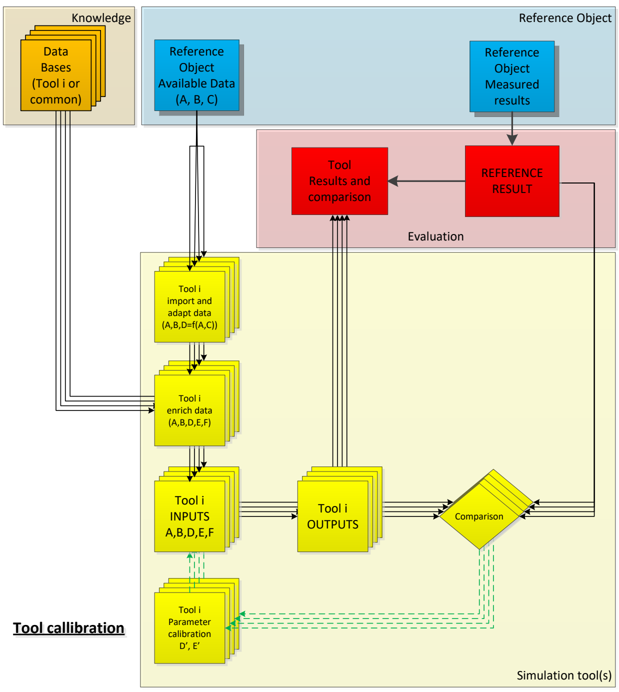

Figure 50 : Tool calibration

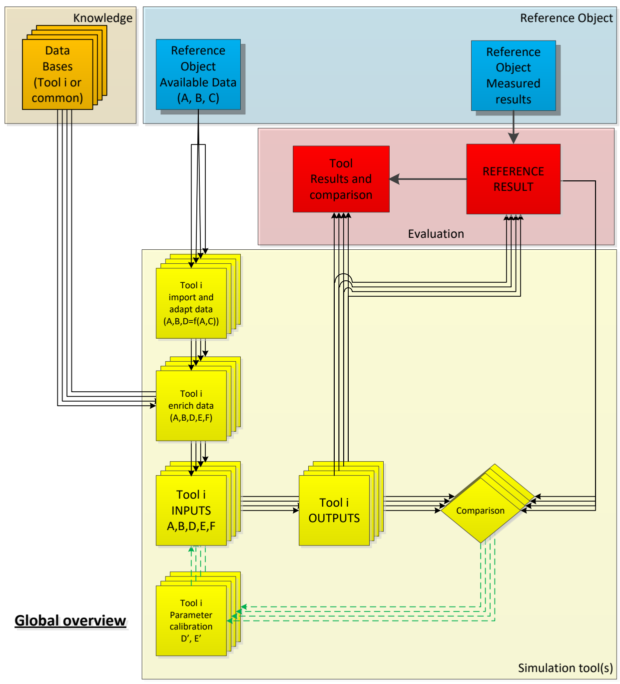

Figure 51 : Global picture of comparison/verification

Proposal of actions facilitating the verification of simulation tools on a district scale

Based on the definitions that have been structured in the previous sections, a draft methodology for commonly starting a verification methodology in the “district energy research community” is presented hereunder.

Three types of actions seem necessary to ensure the accuracy of district simulation tools within a specific objective:

- Validation or justification of the choice of unitary models (e.g. generators, building envelope etc.):
    - Elaboration of a database of available test cases (and reference results) for validation (ASHRAE BESTEST, other test cases for low energy buildings, test cases for systems etc.)
    - Collect additional of measured data that might be useful to enlarge the panel of reference tests and the database

  This type of validation is crucial for the validation of the modelling of diverse physical phenomena (e.g. solar mask calculation) that could not be covered in the second action (the validation of diversity might hide or compensate errors in unitary models).

  This validation type can either be on a model comparison or by using reference measurement data.

- Validation of aggregated outputs by comparison with reference values:
    - Annual consumption per energy type (electricity, gas, heat) and energy end-use
    - Monthly or weekly energy consumption
    - Shape of the intra-day load curve
    - Rate of indoor discomfort or indoor comfort conditions (summer and winter)

  This validation might be supported by a calibration method which raises several questions:

    - Which parameters should be chosen in priority for the calibration process?
    - Which identification method should be used?

- Validation of the “diversity”:

  Remark: for district simulation, statistic/stochastic approaches are wrong for one or several buildings but get valid when a sufficient number of buildings is considered. The minimum number of elements (or buildings) to represent the desired level of diversity should be examined (reduced model of diversity?).

  It is possible to validate:

    - by considering available input data and measurement results of real districts: this would be the most realistic approach. However, it would be surprising if all necessary data was available (input data and measurements) to validate the models.
    - by considering virtual districts: in this approach on the one hand all necessary data can be generated, but on the other hand the validity of the reference data will depend on the tools that have allowed to generate the data (the question is then if the best and most detailed available model satisfies this need).

  In a general manner and for both possible options, the proposed approach would consist to use as starting point the highest level of available data and measurements and, in different steps of validation, to progressively reduce the available input data for the tools:

    - Starting point: District with an information level of 90%+ of the input data

- Degradation of the envelope input data:
  - From the initial description of envelope layers to downgrade to lower level input (e.g. U values, position of insulation and type of building structure)
  - Random removal of input data on several buildings or zones to test the quality of filling of blank spots of the tools
  - Replacement of geometries by of areas (the calculation of solar masks will thus not be possible and eventually replaced by estimated coefficients
  - Removal of other phenomena such as long wave radiative heat exchange between buildings etc.
- Degradation of system input data:
  - Characterisation of input data for systems:

    Random removal of input data related to systems to test the quality of filling of blank spots of the tools (for the system type itself or input data for a specific system such as efficiency etc.)
  - Characterisation of the control/management related input data for systems

    Random removal of control-related input data of systems (for the generation, storage, distribution and emission) such as set points, economy periods or control laws (On/Off, proportional, proportional-integral etc.)
- Degradation of input data related to occupants and equipment
  - Number and type of occupants and occupancy profiles
  - Type, energy class and number of equipment
- Degradation of input data related to networks (mainly thermal networks and in a second step electrical networks):
  - Starting point: a network described in detail (e.g. for thermal networks the topology, sections, thickness of insulation etc.)
  - Removal of insulation thicknesses and sections (test of auto-sizing methods)
  - Removal of the topology and automatic generation based on road topology (optional)
- Degradation of microclimate input data:
  - Removal of input data on position and size of external system components such as air source heat pumps that affect the micro-climate
  - Removal of external system components such as air source heat pumps that affect the micro-climate
  - Removal of traffic related input data
  - Removal of traffic phenomena

This approach has to be further detailed since it is only a preliminary list of ideas.

To ensure the validity of the conclusions of such a sensitivity study, the analysis should cover several districts (different typologies from compact to not compact districts) exposed to different climate zones.

Extending validation approaches on districts to an international level will add some additional complexity since national impacts might be difficult to manage (e.g. user behaviour, equipment types, material databases and types etc.) and the filling of blank spots will be rather difficult if not impossible.

3.6 MODEL OR TOOL CALIBRATION

As already stated previously in this report, a model is always affected by a certain uncertainty. To prevent too high modelling errors, models are usually compared to measurement or theoretical data in order to minimise the errors of conclusions of the simulation. In case of setting a threshold of validity to the outcomes of the model, this is typically called “validation”. However, it is very difficult to generalise a method with reasonable values of this threshold and to pick the right performance criteria.

To minimise the error as much as possible, and assuming that historic data is available, model calibration is used in some cases. This has the advantage that it does not necessarily require a “validation” threshold since the method will simply try to fit simulation results as close as possible to measurement. In case of discrepancies, the model choice will be in question. However, the choice of calibration criteria (variables) and weights will certainly be an issue.

Model calibration follows generally the methodology in *Figure **52***. Starting from a description of the problem with for example building geometry and other building or system parameters as well as the boundary conditions (weather, occupants etc.), the simulation model is built. In a calibration procedure, the key model parameters (which have of course to be chosen properly) will be adapted in order to reach the best fit with measurement data. Ideally this is done with complete time series (best fit for all time steps), but unfortunately the available data does not allow this. In the latter case, final energy values can be used in order to reach the best fit for the integral of powers, thus the energy demand or consumption at a certain point and period. The fitting procedure used typical minimisation or optimisation methods as described in §5.1.

One the best parameter set detected, the calibrated simulation model is available for the real simulation or parametric studies.

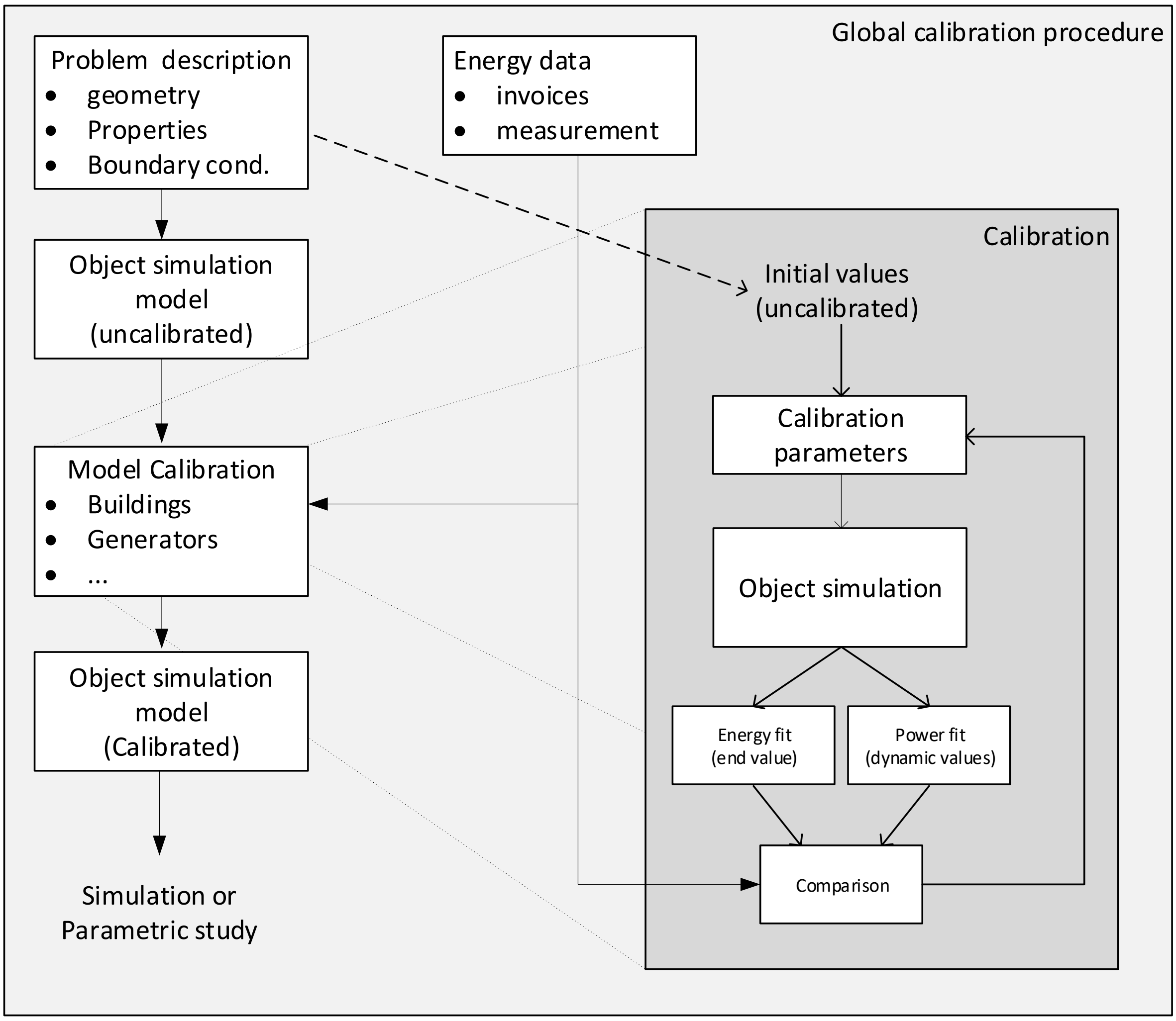

Figure 52 : Calibration methodology for district energy system model

3.7 MULTI-OBJECTIVE EVALUATION METHODS

Simulation as discussed in this document has many advantages since it allows, if used with caution, to analyse very deeply almost any problem. However, simulation produces a large amount of data and time series. This large amount is related to the fact that many simulation runs can be done easily and thus producing several data sets.

But the other point is that many variables are available (it can be imagined as a virtual sensor that can be placed easily anywhere in the system to be simulated). The number of variables is thus also increasing, leading to a more and more complex analysis of key performance indicators (KPI's).

The situation is very simple if only one key performance indicator is chosen. But in many cases, there is a large variety of indicators from the fields of energy, environmental, comfort or economics. As soon as there are at least two, the indicators must be weighted if a choice shall be taken based on one global performance. The more performance indicators exist, the more it is complicated to compare sets of solutions (data sets produced by parametric simulation runs). Therefore, it is important to also analyse in detail ways to combine (or weight) different KPI's depending on the objective of the simulation.

The use of a multi-criteria decision analysis method becomes essential to assist the results processing and to provide the necessary information for the sorting, the selection and the ranking of the issues while providing information on possible conflicts between the solutions.

Different filter and classification methods have thus been defined in the past. The main classes exist for this type of methods:

- Methods with a single criterion: these methods are simple but require the aggregation of all specific criteria into one (weighted sums etc.)
- Interactive methods have been defined for less structured decisions and require the intervention of the decider during the process and at different intervals.
- Outranking methods which allow the comparison by pairs preventing compensations. While these methods are more complex as the two others, they deliver more complete results.

The objective in this report is not the analysis and discussion of different methods, a list of three classification methods is thus provided here for further information:

- ELECTRE III[43]: this method is based on 2 concepts which are the outranking in pairs with indices of concordance and discordance as well as the importance of non-comparability. The application and parameter setting of this method requires a very good knowledge of the method and the adaptation to new datasets.
- PROMETHEE II[44]: It is based on one single indicator close to concordance, the preference indicator which relies on a fuzzy outranking method. The simplicity of this method is an advantage but implies also the reduction of information of the results.
- ATLAS method[45] (Assistance for decision support to Assess and Sort): this method represents a combination of the two previous methods in order to combine the advantages of them.

The last one has been developed at CSTB and been applied to the optimisation of a district energy system.

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[43] Roy, Bernard. 1978. «ELECTRE III : un algorithme de classements fondé sur une représentation floue des préférences en présence de critères multiples». Cahiers du Centre d'Etudes et de Recherche Opérationnelle (Belgique)20:3‑ 24.

[44] Brans, Jean‑ Pierre, Vincke, Philippe, Mareschal, Bertrand. 1986. «How to select and how to rank projects: the PROMETHEE method». European Journal of Operational Research 24:228‑ 238.

[45] Perez N., Mailhac A., Inard Ch., Riederer P. Outil d'aide à la décision multicritère pour la conception de systèmes énergétiques à l'échelle du quartier. IBPSA France conference 2016, Champs sur Marne

3.8 HOW TO DEAL WITH UNCERTAINTY IN THE ANALYSIS

Uncertainty of simulation is very difficult to analyse analytically. The simplest way to quantify uncertainty of simulation is by using brute force techniques such as Monte Carlo analysis. The variation of all relevant input parameters can be done using error distribution of inputs (e.g. gaussian). Running all these combinations will lead at the end to the distribution of uncertainties on the final KPI's.

This approach is simple to set up and will give relevant results. However, in case of detailed simulation models which lead to high calculation efforts and simulation time, this approach might not be feasible since the number of simulations increases exponentially with the number of parameters that are affected by uncertainty. In these cases, other methods that allow the reduction of the number of cases to evaluate will lead to accurate results in much shorter time.

An example of a Monte Carlo analysis is shown hereunder for the estimation of uncertainty of the measurement of seasonal performance factors of an air to air heat pump. The analysis has been undertaken in order to estimate the uncertainty of the measurement of heat pump performances. The analysis combines parametric models of the parameters inputs (*Figure* ***53*** and *Figure* ***54***). But it could also be uses based on simulation models for the heat pump itself.

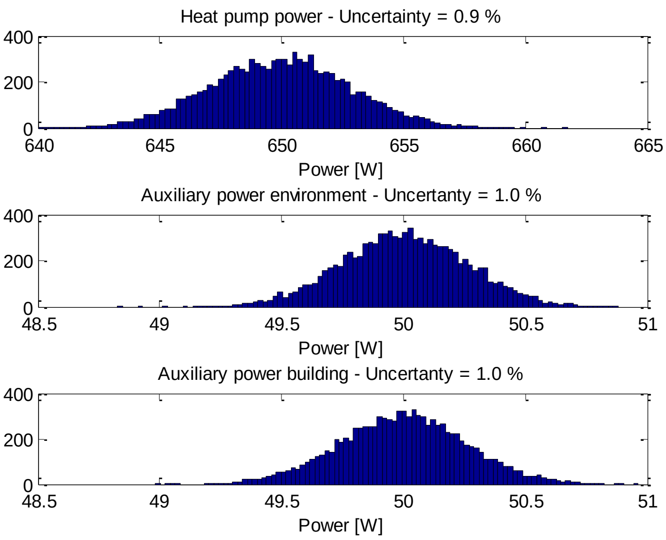

Figure 53 : Uncertainty of electric power measurement of heat pump and auxiliaries

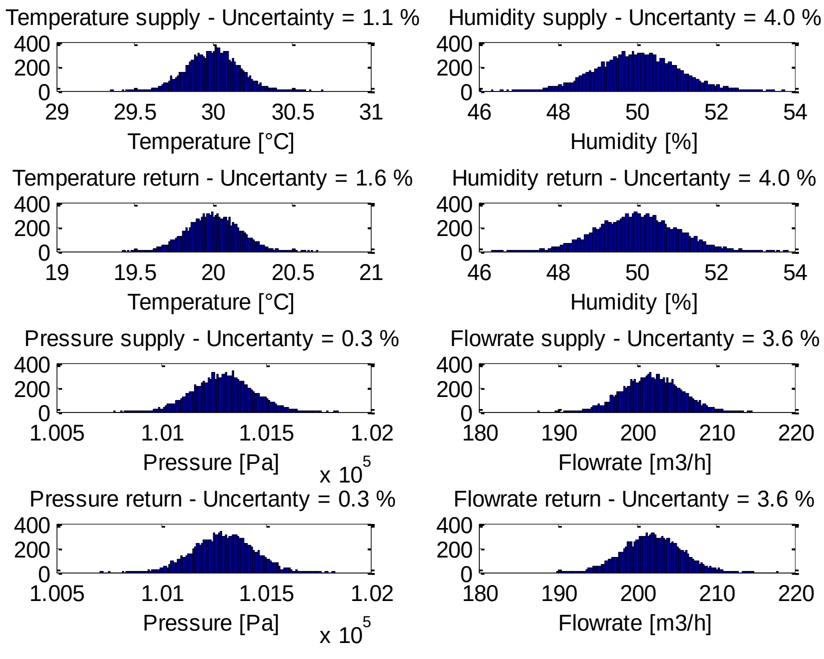

Figure 54 : Uncertainty of air temperature, flow rate and humidity of the heat pump

The result of these input uncertainties will lead then to the KPI performance functions as shown in *Figure **55***. Seasonal performances factors (SPF 1-4 as defined in [46]).

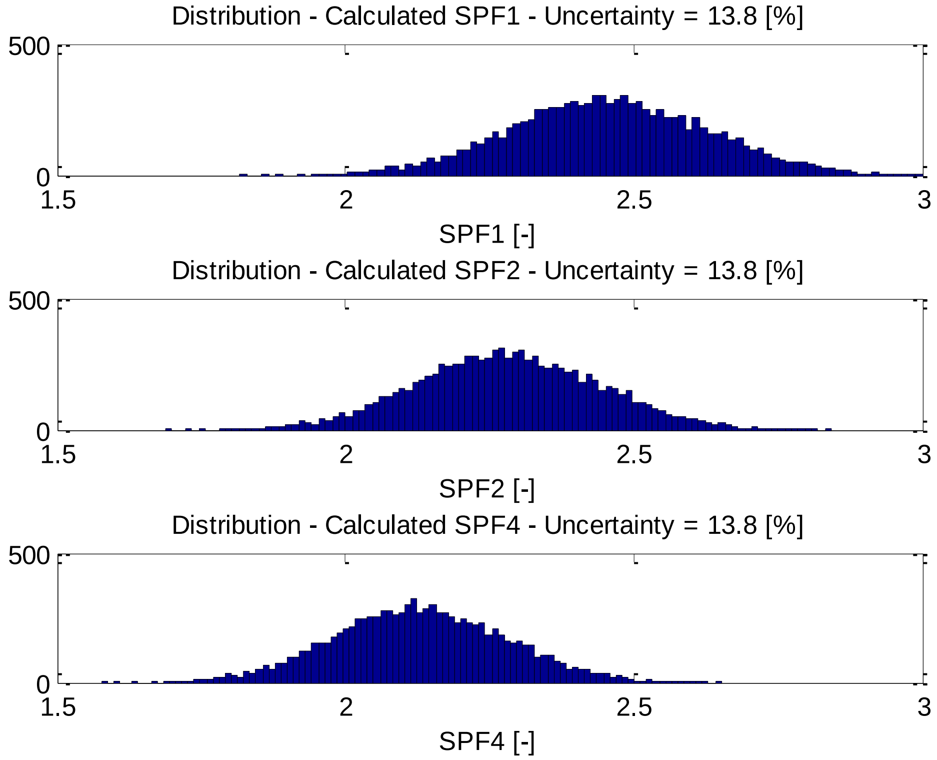

Figure 55 : Uncertainty of electric power measurement of heat pump and auxiliaries

The resulting distribution of seasonal performance factors and the related uncertainty is about 14% in this example.

As has been mentioned above, this type of analysis can be time consuming. Also, the analysis has been carried out for 1 operating point.

The real impact on a complete heating or cooling season or even a complete year can only be calculated by quantifying the uncertainty at each time of the year. This analysis can be done for example on the basis of a yearly simulation with hourly time step. Then, uncertainty is more correctly calculated also in part load conditions and integrated over the whole year.

An example of this is shown for a parametric study of a district heat sharing network in the frame of the European ReUseHeat project. The energy source is heat from a sewage plant and the low temperature network provides the source for decentral heat pumps in each connected building.

The analysis is based on a set of parameters with at least 3 different values per parameter. The corresponding graphs in *Figure **56*** and *Figure **57*** show the distribution of possible values for the thermal power extracted from the sewage plant. While *Figure **56*** shows the total period of one year, with, at the right hand, the distribution of the minimum, average and maximum result, *Figure **57*** shows a zoom on an arbitrary winter and summer week. In this way, the real operation should be inside the simulated range of distribution.

[46] COMMISSION DECISION of 1 March 2013 establishing the guidelines for Member States on calculating renewable energy from heat pumps from different heat pump technologies pursuant to Article 5 of Directive 2009/28/EC of the European Parliament and of the Council (notified under document C(2013) 1082) (2013/114/EU)

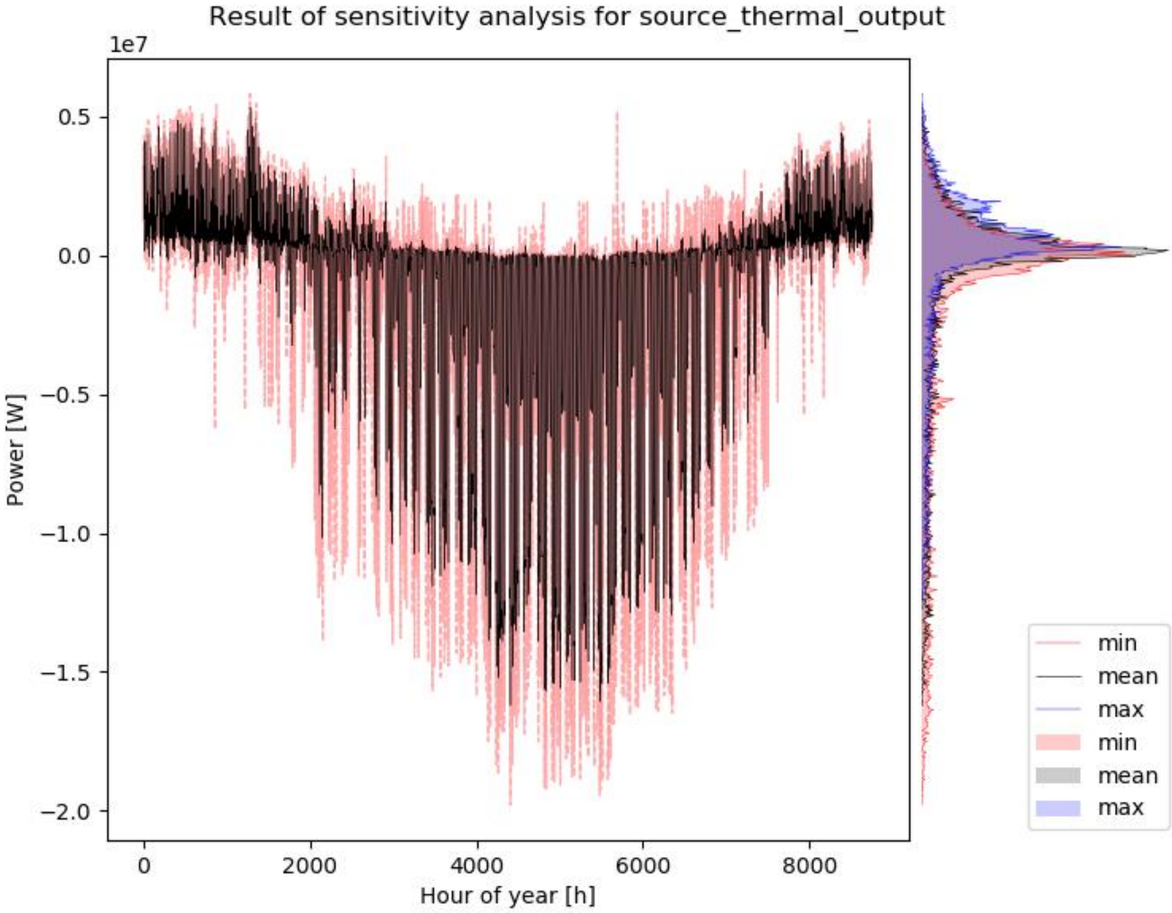

Figure 56 : Sensitivity analysis of a district heating and cooling network – thermal load of network

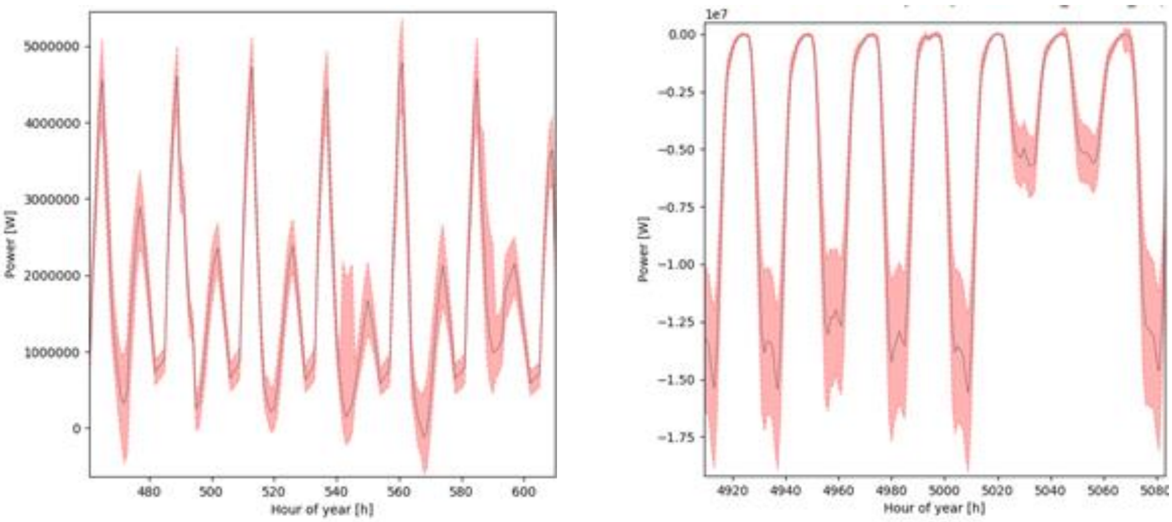

Figure 57 : Sensitivity analysis of a district heating and cooling network – thermal load of network in winter (left) and summer (right)

For this example, heating and cooling loads, depending on an assumption of parameter uncertainties, represent a total possible range of:

- Heating loads: in between +22% and -19%
- Cooling loads: in between +38% and -46%
- Electric loads: in between +29 and -26%

4. THE USE OF EMULATION FOR THE ANALYSIS AND TEST OF ENERGY SYSTEMS

4.1 EMULATION AS THE PERFECT MIX OF ADVANTAGES OF MEASUREMENT AND SIMULATION METHODS

As already mentioned in the previous chapters, measurement and simulation can help to analyse performance of building, districts and energy system components or concepts. Their advantages and disadvantages will be discussed in this section.

4.1.1 DISCUSSION OF IN-SITU MONITORING FOR THE ANALYSIS OF ENERGY SYSTEMS

Measurement, carried out in-situ, will allow to correctly obtain the KPI's of the analysed energy system. It is certainly the more accurate choice compared to simulation if the real performances shall be obtained, since the real product behaviour is observed.

In-situ measurements are used to characterise performances or characteristics under real operation of products. The boundary conditions for in-situ measurement are not managed at all.

Even if there might be a critical point related to the impact of sensors or meters to real behaviour, e.g. pressure drops in the piping network, the observed performances mainly rely on the accuracy of measurement equipment, which is in most cases not an issue, especially today with the massif deployment of "smart" metering devices.

However, and this is the point where simulation finds its place, monitoring has three weak points:

- Measurement is very time consuming: to obtain annual performances, a complete season or even a year has to be measured. This represents 1 year of measurement.

- Efforts to guarantee the quality of results: the supervision of the quality and eventual defaults of equipment is mandatory. In most cases it is impossible to guarantee 100% correct data even if modern monitoring equipment with battery backup etc. allows to get very close to this value.

- Boundary conditions: This is the most critical point for measurement. Once an object chosen (e.g. a building to be monitored), the results will be valid only for this object and the corresponding boundary conditions. Most of these conditions cannot be controlled since weather conditions, occupant behaviour and other factors will make this monitored period unique. The word "unique" must be understood here in the sense of not valid or exportable for many other cases. For example, if an energy system is installed in a building and occupants are on holidays for a long period, the results for this period will probably be not allow any evaluation for this time. And this is the key point where simulation with fully controlled boundary conditions has an added value.

A way to overcome this problem is the massive deployment on the market with smart metering devices. Even if measurement accuracy of these cheap digital products is low compared to laboratory measurement equipment, it allows to give a much broader picture of the operation of these products in-situ. And the global accuracy for a large-scale measurement campaign with low measurement accuracy will still be much higher than a small campaign with high accuracy equipment. In the latter case, the impact of boundary conditions will completely erase the gain produced by high accuracy measurement.

4.1.2 DISCUSSION OF LABORATORY TESTS FOR THE ANALYSIS OF ENERGY SYSTEMS

Laboratory tests are widely used to determine product characteristics in steady state or, partly, dynamic tests. The results are needed for several purposes which can be product certification (a standard testing method is thus used), research (develop new products, tests are thus needed to validate innovative concepts) or for better characterising product performances in a wider range of operating points (to produce or refine catalogue data for example). Boundary conditions are here fixed following the test protocol.

Again, even if laboratory tests are widely respected as the most accurate method to test the intrinsic behaviour of a product, they are affected by the following disadvantages:

- Measurement is relatively consuming: the time needed to obtain product instrinic characteristics such as operating points is still acceptable with from several hours to days. On the other hand, to obtain seasonal or annual performances, a complete season or even a year has to be measured. This represents 1 year of measurement and is thus not feasible from an economic point of view.

- In most cases, laboratory tests are conducted under steady state and relatively abstract boundary conditions. This is necessary to create the wished outcome (e.g. performance tables), but these conditions are sufficient to determine real, integrated behaviour of products.

4.1.3 DISCUSSION OF SIMULATION FOR THE ANALYSIS OF ENERGY SYSTEMS

As already mentioned, measurement is, and will always be the reference for analysing energy systems. Simulation, which is, by definition, only a tentative to approach real behaviour and thus, due to the errors in prediction, will never completely replace measurement.

However, as also mentioned, measurement does not allow to obtain a fully generic picture of the whole range of operation of an energy system due to the high costs and time required for the analysis.

Simulation on the other hand has its great advantage in the perfect control of boundary conditions. This, together with small time necessary for calculation (at least compared to measurement), highlights a complementary potential of simulation compared to measurement. It allows to study an object for a large number of simulation cases and thus increases confidence in the results. Such a sensitivity analysis gives a very good picture of system behaviour as we know the range of potential results. And this range includes at the same time modelling errors but also errors in boundary conditions. Several techniques exist for this type of analysis, the most well-known is certainly the Monte Carlo analysis.

4.1.4 EMULATION AS PERFECT COMBINATION FOR THE ANALYSIS OF ENERGY SYSTEMS

As shown in the previous paragraphs, monitoring, measurement and simulation have their advantages and disadvantages, mainly related to:

- Necessary time for the evaluation

- Reproducibility of results

- Validity of results in terms of accuracy and realistic behaviour

- Ability to cover a large operation range including part load

Emulation, if well applied to the specific question, can allow to combine perfectly all advantages while excluding most of the disadvantages of measurement and simulation.

In the field of HVAC systems and buildings, work on emulation has been started in the late 80s (Gruber[47]). It has been developed mainly to test building energy management systems (BEMS) by connecting real BEMS to virtual buildings.

Several years later, emulation has more widely been applied to products other than controllers but to complete products or systems (EvalSSC[48], an overview in the Quaist project[58]).

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[47] P. Gruber, A. Duppenthaler, PVHS – Ein Simulator von polyvalenten Heizsystemen, Viertes Schweizer Status-Seminar, Energieforschung im Hochbau, 2/3 Oktober 1986, ETH Zürich, 1986

[48] Développement d’une méthode d’essai globale des SSC (Eval-SSC), projet Ademe, 2007

The advantage of emulation for a product test is that it allows on the one hand to carry on simple test protocols to determine performances tables, but that the test can later be enlarged to real test hours, days or weeks. This will embed the product into a realistic environment such as a building, with fully realistic boundary conditions.

*Figure **58*** shows a qualitative comparison of the use of measurement, laboratory testing, simulation and emulation for product testing. The scores have been estimated from the experience of the author for the example of the determination of real product performances. They will vary depending on the exact application and product as well as testing objectives.

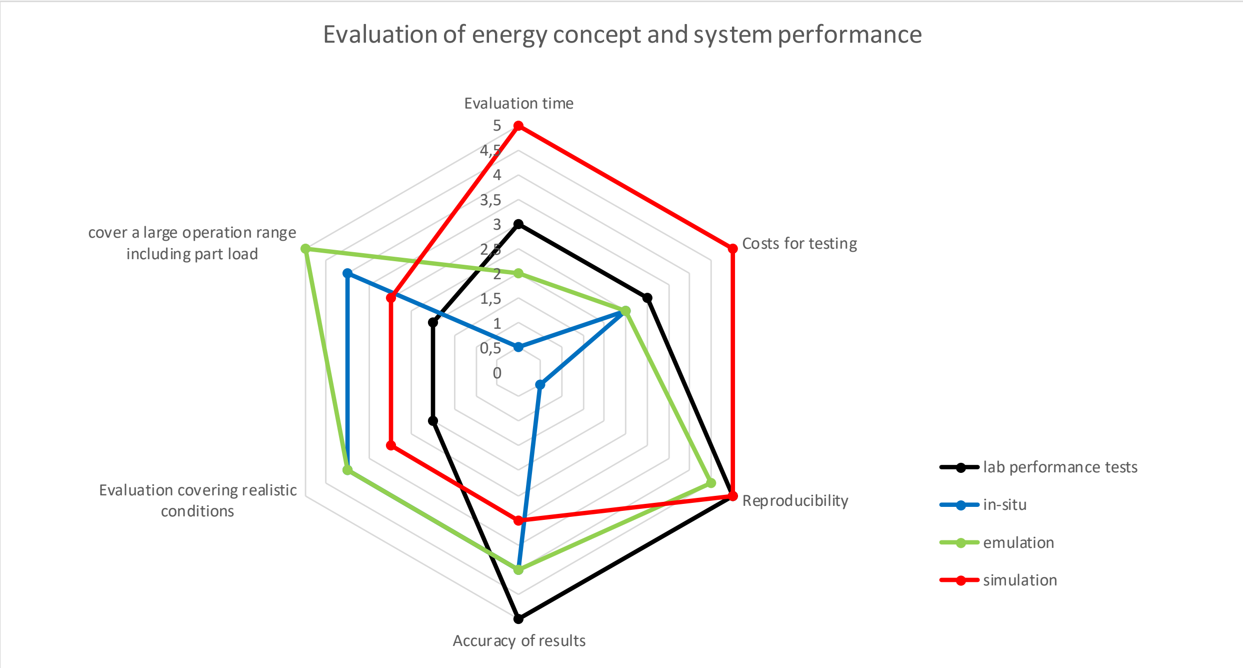

Figure 58 : Use of measurement, simulation and emulation for product testing (scores estimated by the author)

It can be clearly seen that simulation reaches best scores in terms of evaluation time, costs for testing and reproducibility. On the other hand, laboratory testing scores best in terms of reproducibility and accuracy of results. In-situ measurement shows good scores for the accuracy, the ability to cover realistic conditions (with the restriction to boundary conditions) as well as to cover a broad range of operation.

Emulation shows in this case a very good compromise. The two negative points will be the evaluation time (compared to simulation) and costs. However, the scores are still acceptable and the high flexibility of emulation tests to offer a very powerful tool for manufacturers or researchers compensates easily these two weak points.

Emulation will be described more in detail in the next paragraph.

4.2 VARIANTS OF EMULATION CONCEPTS

While emulation has always the same signification, to embed a system or product to test in a virtual environment, there are different concepts and aspects around this definition.

Also, the use of emulation can have different purposes. Either the test is carried out to evaluate performances of a system, for example for certification (Eubac[49]), following performance criteria, or it aims in testing and improving energy systems that are composed of several components.

Both cases may be different since the border between the product to be tested and the simulated part can be adapted specifically to each study. However, if the objective is the certification of a product, generally the whole product will be emulated. But there are specific cases which will be shown in the next paragraphs.

Different approaches can be listed, for example:

- Component and global testing methods (and/or standards)
- Steady state and transient testing scenarios
- Abstract (EUBAC) versus realistic testing scenarios (SSC[48])

A good example for a distinction in the emulation method is the evaluation of solar thermal systems. The following standard define tests for solar thermal systems:

- Custom built systems (prCEN/TS 12977-2-5): this standard assumes that a system is composed of several systems for which standards already exist. The evaluation of the global performance will thus be by simulation, whereas individual components are tested either by classic laboratory tests or emulation tests. This will be described in §4.2.2.
- Factory made systems (EN 12976-1-2): this standard defines to test the system as a whole. This type of method will be described in §4.2.3 .

In the next 3 paragraphs, three general emulation concepts are shown which are:

- Emulation of controllers
- Component testing and system simulation method
- Global system emulation technique

4.2.1 General concept of emulation applied to control systems

*Figure **59*** shows the typical layout of a feedback control loop controlling a process that is exposed to one or several external disturbances. One or several variables of the process are measured by a sensor that is connected to the controller. The latter will compare the variable to be controlled with a set point. This set point can either be fixed or variable. In the case of a variable set point this can be a schedule (e.g. night setback) or can be calculated from external modules ("additional information" in the figure).
In the case of standard feedback control, the setpoint can be sent from an external optimisation or planning module. In the case of a feedback control embedding its internal optimiser, the setpoint will be defined in the controller algorithm. The algorithm will thus define a set point that allows to maximise (or minimise) an objective function.
These algorithms can define dynamically set points in order to minimise energy consumption, operation costs or CO2 emissions while maximising renewable energy share and occupant comfort. The set point input can thus be adapted by these additional inputs or set directly.

[49] https://eubac.org/about/product-certification/

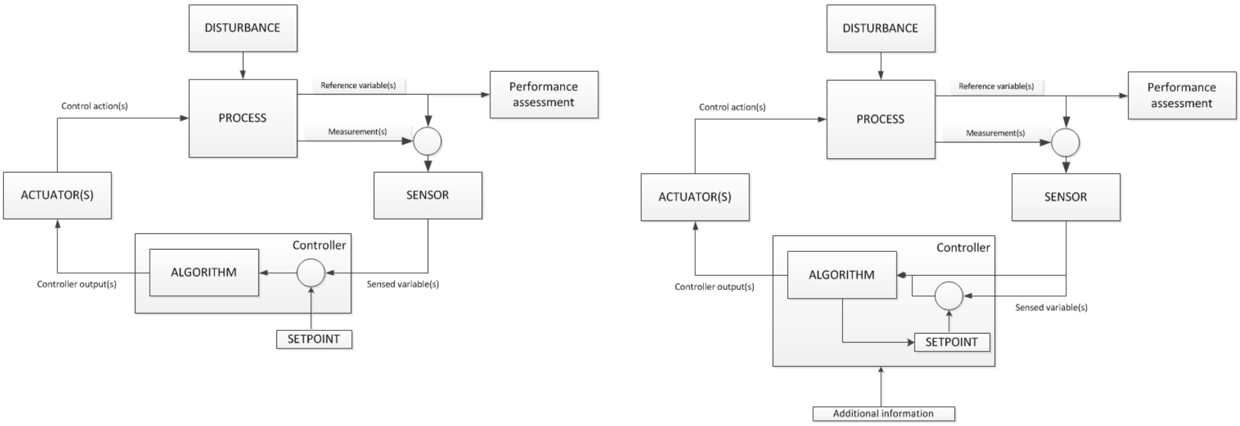

Figure 59 : Typical layout of a control loop (left: classic feedback control; right: with embedded optimiser)

The algorithm will then calculate the necessary controller outputs for controlling the actuator(s) of the process to be controlled. The outputs can take different forms such as a valve position, a command for the burner of a boiler, a pump, fan etc. The actuator itself can react approximatively as with a time delay or time constant (e.g. opening time for a valve), the control action(s) will thus be function of the controller output(s) and actuator(s) characteristics.

If one (or several) controllers shall be emulated, the main question is linked to the choice of the boundary between the process simulation and the controller or control algorithm to be emulated.

In the case of emulation this is generally chosen as shown in *Figure **60*** where the controller outputs are sent to the simulation via an actuator. This actuator can be real (Eubac), the actuator output signal (e.g. valve or relay position) is thus measured and sent to the simulation part. The advantage of this choice is that real actuator characteristics are considered. On the other hand, the actuator can also be simulated. The actuator has then to be modelled in the simulation environment, adding modelling uncertainty to the test.

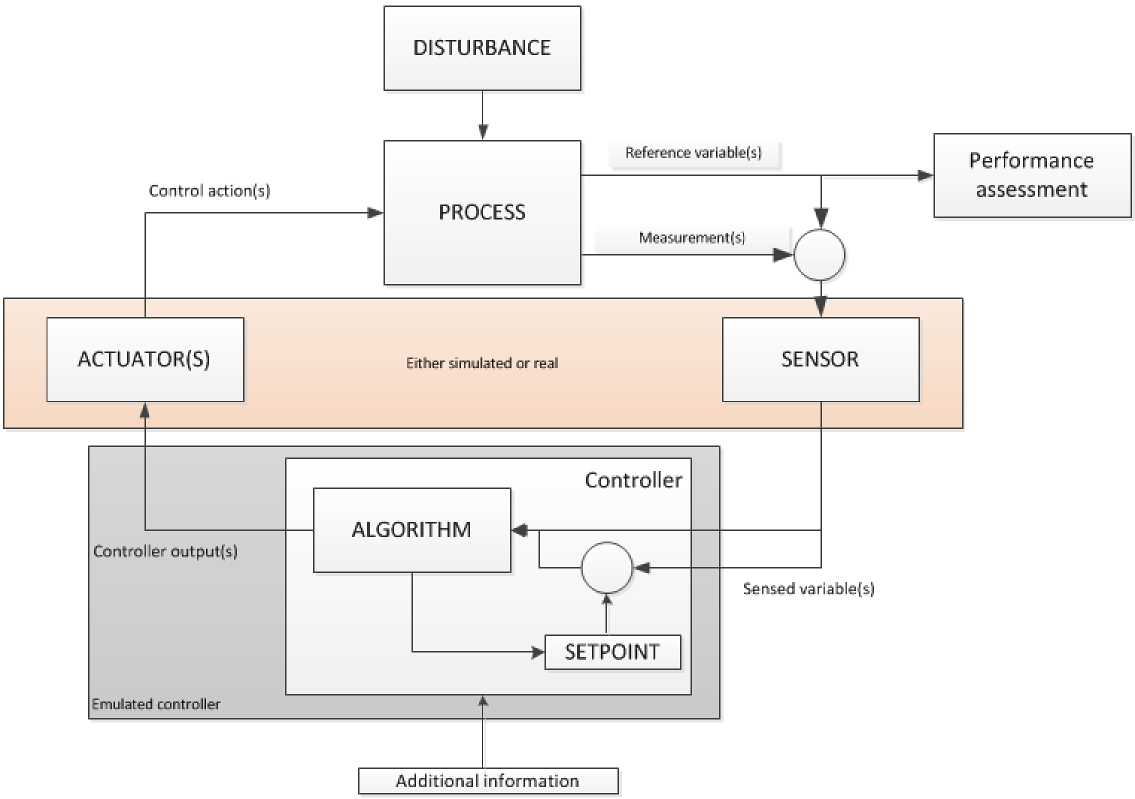

Figure 60 : Typical layout of real control emulation

On the other hand, output signals from the simulation (measurements) have to be sent to the emulated controller. Again, the choice has to be made between simulated or real sensors. Since sensor measurement phenomena might be very difficult to place in the real world (e.g. room temperature sensor), the choice is often towards sensor simulation.

In both cases and independently of the choice of simulated or real actuators and sensors, the input/output signal has to be sent to the simulation via an input/output interface. This interface can take different types:

- Analogue inputs/outputs that are measured using analogue-numerical converters
- Standard communication buses (e.g. building communication buses such as BACNET, KNX, M-bus, Modbus etc.) that are already supported in the real controller and that could be implemented in the simulation environment
- Direct data exchange using other communication (e.g. socket) and custom or standardised protocols

A simple layout of building controller emulation with communication bus is shown in *Figure **61***. The corresponding picture of a real test rig is shown in *Figure **62***.

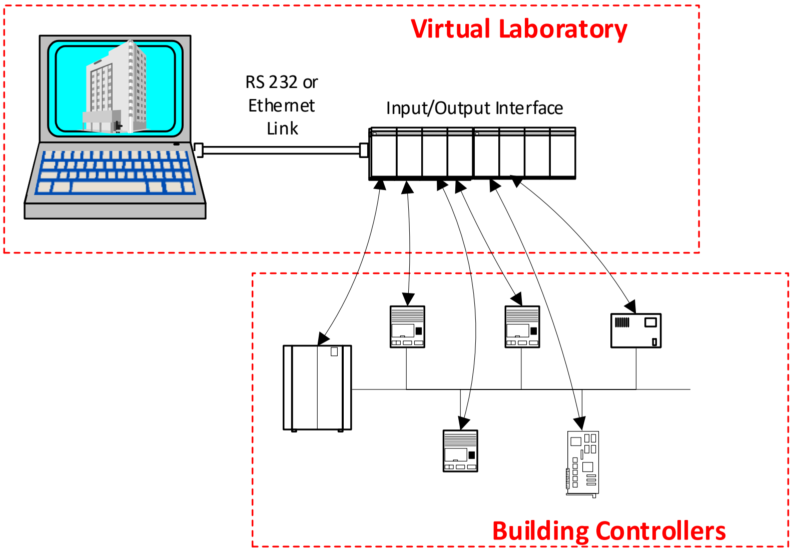

Figure 61 : Controller testing using emulation techniques (layout)

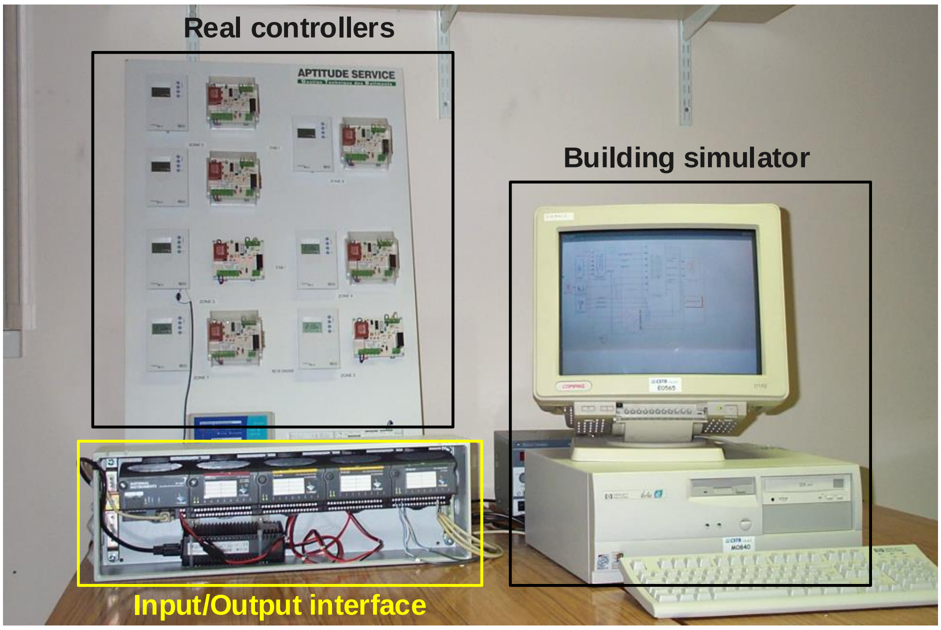

Figure 62 : Picture of test bench for controller testing using emulation techniques

While analogue inputs/outputs or communication buses (more convenient) are a very good choice for real controller emulation, the easiest choice for emulation of controller algorithms is to use data exchange via socket communication since it is much easier to implement and more flexible. However, there is no relevant standard available to date.

It has to be mentioned, that in any case of simulation, the time has to be synchronised between both parts, the tested part and that representing the virtual environment. This is in many cases real time (the simulation is thus slowed down) but approaches with accelerated time have also been studied, as described in Salque[141].

In case of this co-simulation there is a second option for sending controller outputs to the simulation. This option is to send directly set points to the simulation environment assuming thus that control (e.g. PID) is applied perfectly. This choice is best if the objective is the evaluation of energy management and not real control. The main advantage of this option is that in many cases (for example in the Thermoss[50] project related to district energy management optimization), the consideration of actuator and real control problems (On/Off, proportional, proportional-integral, or even proportional-integral-derivative control) will need to tune controller parameters which is a tricky problem, especially if a large list of controllers shall be co-simulated. The comparison of different optimization algorithms is then biased by differences in real control and the question if the difference is more influenced by control stability than by the optimization algorithm itself which is mainly energy and cost oriented (and thus more closely linked to energy management than control).

In the Thermoss project, these both types of control have been implemented into the Dimosim platform:

- Real control based on the physical control loop (process, sensor, controller, actuator…);
- Idealized control where the set points can be imposed externally and the component will iterate in order to find the corresponding operating point (e.g. if the zone temperature set point is imposed from the optimization algorithm, Dimosim will iterate on the valve position of the emitter valve).

Both options have been implemented and were tested in the Thermoss project. From this expercience it is recommended to use the idealised control option in order to get rid of controller tuning problems which are irrelevant for energy management optimization analysis. Also, the simulation time step would have to be lower than the default time step (10-60 minutes).

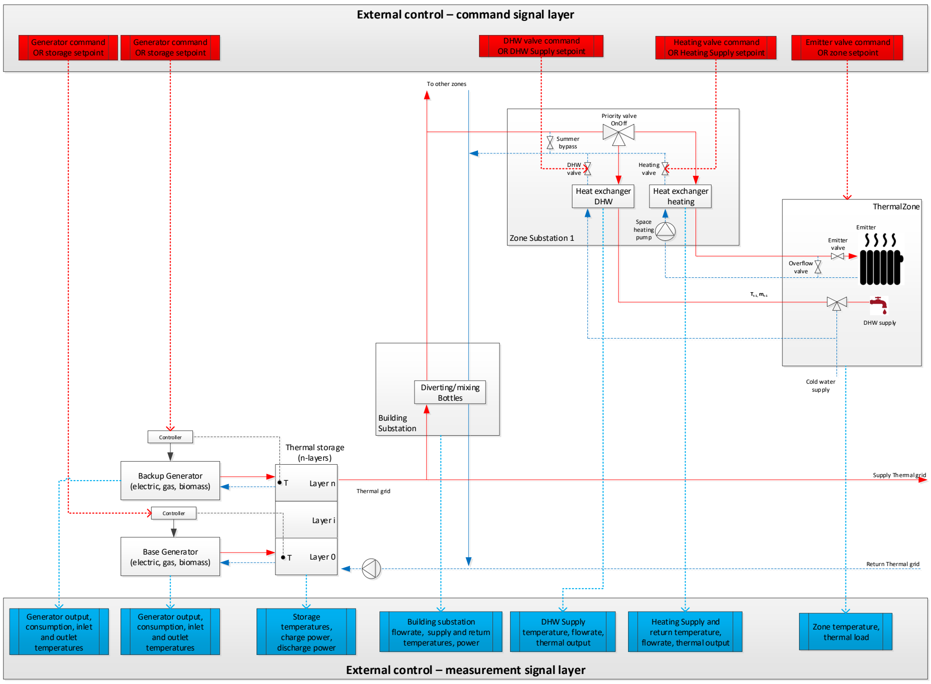

Figure 63 : Example of district energy system control emulation

4.2.2 COMPONENT-BASED TESTING METHODS FOR COMPOSED THERMAL SYSTEMS

The component-based emulation approach is in reality not a real emulation as defined previously since it can be a combination between simple, steady state laboratory tests and simulation. The idea is to split a global system into several elementary modules that can be tested individually. The test of each module will then allow to identify a corresponding numerical model. Once all models identified, system performances can be estimated by a global simulation where all individual component models are used to build the global system to be evaluated.

The typical example for this method is the evaluation of solar thermal systems. The standard for custom built systems (prCEN/TS 12977-2-5) includes 3 component standards where associated testing methods exist:

- Solar collectors NF EN 12975-2: laboratory test of the collector exposed to natural solar radiation.
- Storage tanks: EN 12977-3 and prCEN TS12977-4: Emulation test of a storage tank with water draw profiles.
- Controller: prCEN TS 12977-5: On/Off control of solar pump, Control of three-way valve, Control of back-up heater

Finally, the system performances are calculated based on a standard with the related calculation method (prCEN/TS 12977-2) for different climate zones. The resulting global model can be used for system conception, sizing and simulation on the operation.

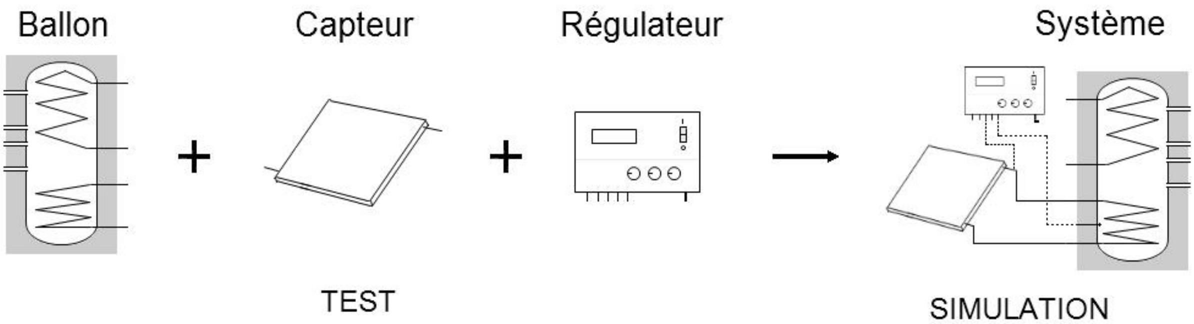

Figure 64 : Component based-testing methods for solar thermal systems (CTSS)

This testing method is similar to any numerical simulation strategy: unitary component simulation models are developed and validated. From this simulation « library », a complete system can now be simulated and from there, annual performances are calculated.

This testing method is quite flexible and allows even to test what would happen for a non-standard market configuration. However, the limits of this prCEN/TS 12977-2 approach cannot be neglected for some systems for the following reasons:

- More and more innovative controllers and control strategies make the test of controllers more difficult or even impossible; new testing methods will have to be developed.
- Several solar thermal systems are on the market where all components are integrated in one global product. These systems fall under the « factory made systems since they cannot be tested and evaluated as components.
- Higher uncertainties due to a performance assessment of the system completely based on simulation
- The whole system is not tested in its complete configuration, the test can thus not evaluate the system as a whole
- Floor heating can be an active part of the system as a storage: the technical specifications do not include this phenomenon

[50] Building and district thermal retrofit and management solutions (Thermoss), Horizon 2020 research and innovation programme, Grant Agreement 723562

4.2.3 GLOBAL TESTING METHODS FOR FACTORY BUILT SYSTEMS OR COMPLEX SYSTEMS

This third group of emulation can be considered as the most accurate solution of evaluation for composed systems. The method has initially been developed for solar combi-systems[58] and later been adapted to other systems such as heat pumps[57]. These solar systems are rather difficult to split into smaller parts since the complete system is difficult to model in enough detail (e.g. different storage types, much more complex control strategies, complex hydronic configurations).

By testing the system as a whole, the test results are much closer to the real operation as for a test of the controller alone (with a fully simulated system) or using the CTSS method. Only the solar collectors are switched to virtual in order to be independent of real weather conditions. The models being well known for solar collectors, the results are thus almost equal to the real case. Examples of validation by in-situ monitoring can be found in the EvalSSC[54] project.

Some examples of test layout are shown in *Figure **65*** for the example of a solar combi-system. As mentioned previously, only the solar collectors are taken off from the real system.

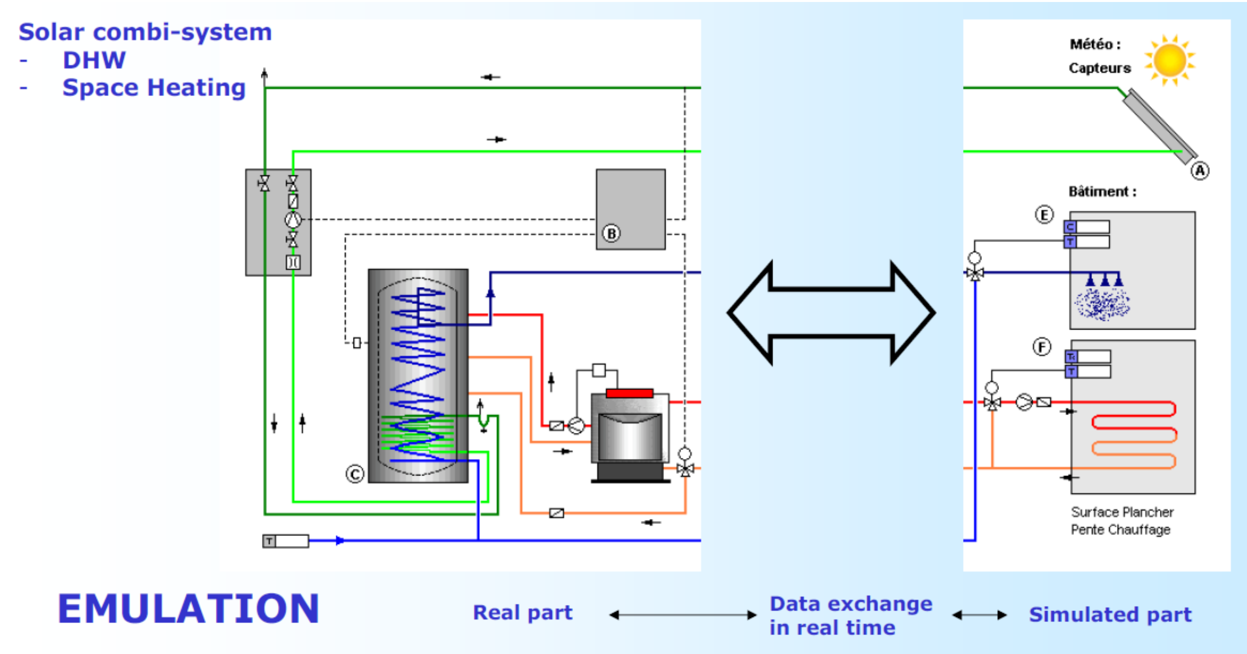

Figure 65 : Global testing method for solar combi-systems

Of course, to allow the data exchange between virtual and real part, several physical interfaces are necessary to connect for example a physical water flow with a certain temperature to the virtual part and vice-versa. They will be described in §4.5.

Besides this, the choice of the best suited border between virtual and real part is crucial. As for the example of the solar combi-system, for which solar collectors were moved to the simulated part, expert judgement is extremely important in order to select the optimum of test simplicity and reproducibility (the solar collectors have been moved to virtual in order to control perfectly the solar radiation) while not dropping too many components from the real part. §4.3 will introduce this point. It is also closely linked with Chapter III on the appropriate selection of model details for a given problem.

And last but not least, the core of such a test method is the test sequence itself. Even the most detailed simulation (the virtual part) and equipment with highest accuracy will not help improving the significance of results if the test sequence is not appropriated to the evaluation objectives and the system to be tested. Several methods exist and will be introduced in §4.4.

4.3 SELECTION OF APPROPRIATED BORDERS IN EMULATION

As already introduced in §4.2.3 for global emulation test methods, the choice of the border between virtual and real part is very important.

The criterion for this choice is to obtain most accurate results while simplifying as much as possible the real system installation (costs and complexity) and allowing also a perfect reproducibility of the test(s). Being dependent of real weather conditions for solar radiation for example, will drastically diminish the test reproducibility.

Other examples exist, where the choice of a model is better than to keep the real component. A very good example is, for the case of a geothermal heat pump (*Figure **66***), to move the borehole(s) to the virtual part. Using a real borehole for the test would bring two disadvantages:

- Reproducibility: if, for any reason, the test has to be restarted or repeated, it is impossible to restart the test with identical initial states in the ground around the borehole drilling. In a simulated borehole, the initial state is perfectly managed and will thus give very good results.
- Costs: it would be extremely cost intensive to drill one or several boreholes for a laboratory test. Another solution would be to connect the test bench where the heat pump is installed to a second test bench for geothermal testing. An example is given in §4.5 for a multi-site testing methodology that has been developed between CSTB and BRGM in a project funded by ADEME, the French environmental and energy agency.

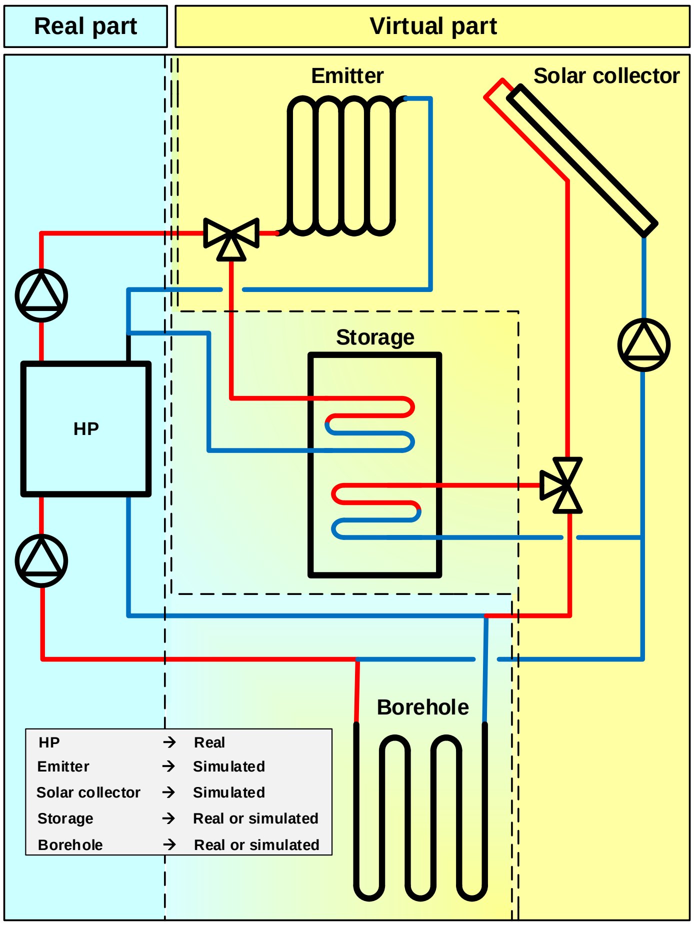

Figure 66 : Global testing method for geothermal heat pumps with solar thermal for space heating and DHW

As shown in *Figure **66***, not only the borehole could be moved from real to virtual. In fact, any of the components would change its situation. For example, the thermal storage could also be moved. In the latter case, the ability of the available simulation models to reproduce real behaviour (including internal convective phenomena and transients) will be the criterion for the choice. Also, thermal losses in hydronic connections which are very difficult to model (thermosyphon effects or pressure phenomena) can be a reason for keeping components in the real part.

*Figure **67*** is another example of a chosen test boundary for a geothermal DHW heat pump. In this case, the choice is rather simple since it seems logic to install storage and heat pump in the real part while the hot water draw profile and geothermal borehole remain virtual.

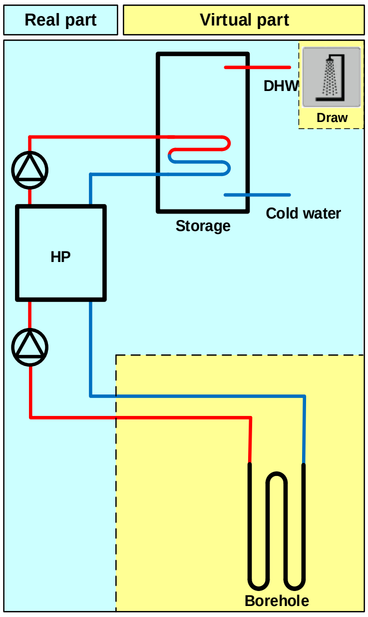

Figure 67 : Global testing method for geothermal heat pumps with solar thermal for space heating and DHW

A crucial point in replacing real parts by a virtual representation is the knowledge about the validity of the numerical model. For example, in the case of the DHW heat pump from Figure 67, a detailed geothermal borehole model has been developed and validated to ensure the correct test results. Especially transients must show very good agreement with real behaviour.

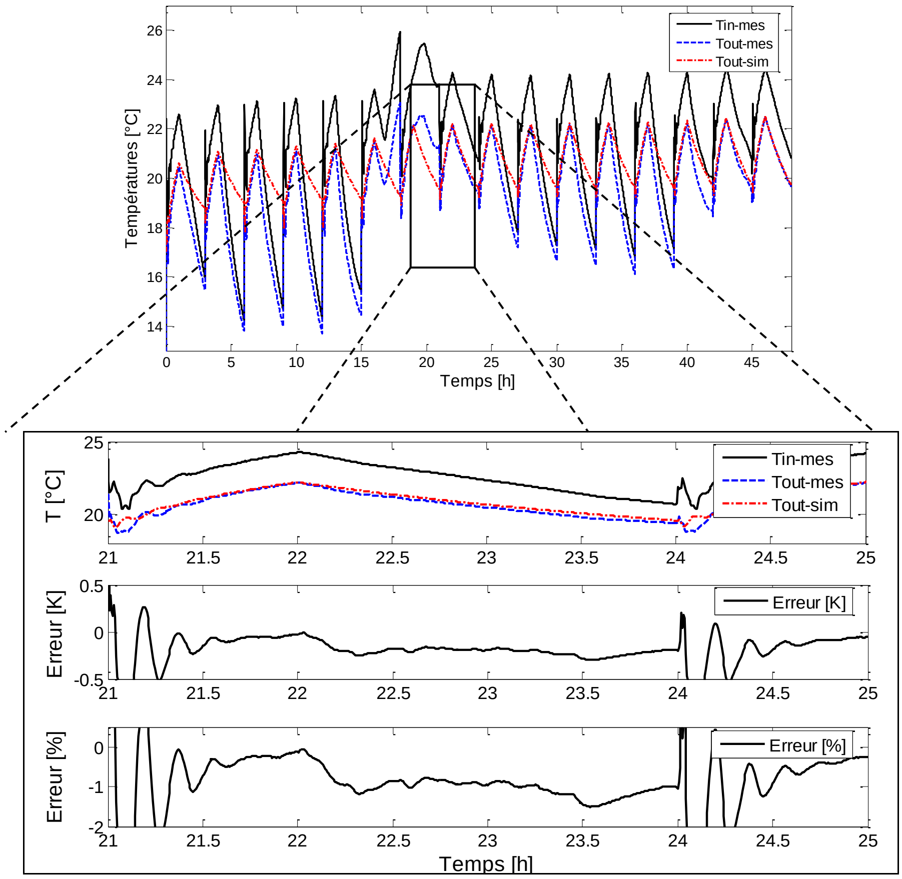

Figure 68 : Comparison of the geothermal borehole model with experimental results (inlet and outlet temperatures)

Finally, *Figure **69*** shows another example for an air-water heat pump with solar PV system and electrical storage. In this layout, other aspects of emulation are shown:

- the integration of the electrical vector for the solar PV panels and battery storage
- the necessity for climatic chambers to simulate external air conditions (controlled following weather data from files) where the external unit of the heat pump is installed in.

While these last two additional vectors seem simple, they complicate the control of the test bench. Electrical phenomena are related to very high frequency phenomena compared to thermal phenomena in the system (e.g. voltages and currents vs temperatures). And for the outdoor unit of the heat pump, the need for a climatic chamber will add additional detail as for example real defrosting which would be difficult to simulate (the defrosting algorithm in the controller would be connected to virtual defrosting). This means, in theory, the testing boundary conditions will even be more realistic. On the other hand, these new aspects render an accurate control of the test bench very difficult. For example, a defrosting cycle will release a large amount of humidify into the air of the climatic chamber within several minutes. This humidity must be quickly evacuated from the chamber to be able to follow the humidity set point which is delivered by the weather file. Then, between two defrosting cycles, the air in the chamber must be humidified since ice will be hold by the evaporator of the unit.

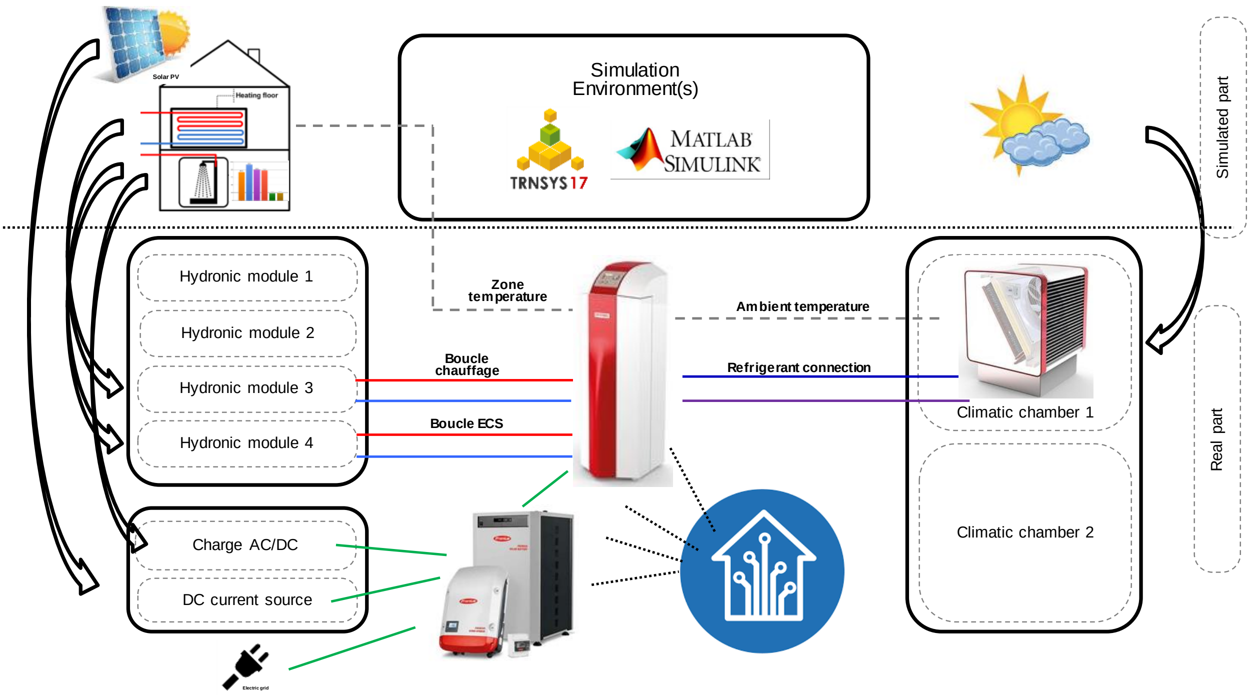

Figure 69 : Global testing method for heat pumps with solar PV for space heating and DHW

Finally, if an air-air system shall be evaluated, the phenomena still get more complex.

The test of a heat recovery ventilation system can be realised with a second climatic chamber. One climatic chamber will thus simulate the external conditions from where external air is taken from, the second climatic chamber reproduces indoor air states. If the ventilation system does not control the indoor temperature and/or humidity, the test is feasible with reasonable effort.

If the heat recovery ventilation system is at the same time controlling indoor air conditions, or if for example an air/air heat pump shall be tested (Figure 70), an additional difficulty is added:

- the real controller of the system to be emulated will control on the indoor air conditions (temperature, humidity, CO_2…).
- The indoor air is simulated in the virtual building model
- The virtual building model, to be able to calculate indoor air conditions, requires the incoming air flow with a very good accuracy. For example, if temperature control is tested for a heating case, the heating power from the air/air system has to be measured

with a rather high accuracy since this thermal power will be injected in the virtual building (model). Yet, to measure this output with a sufficient accuracy is very difficult since air is blown generally over a big area with inhomogeneous conditions (e.g. air blown by the internal unit of an air conditioner) on the air side. The power can also be measured on the refrigerant side, but this would require the modification of the heat pump system itself. Even if non-intrusive methods have been developed (Cong-Toan[60] or Sepemo[16] project) the accuracy and difficulty of these methods is still an issue.

Additional features and concepts have thus to be added in order to guarantee the best feasible accuracy of the test.

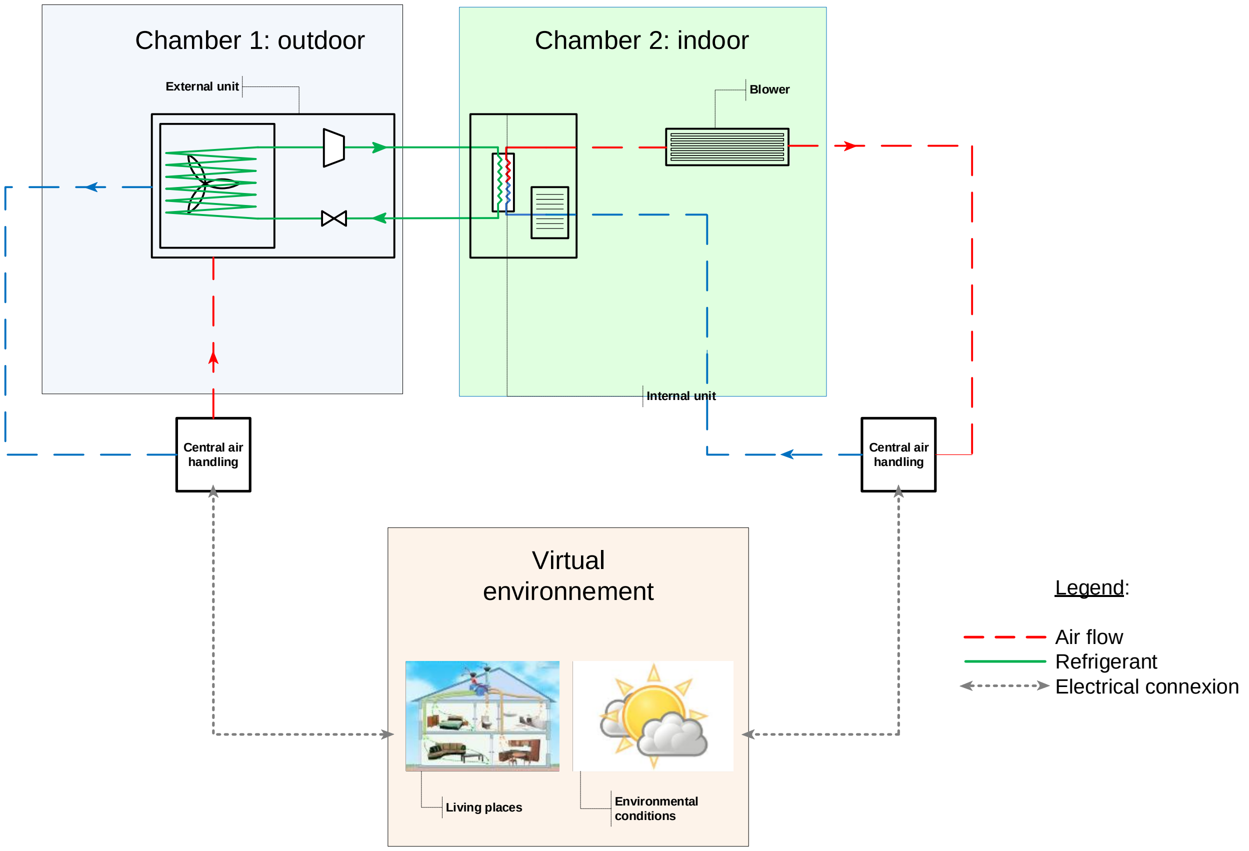

Figure 70 : Global testing method for an air/air heat pump

4.4 TESTING SEQUENCES OF EMULATION TESTS

Depending on the system or component to be tested and the objective of the evaluation, the type of test can be in one of the following two main categories, direct and extrapolated testing methods.

4.4.1 DIRECT TEST METHODS

In direct test methods, the test will cover one or several independent test sequences. These sequences will allow to calculate the test KPI's without any interpolation or extrapolation. Again, two subcategories can be defined:

- Abstract tests: Abstract test sequences represent only a partly realistic case. They have been defined in this manner to allow, in a test sequence with maximum simplicity, to evaluate characteristic behaviour of the component to be tested. An example is the test sequence for room terminal controllers applied in the eu.bac certification test scheme (*Figure **71***). The test corresponds in the emulation of a room terminal controller with 3 main test periods where internal gains of the room are changed between each period. The 3 test periods of 3 hours each will then lead to a response of the controller which is evaluated following the KPI's that have been defined as CV (control variation) and CSD (control to set point deviation).

  This emulation test is certainly not realistic compared to a real case. But, since the objective is to evaluate the ability of the product to maintain the required set point, this type of test is certainly more representative as a real day that could be tested.

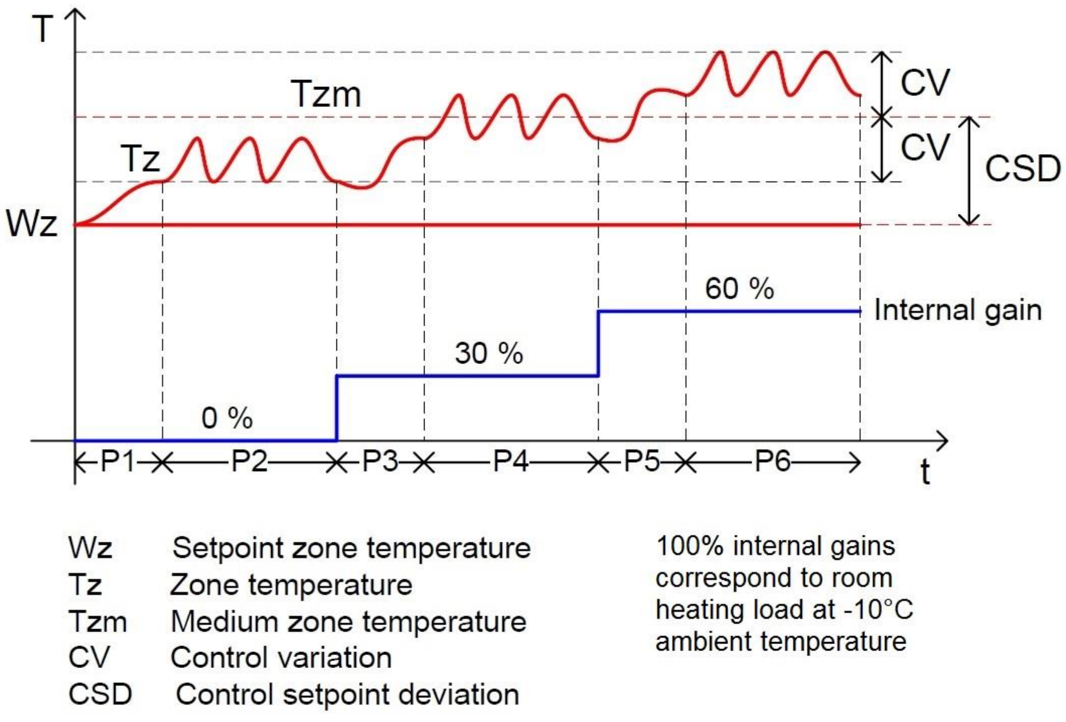

Figure 71 : Abstract test sequence of the Eubac certification scheme for room terminal controllers

- Realistic tests with real conditions

  In this type of test sequence, the virtual part will be as close as possible to a real case. The objective is not the certification anymore, but to test a product (controller or system) as close as much to real conditions. Fixed internal gains will not exist here, but mainly internal gain profiles generated using statistical/stochastic modelling in order to be as close as possible to the real application. These test sequences will allow either to analyse the robustness of control of a product, to evaluate performance on a typical winter, mid-season or summer day. The test result will in most cases not allow to derive performances over a longer period but only to verify how the product operates under these typical conditions.

4.4.2 EXTRAPOLATION TEST METHODS OR SEQUENCES

If the objective is to evaluate seasonal or annual performances of a product (controller or system) using emulation techniques, test results are extrapolated from a shorter time period to the whole period (season or year).

In general, and relative to almost any case of energy system to date, seasonal or yearly performances are evaluated using a combined testing and calculation method:

- test sequences that are not based on emulation are applied (e.g. standard test of heat pumps for different operating conditions and points)

- based on the obtained matrix of operating points, an additional calculation method (bin-method[51]) will provide the integrated performances over a certain period (e.g. season).

This approach is the most common one due to the simplicity and robustness as well as the ease to define all conditions in a standard (CEN, ISO etc.). However, if systems performances are highly linked with control algorithms, the correct evaluation of real performances is difficult to evaluate using this approach, if not impossible.

In this case, emulation provides a very flexible and powerful tool. In fact, instead of an abstract performance test, realistic test sequences are applied on the product to be tested. In almost all cases, the tested period is based on a daily period (but can be also smaller, such as for example only 12 hours). These days represent typical days and results can then be extrapolated from several characteristic days to a complete season or year.

The AC/DC (Annual calculation / Direct characterisation) method[52] for solar combi-systems for example is based on days in winter, 2 in mid-season and 2 days in summer. A second method is the CCT test sequence[53] with 12 typical days, each day representing one month of the year. The extrapolation is then very simple, it only needs the multiplication, of energies by the number of days in the corresponding month. In the French "EvalSSC"[54] project, an improvement of the CCT method has been further improved and validated.

Each of these methods is divided into three key phases:

- an initialisation phase where real components and the numerical models initialise to typical states. The initialisation phase can be divided into several sub-initialisation phases as shown for the example of the AC/DC method in *Figure **72***.

- a core phase where the real test is carried out and results are collected

- a final phase to terminate the test and to set back states to the initial ones (e.g. a thermal storage tank which is emptied to the same energy as at the start of the test).

Independent of the number of days, the most important question of all emulation test sequences is how to define or select the typical days. This will have a key impact on the validity of energies (and to some extent efficiencies) extrapolated to the complete season or year. While AC/DC is based on a qualitative method to define test days[52], the CCT method[55] uses a method which is not documented clear enough publicly. In the SSC project, however, typical days following this method can be any day of the year, with the only condition that it fits with the monthly days have been selected randomly from the weather file in order to fit with the monthly average of heat demand of the corresponding month.

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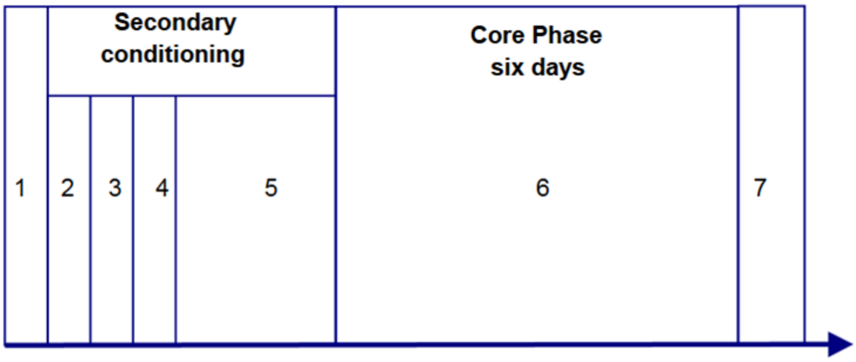
[51] IEA HPP Annex 28, publication 140

[52] Chris Bales, Combitest – Initial Development ofthe AC/DC Test Method, A Report of IEA SHC - Task 26 Solar Combisystems, October 2002

[53] Peter Vogelsanger, The Concise Cycle Test Method -a Twelve Day System Test. A Report of IEA SHC - Task 26 Solar Combisystems, November 2002

[54] Riederer P., Papillon P., Albaric M.: Méthode d'évaluation pour les Systèmes Solaires Combinés, Rapport n°2, Convention ADEME no 0605C0053, décembre 2008, 55 p.

[55] Peter Vogelsanger, The Concise Cycle Test Method -a Twelve Day System Test. A Report of IEA SHC - Task 26 Solar Combisystems, November 2002



Nr	Name	Period [h]	Description
1	Conditioning	→ 0	Conditioning of the store to a uniform temperature of 20°C.
2	Secondary-	0 → 8	Full charge of store with winter auxiliary heater. Automatic heaters on from this point onwards.
3	...	8 → 20	(Constant) space heating discharge.
4	condition-	20 → 24	DHW comfort test.
5	ing	24 → 48	Final conditioning.
6	Core Phase	48 → 192	Six days of realistic conditions (climate and load).
7	Final Discharge and mixing	192 → ?	Discharge of DHW until the DHW outlet temperature goes below 30°C, followed by mixing of the store contents or alternatively conditioning to 20°C.

Figure 72 : AC/DC test sequence with 7 periods[56]

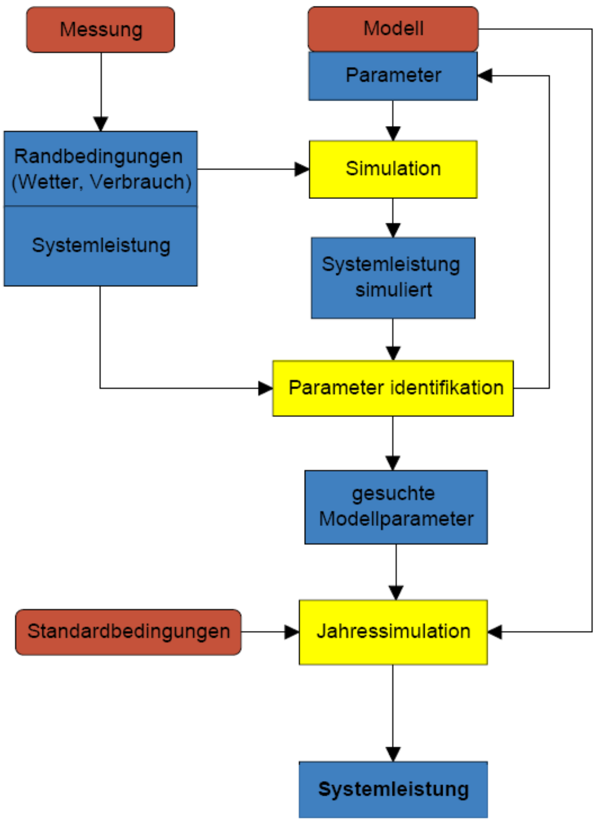


Figure 73 : CCT evaluation methodology[55]

[56] Chris Bales, Combitest – Initial Development ofthe AC/DC Test Method, A Report of IEA SHC - Task 26 Solar Combisystems, October 2002

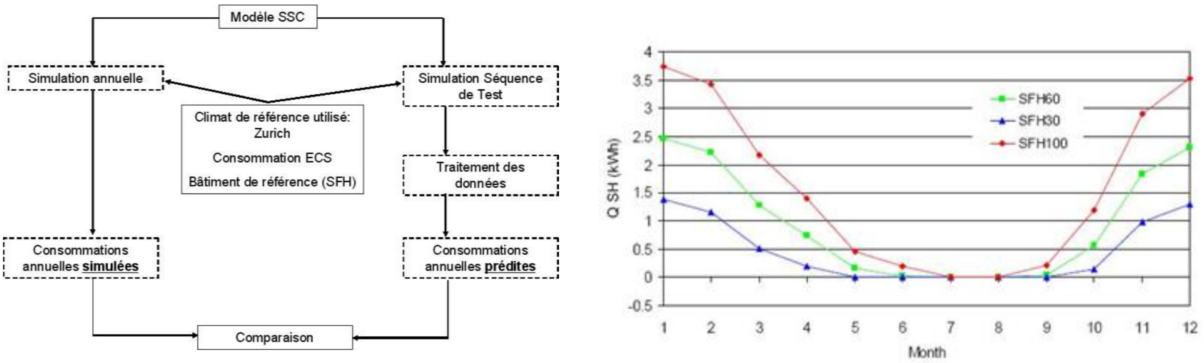


Figure 74 : Methodology for the definition of 12 test days[57]

A method has been specifically developed for heat pumps (even if it could be applied to any thermal building system), where the closest day of a month is chosen, in order to keep real days of the same month[57]. This project has also allowed to compare, in detail, different approaches on how to define typical days.

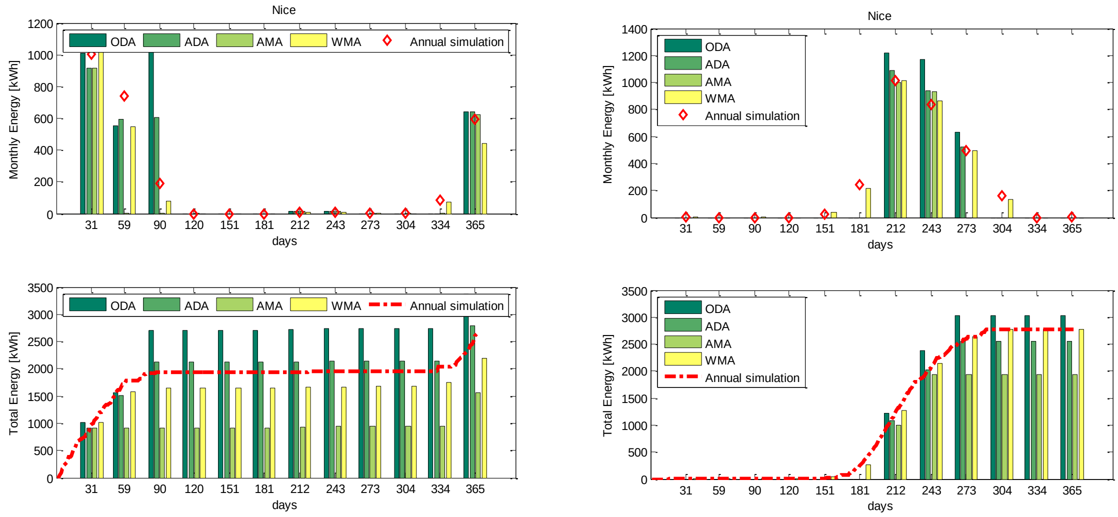


Figure 75 : Heat pump emulation method – comparison of 4 methods for typical days (building energy demand)

The results are very promising but showed that it is crucial to select appropriate test days. While for example in Nancy the impact of the choice of the day was less, in a milder climate as for example Nice (Figure 75) the difference was very high. The so-called WMA (Weighted momentum approach) fitted very well with all 4 tested climates.

A particularity of this method lies in the fact that the method has been developed for geothermal heat pumps. The geothermal boreholes were simulated in the virtual part in order to guarantee a perfect reproducibility but also the possibility to run the test in only 12 days. In fact, the thermal inertia in the borehole (and the surrounding ground) is so high, that it would make a test impossible. The test method has thus been structured as shown in *Figure **76***. The idea is to run a yearly simulation with the building and geothermal borehole model. The building and borehole will thus be either connected to the real heat pump or a simulated heat pump. While the days which are simulated serve as continuous conditioning of states for the next real test days (and run with high simulation speed in the order of seconds for 1 month), the test will be slowed down to real time for the real test days. The real heat pump will thus be connected to the building and borehole models which are perfectly initialised for the new test day (month).

The heat pump model used for the continuous conditioning is identified as a black box model (polynomial, neural network etc.) with the data of each real test day. At the end of the test, the

[57] Riederer P., Partenay V.: Dynamic Test Method for the Determination of the Global Seasonal Performance Factor of Heat Pumps Used for Heating, Cooling and Domestic Hot Water Preparation, Proceedings World Geothermal Congress 2010. Bali, Indonesia, 25-29 April 2010

heat pump models has thus been trained on all 12 test days and is thus in very good agreement with the whole test data set.

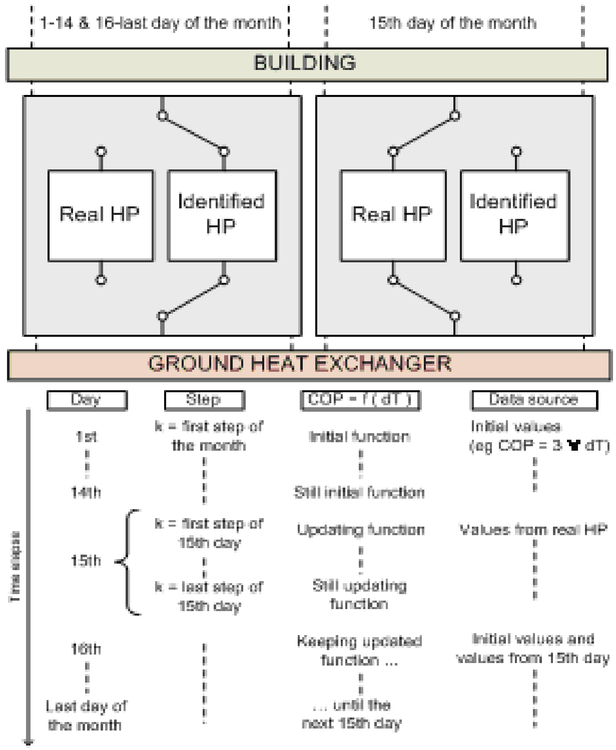


Figure 76 : Heat pump hybrid emulation method

In general, it can be stated that for direct and hybrid emulation methods, intermediate “conditioning” periods based on simulation will allow for considering thermal inertia aspects (e.g. simulated geothermal borehole, storage tank, etc. as part of the test environment).

Figure ***77*** also shows this approach more generic for the test of any system by hybrid emulation.

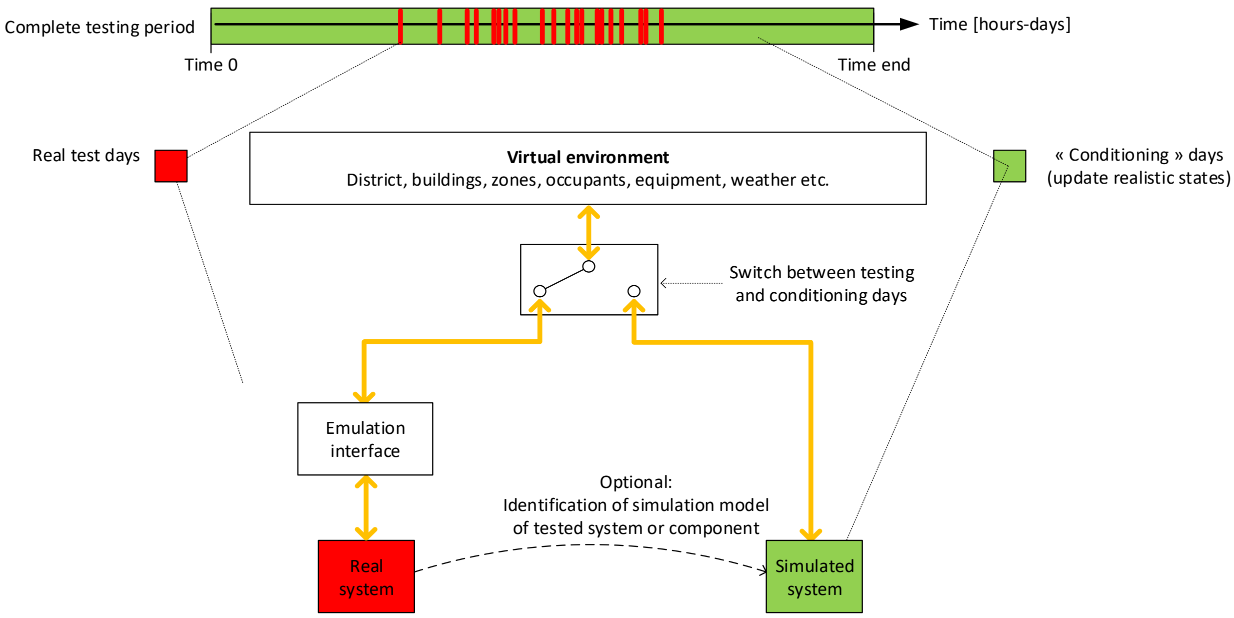


Figure 77 : Hybrid emulation test routine with mixed simulation/emulation periods

4.5 NECESSARY MEASUREMENT AND PHYSICAL EQUIPMENT IN EMULATION TEST RIGS

The type of necessary equipment for emulation tests is various. Each system might require other communication interfaces between the virtual and the real part.

The simplest interface in terms of complexity and accuracy is surely for the emulation of a terminal controller of electric heating. This type of emulation only needs the transfer of the room temperature to the virtual part. This is usually done using a programmable resistance box since most sensors are still RTD sensors which correspond to a temperature/resistance function of the sensor. On the other hand, the control output signal of the controller is generally a relay or triac. This binary signal can easily be set and measured. With these two interfaces of input and output, the emulation test can be run (remark: the main difficulty will be to synchronise between the measurement time step of the control signal in the magnitude of a share of a second and the time step of the simulation which does not need such small time steps).

One step higher, for example the test of a water/water or geothermal heat pump, the physical interface between real and virtual part must include the control of water in terms of flow rate, temperature and pressure. This is shown in *Figure **78***. In the middle, between virtual (right hand) and real (left hand) part, the two main elements are shown:

- Water control module (control of temperature, pressure and eventually flow rate)
- RTD sensor simulator

The data acquisition system and industrial controllers represent the link between the computer and the water control module.

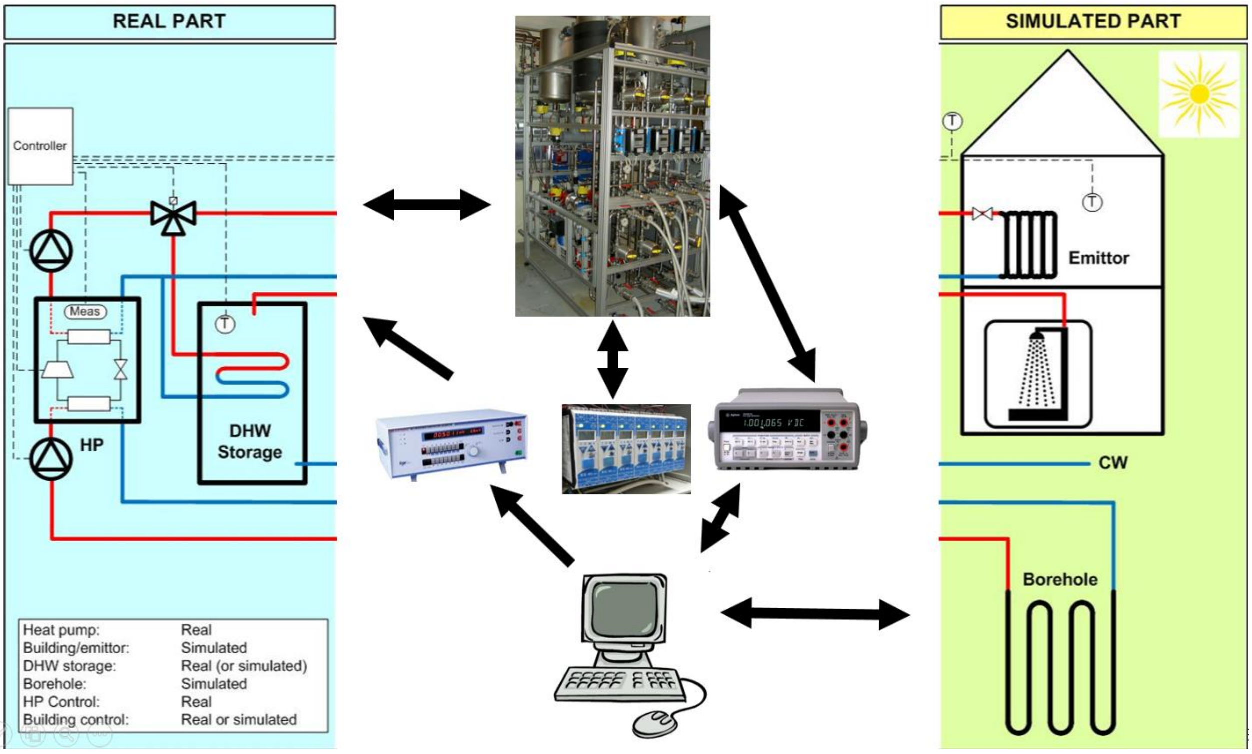


Figure 78 : Physical interfaces between virtual and real parts

An overview of test facilities[58] has been produced in 2020 and list the laboratories that have been working on such type of test benches at that time. Only few new players exist to date on this topic.

[58] European test facilities for solar combisystems and heat stores. A Report of IEA SHC - Task 26 Solar Combisystems. December 2002

Besides the vectors that have been described previously, it is simple to list the interfaces as follows:

4.5.1 MEASUREMENT AND SENSOR INTERFACE

This interface has already been described for resistances sensors. Other interfaces for measurement signals exist:

- Resistance
- Current or voltage signals (e.g. 0-10V or 4-20mA)
- Ethernet or serial connection (wired or wireless) with bus communication protocols as Modbus, m-bus, z-wave, zigbee etc.

With modern sensors, digital sensors and wireless bus communication get more and more common. However, low level control is still carried out using wired resistance sensors due to the high frequency of data exchange (e.g. PID control).

4.5.2 WATER INTERFACE

The water interface is realised with charge or discharge modules. An examples is shown in *Figure **79*** for a generic module (charge and discharge function including electric post-heater) and in *Figure **80*** for a test bench for heat pumps with low energy consumption. This interface allows to connect a water-based system to a simulated hydronic loop. For example, a boiler which is connected to a floor heating system can be emulated in this way. The floor heating system being simulated, the water interface allows to measure the water flow and temperature output to send this water supply information to the virtual part and, once the return temperature (and eventually pressure) calculated, control the water flow leaving back to the boiler controlled to this new set point. This operation is repeated for each time step of the emulation. The real boiler operates thus as in a real building.

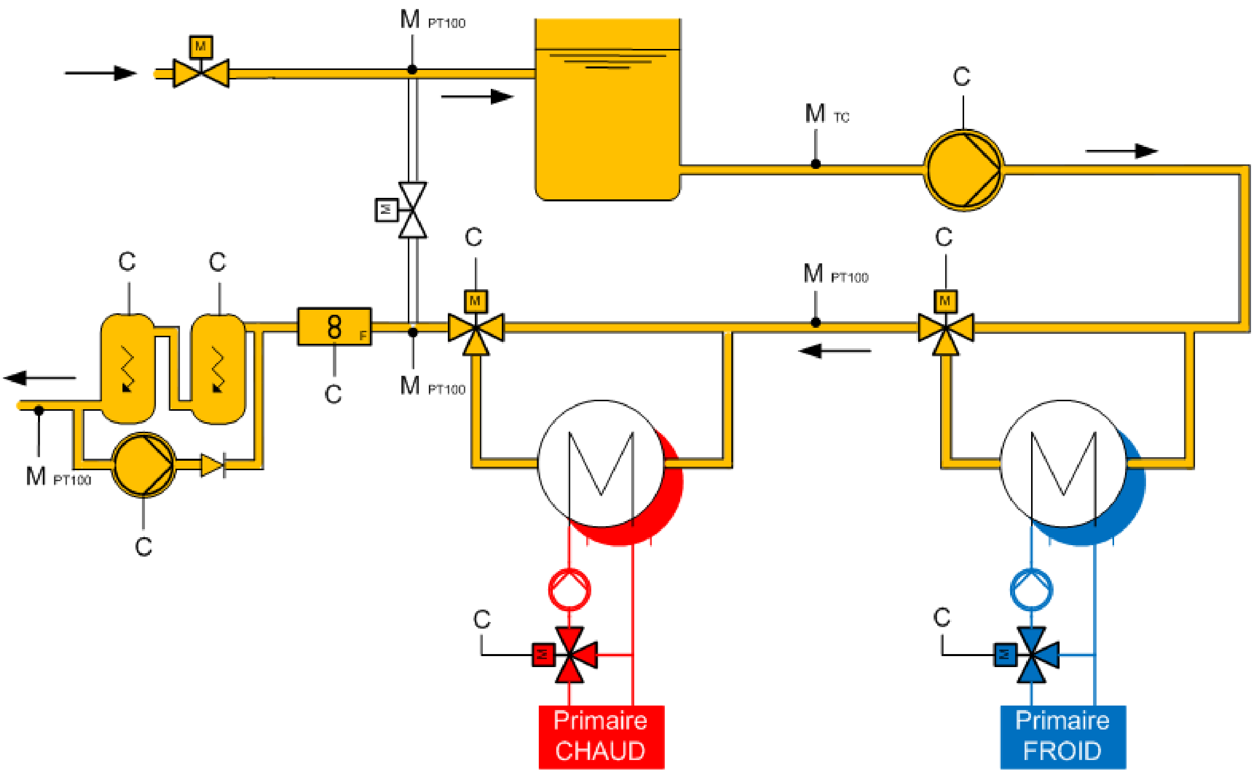


Figure 79 : Water charge/discharge module

Each module has implemented several temperature and pressure sensors as well as flow meters. The accuracy of these sensors and meters must match with the required level of testing and modelling which is a crucial question.

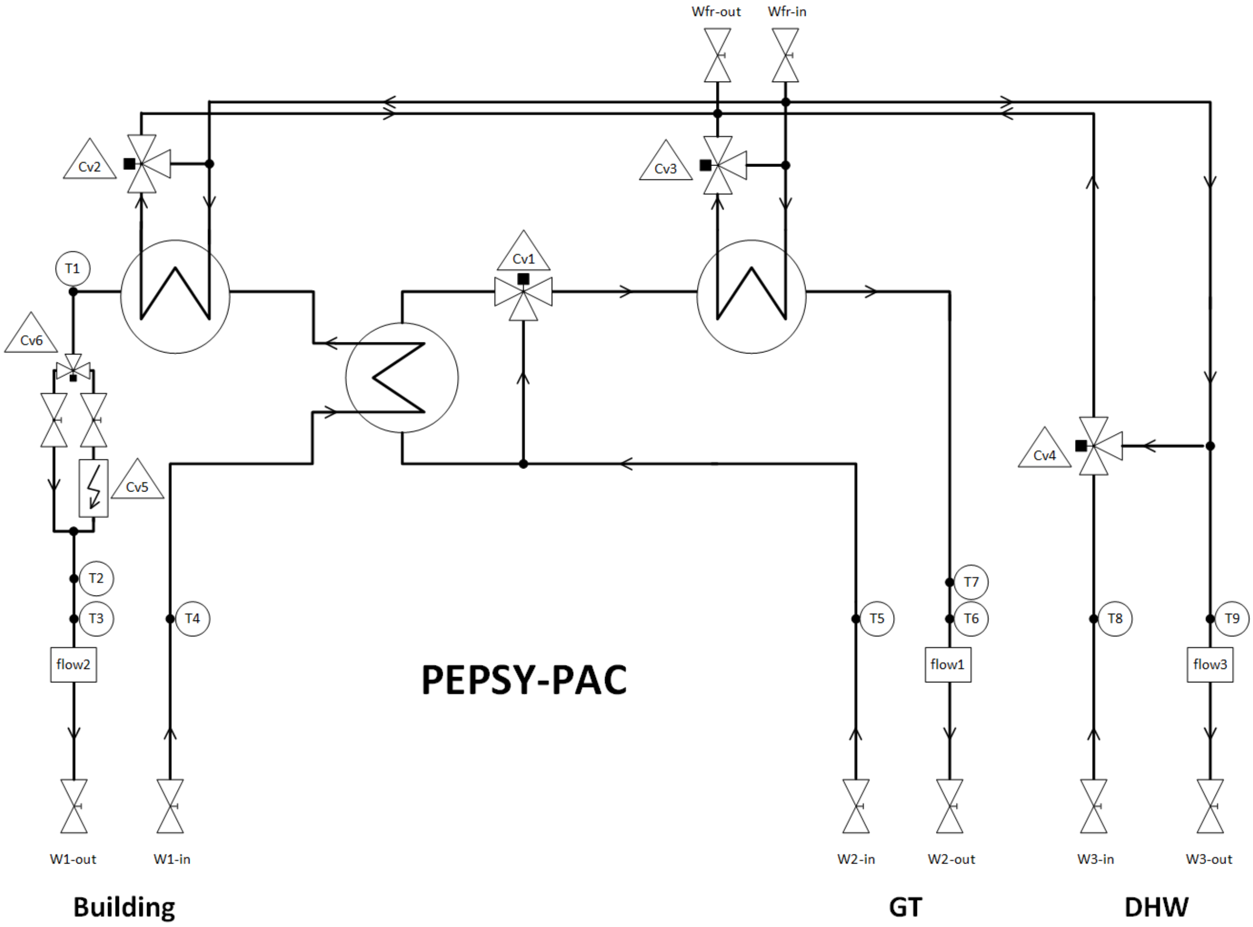


Figure 80 : Low energy test bench configuration for water/water heat pumps

Also, the control has to be done with industrial controllers with very high frequency in order to follow dynamically the setpoints. An example of control validation is shown in Figure 81. As for any control, a compromise between fast reaction and smoothness has to be found in order to avoid too high overshoot or too slow controller response.

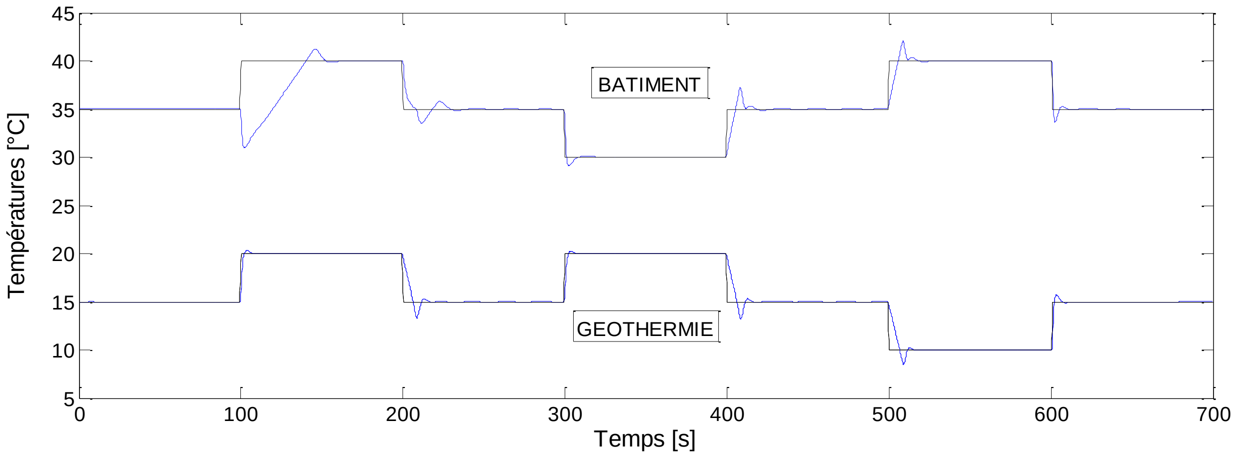


Figure 81 : Validation of temperature control of the heat pump test bench

With such interfaces, any water based system can be emulated easily. Since emulation of thermal energy systems requires the measurement and control of thermal power, the water interface facilitates this task since metering even at small time steps is easily feasible (electromagnetic or mass flow meters combined with PT100 temperature sensors).

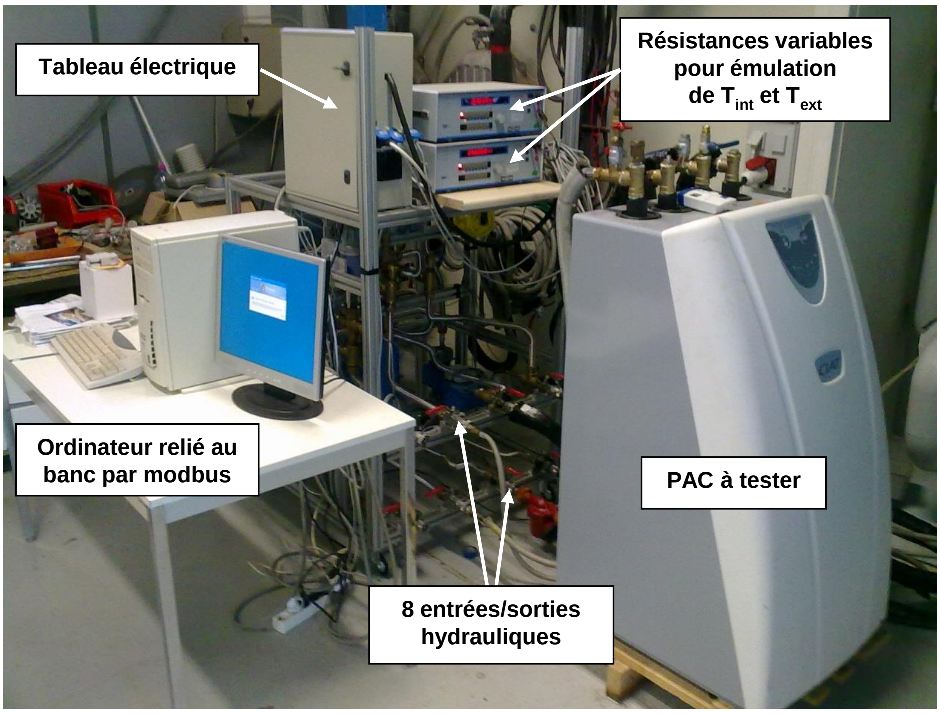


Figure 82 : Picture of water-based heat pump emulation test bench

4.5.3 AIR INTERFACE

An air interface is necessary for any system where the output to the building or any other component is done by air. This is the case for ventilation systems, air/water or air/air heat pumps or simply if a real sensor has to be place in air controlled to a set point temperature (outdoor or indoor air).

For an air/water heat pump this means that the outdoor unit is placed in a climatic chamber which is controlled to outdoor temperature and humidity conditions (or those in an annex room of the building such as the cellar or a garage if a DHW heat pump is placed in there). These conditions are either loaded from the simulation weather file or, in the case of an annex room, from the simulated part.
*Figure **83*** shows an example of such climatic chambers. Additional, removeable curtains prevent air bypasses between air inlet and outlet of a product to be tested.

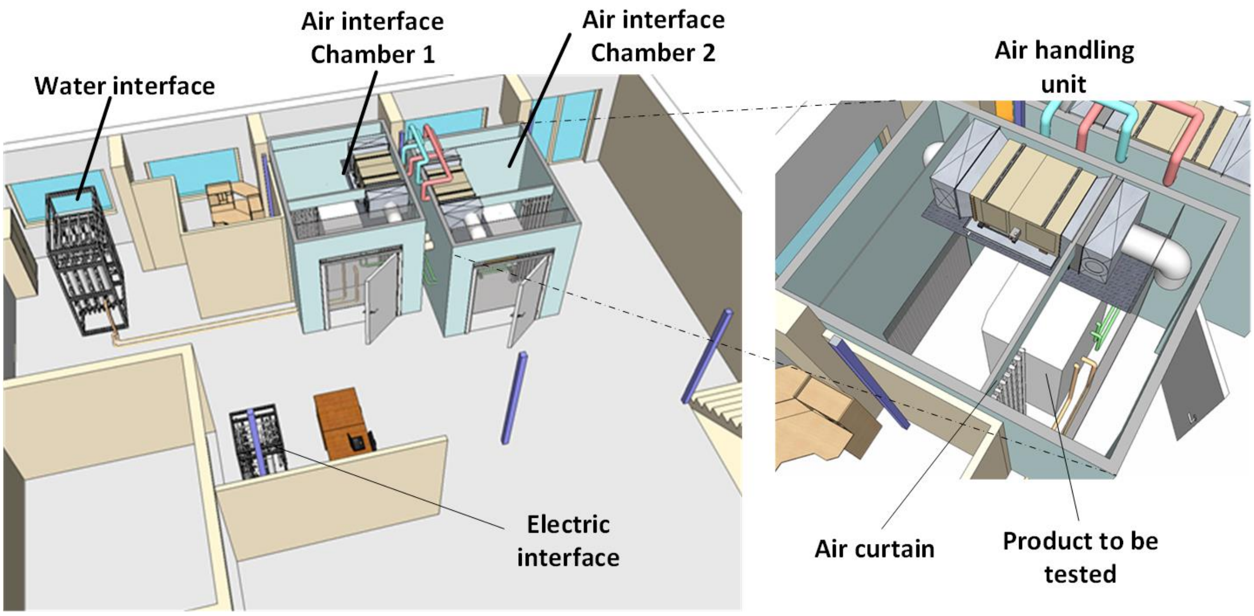


Figure 83 : Emulation laboratory with climatic chambers (air interface), water and electric interfaces

In the example of the figure with two climatic chambers, and air/air system can be tested. Each climatic chamber is equipped with an air handling unit that allows to control the air conditions (temperature and humidity) inside the climatic chamber. The air handling unit can be inside the chamber as shown in the figure or outside of it.

To optimise the conception of the air vector (and all other vectors in general), it is recommended here to use numerical simulation to simulate the whole coupled system of the product to be tested, climatic chamber and air handling unit as well as future test scenarios. The numerical models should be transient in order to represent all dynamic phenomena of the test bench control. *Figure **84*** shows an example of such a simulation of a climatic chamber during a test using the SIMBAD HVAC and Building toolbox within a student project[59]. It can clearly be seen that temperature control is much easier than humidity control where humidification and dehumidification represent transient phenomena which are more difficult to control. But again, numerical simulation is a perfect tool for the conception of emulation test benches and assist in the best choices of possible conception options.

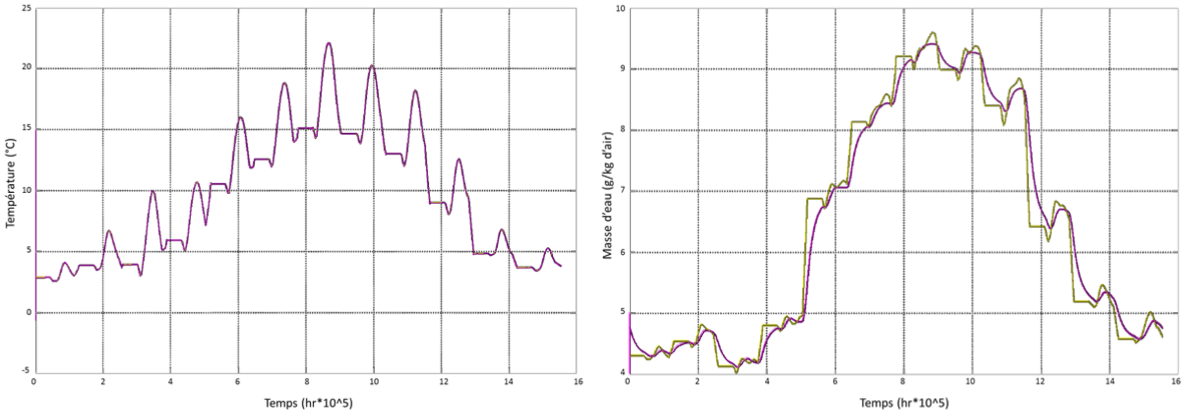


Figure 84 : Simulation of control of climatic chambers for temperature (left) and humidity (right)

A shortcoming of air interfaces is the difficulty of measuring and controlling thermal outputs. If an air flow can be measured inside an air duct, it is relatively simple to measure thermal power, except that one must consider inhomogeneous velocity and temperature profiles inside the duct. Standard exist to measure and integrate the profiles in order to allow thermal power calculations. However, the effort is more complicated, uncertain and cost expensive as compared to equivalent measurements of the water vector.

When the thermal power of air/air heat pumps shall be measured, this is trickier. The air outlets of these units render the measurement of thermal power more uncertain. Three methods have been applied and analysed in the literature[60]:

- Air profile measurements at the air outlet;
- Measurement in ducts (calibrated flow plate, duct velocity measurements, pressure drop etc.), for example using a hood and a duct with extraction fan to avoid additional pressure drop (*Figure **85***);
- Measurement in the refrigerant cycle (*Figure **86***).

While the first measurement does not require any modification of the product itself, the two other need adaptations or changes in the system. This is a critical point since the product is not the same anymore and performance results might be affected.

Also, each of these methods is affected by uncertainties and will thus not guarantee an error which is comparable to water driven systems.

[59] Nicolas Perez (2012). Création d'un banc d'essais semi-virtuel aéraulique, ENS Cachan, 3 months
[60] Cong-Toan TRAN, Méthodes de mesure in situ des performances annuelles des pompes à chaleur air/air résidentielles, Thèse de l'École nationale supérieure des mines de Paris, 2009 – 2012

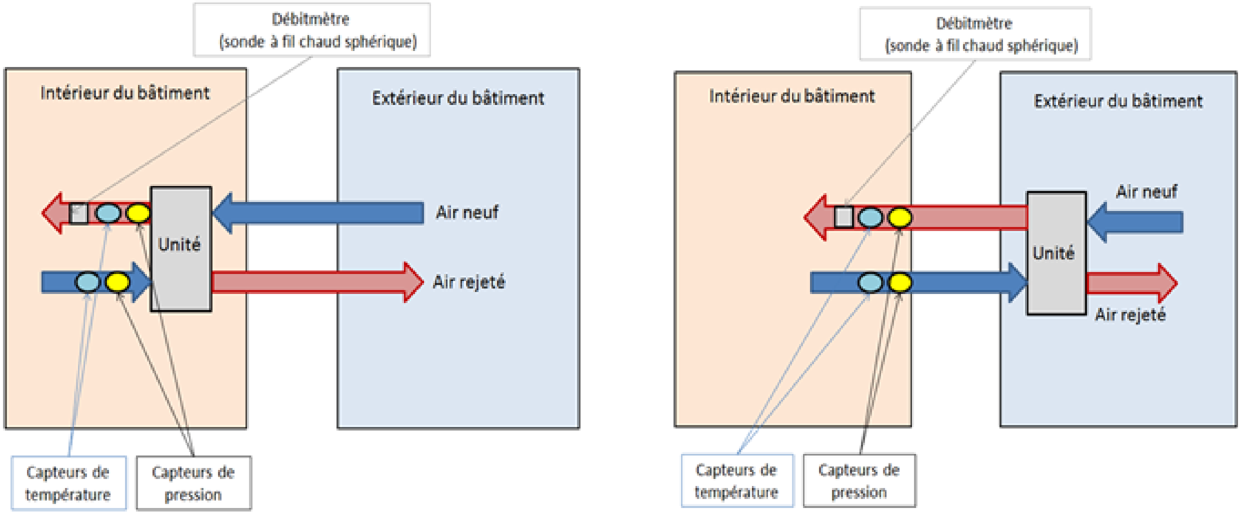


Figure 85 :Measurement of thermal power of an air/air heat pump (ducted version)[60]

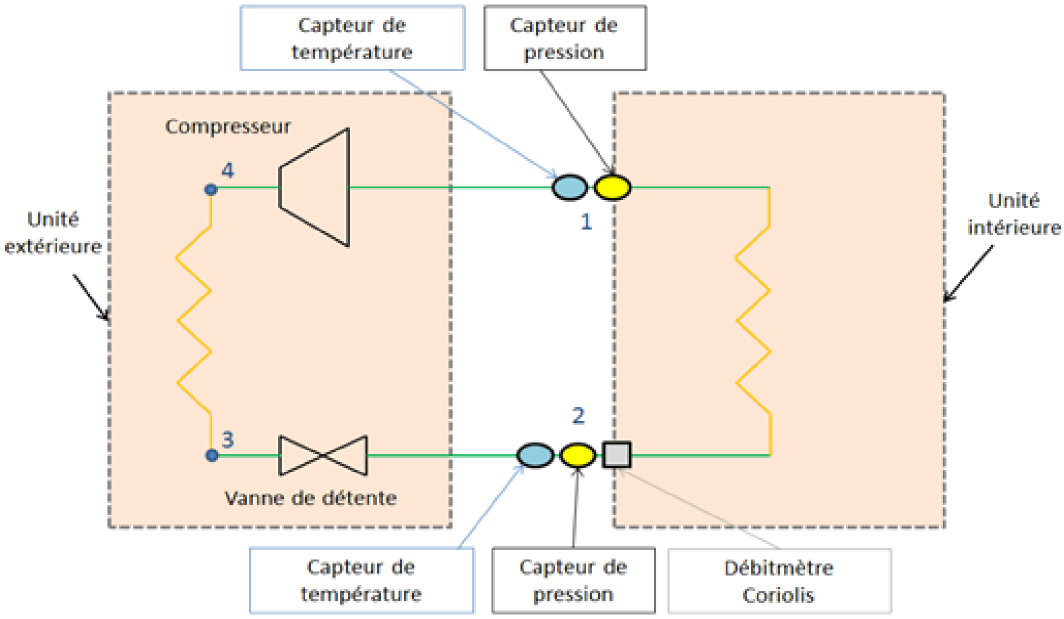


Figure 86 :Measurement of thermal power of an air/air heat pump[60]

While the direct measurement on the refrigerant side is probably the most accurate solution, there are nevertheless several points that have to be analysed in detail, especially the phase of the refrigerant which is not always 100% liquid or gas and affects thus the accuracy of calculations. The measurement of the refrigerant includes a mass flow meter that can be used in liquid or gaseous flows of the refrigerant. Pressure and temperature sensors complete the measurements.

A second variant of air interface can be mentioned if a sensor (temperature or humidity, eventually pressure) is part of the emulated controller and cannot be replaced by a programmable resistance. In this case, the complete sensor box can be placed in a small climatic chamber. This has been demonstrated in the Simtest-Elec project[61] in which terminal controllers of electric heating systems should be tested by emulation techniques. The particularity of these thermostats is the current passing the thermostat heats up the temperature sensor (self-heating). The sensor measurement for these products is thus corrected by the algorithms, making the classic emulation with a programmable resistance box impossible.

[61] Elaboration d'une méthode pour le test de régulateurs de systèmes de chauffage électrique avec correction de la sonde selon la procédure adoptée par le CEN TC247 (SIMTEST-Elec-II), client: EDF, 2003, 9 months

A new testing approach with air interface has thus been developed in this project as shown in *Figure* ***87*** and *Figure* ***88***.

An external air chamber with temperature control allows to prepare air following the setpoint from the room simulation. A small box is put into this first chamber with the thermostat fixed at the rear wall. Small fans on the bottom and rear wall of this box are dynamically controlled in order to guarantee the air velocity around the thermostat to be tested. The thermostat is thus operating as in a real room and self-heating is accounted for in a correct way.

A new project to further improve this climatic chamber has been initiated by EUBAC (reference) in order to include this to certification tests of room terminal controllers for HVAC systems.

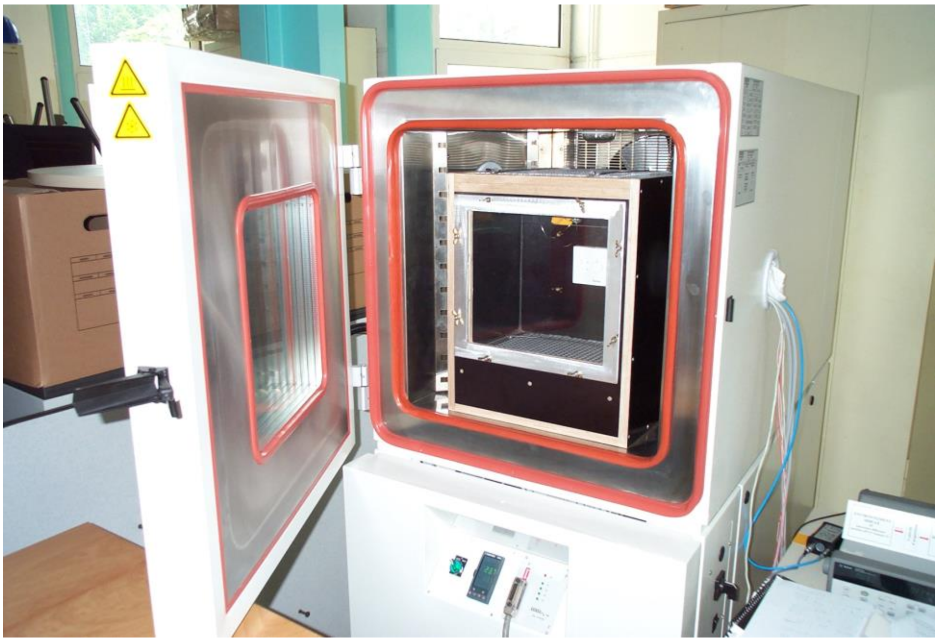


Figure 87: Air interface for controllers (external air chamber with temperature control)

Figure 88: Air interface for controllers (inside view with controller)

As for the first air interface, numerical simulation can be used in order to optimise the conception of this test bench component (CFD modelling).

4.5.4 ELECTRIC POWER INTERFACE

Electric power interfaces may be required in emulation tests for 2 reasons:

- Simulate the real behaviour of an electric power source (AC or DC)
- Simulate electric loads in a building or dwelling

The applications can be various. For example, a solar PV collector can be simulated, and real behaviour is reproduced by an electric source. The simulated PV panel can thus be connected to a real converter. Also, electric load profiles that have been generated via simulation can be imposed to a system via an electric sink. The product or controller to be tested by emulation can now be embedded to a fully virtual solar power generation and electric loads from equipment in a building. *Figure **89*** shows examples of electric sinks and sources.

Figure 89 : Examples of electric sink and source

4.5.5 MULTISITE EMULATION LABORATORY

A last interface is in fact a combination of interfaces. The best example is the case of a system that requires interfaces that are not available at one test site. Emulation being finally a link between digital and analogue signals (simulation and measurement and control), there is no difficulty in separating parts of the emulation layout in order to connect two or more emulation laboratories in one single test. The concept is the same as for a co-simulation or emulation.

If for example a laboratory is specialised on electrical interfaces, the emulation test can be combined with a laboratory specialised on water or air interfaces, the complete emulation test can include these both laboratories. There can be a master with the simulation at one of the both test sites and the other test site will be the slave. The master can also be only a computer on which the simulation is carried out and the two laboratories as slaves which are connected to it.

A feasibility study has already been done in 2014 between the laboratories of BRGM and CSTB for the test of a geothermal heat pump (*Figure **90***).

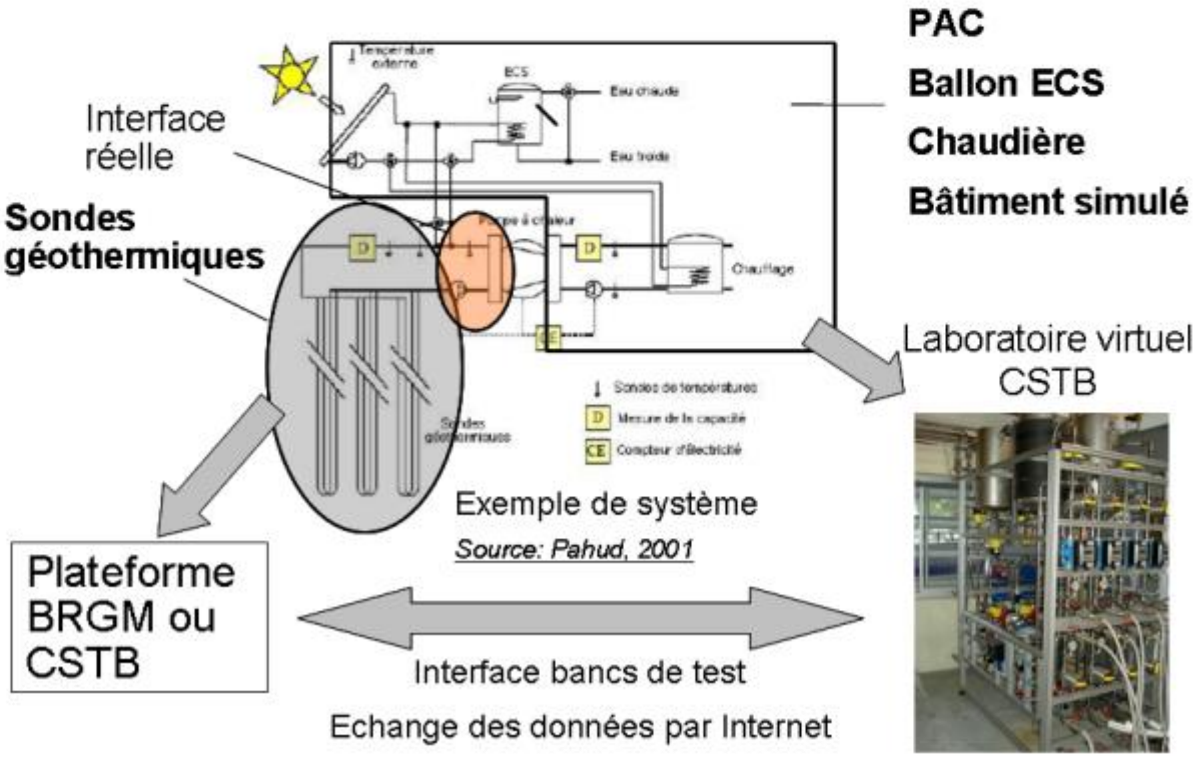


Figure 90 : Multisite emulation platform CSTB / BRGM[62]

[62] Développement d'une plateforme de test de pompes à chaleur géothermiques et Mission d'assistance pour le développement multisite de la plateforme avec le BRGM, client: Ademe, 2008, 24 months

5. OPTIMISATION AND PREDICTION METHODS FOR THE IMPROVEMENT OF THE PERFORMANCES OF ENERGY SYSTEMS

5.1 MULTI-OBJECTIVE OPTIMIZATION

The search for the "best" energy concept must not be restricted to the validation of a single regulatory energy criterion. Thus, it can be an advantage to adopt a transversal approach that combines energy, economic and environmental performances in order to identify the best configurations and include the procedure in a global approach. A multi-objective optimization problem is defined as follows with:

$$\text{Minimize } \{f_1(x), \ldots, f_n(x)\},\ x \in K$$

$$\text{s.t.} \quad g_j(x) \leq 0$$

$$h_k(x) = 0$$

where:

K the search space
P the performance space
$f_i : K \rightarrow P$ with i = 1…n the objective functions defined for the n different criteria,
g_j with j = 1…p the p different constraints of inequality
h_k with k = 1…q the q different constraints of equality

For this type of problem, there is no a priori global optimum, i.e. a single solution that is better than all the others for all criteria. To solve a multi-objective optimization problem, the management of the objective functions can be done in an aggregated or a differentiated way and the search space can be explored using a deterministic or a stochastic method.

In the case of the design of an energy concept, the optimization problem involves both continuous and discrete parameters (i.e. the presence of a network, the power of production systems, the position and thickness of the insulation of the building, etc.) with a non-convex and almost infinite search space. In addition, the objective functions are mainly non-linear since the used simulation tool operates as a black box for the solver of the optimization problem. Thus, the complexity of the problem requires the use of an approach appropriate to the search space and the objective functions.

The various data obtained from the simulations (and associated post-processing) must not be altered by a reduction to a single objective (e.g. economic), which necessarily implies improper use of compensations. Consequently, the objective functions need to be considered simultaneously and independently to find the Pareto front, which is composed of the alternatives that are not dominated by another alternative on the objectives set. Decision-making is carried out after the identification of the optima-Pareto to avoid an alteration.

Finally, a non-aggregated optimization procedure focusing on the search of the Pareto front that considers all the specificities of the analysed problem must be developed. Moreover, the procedure for the optima search should be both effective and efficient while reducing computational time.

5.2 OPTIMISATION OF BUILDING AND DISTRICT ENERGY SYSTEM DESIGN

The optimization of district energy performance is a relatively recent issue while that on the building level has started at least one decade earlier. Although there are several studies on the optimization of complex problems in the field of civil engineering, only a few used multi-objective methods and even less applied them on an urban scale.

Two state of the art studies on optimization applied to the building domain were carried out by Attia et al.[63], Evins[64] and Nguyen et al.[65]. Their work highlights the diversity of approaches used and also shows that the relative effectiveness of the methods depends on the search space and the type of objective functions.

Some work has however similar problems as the optimisation on a district level. For example, Armand Decker et al.[66] developed a methodology to optimize the design of wooden buildings. Another study where energy simulation and bi-objective optimization were combined was conducted by Salminen et al.[67] and concerned the study of a shopping centre. Otherwise, the design of low-energy houses[68] and the renovation of buildings[69] involved optimizing problems that included three different objectives.

These references present optimization procedures which are well adapted to the building scale, but their application to the district scale requires major improvements and adaptations. These problems are simpler to solve due to the limited size of the search spaces. Furthermore, combinatorial explosion is very significant at a higher level.

At the urban scale, Kämpf and Robinson[70] developed a mono-objective optimization procedure that was applied to a simple example. Other applications with multiple objectives such as the use of energy production systems in a district or the design of centralized systems associated with their distribution network were optimized by Jayan et al.[71] and Weber[72] respectively. A methodology to optimize sizing of the energy systems was developed[73], but with a static coupling between the simulator and the optimizer where simulation of the energy demand is performed in the first instance. This optimization of the production system capacities was also carried out at the territorial scale[74].

These studies highlighted the advantages of the multi-objective approach and the use of metaheuristic and particularly genetic algorithms, for solving complex problems. The references, that are summarized in Table 1, have been used as basis for development of a dedicated procedure. The adaptability of the methodology developed to solve the multi-objective optimization problem of the design of district energy concept with an extended parametric set

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[63] S. Attia, M. Hamdy, W. O'Brien, S. Carlucci, Assessing gaps and needs for integrating building performance optimization tools in net zero energy buildings design, Energy and Buildings 60 (2013) 110-124

[64] R. Evins, A review of computational optimisation methods applied to sustainable building design, Renewable and Sustainable Energy Reviews 22 (2013) 230-245

[65] A.-T. Nguyen, S. Reiter, P. Rigo, A review on simulation-based optimization methods applied to building performance analysis, Applied Energy 113 (2014) 1043-1058

[66] S. Armand Decker, Development of a multiobjective optimisation method for timber building: consideration of user comfort, environmental impact and structural safety (in French). PhD thesis, Université de Bordeaux (2015)

[67] M. Salminen, M. Palonen, K. Sirèn, Combined energy simulation and multi-criteria optimization of a LEED-certified building, First Building Simulation and Optimization Conference (2012) 372-377

[68] G. Verbeeck, H. Hens, Life cycle optimization of extremely low energy dwellings, Journal of Building Physics 31 (2007) 143-177

[69] F. Pernodet Chantrelle, H. Lahmidi, W. Keilholz, M. El Mankibi, P. Michel, Development of a multicriteria tool for optimizing the renovation of buildings, Applied Energy 88 (2011) 1386-1394

[70] J. Kämpf, D. Robinson, Optimisation of urban energy demand using an evolutionary algorithm, Eleventh International IBPSA Conference (2009) 668-673

[71] B., Jayan, H. Li, Y. Rezgui, J.-L. Hippolyte, S. Howell, An analytical optimization model for holistic multiobjective district energy management - A case study approach, International Journal of Modeling and Optimization 6 (2016) 156-165

[72] C. I. Weber, Multi-objective design and optimization of district energy systems including polygeneration energy conversion technologies. PhD thesis, Ecole Polytechnique Fédérale de Lausanne (2008)

[73] C. Wang, S. Kilkis, J. Tjernström, J. Nyblom, I. Martinac, Multi-objective optimization and parametric analysis of energy system designs for the Albano university campus in Stockholm, Procedia Engineering 180 (2017) 621-630

[74] M. S. Mahbub, M. Cozzini, P.A. Østergaard, F. Alberti, Combining multi-objective evolutionary algorithms and descriptive analytical modelling in energy scenario design, Applied Energy 164 (2016) 140-151

cannot be guaranteed, although the most appropriate methods can be adapted. These articles emphasize the fact that evolutionary algorithms are the most widely used, particularly the NSGA-II[75], whose main advantages are that it provides fast convergence and is highly adaptable.

Table 5 : Main characteristics of optimisation problems from the literature

Reference	Simulation platform	Optimization algorithm	Scale	Objectives (at the same time)
Decker[66]	EnergyPlus	PSO*	Building	1 & 7 (2)
Salminen[67]	IDA-ICE	NSGA-II	Building	3 & 5 (2)
Verbeeck[68]	TRNSYS	Unknown genetic algo.	Building	2 & 5 & 6 (3)
Pernodet[69]	TRNSYS	NSGA-II	Building	2 & 5 & 6 & 7 (3)
Kämpf[70]	CitySim	CMA-ES & HDE**	District	1 (1)
Jayan[71]	Simplified modeling	NSGA-II	District	5 & 6 (2)
Weber[72]	Dedicated modeling	Branch and bound and QMOO***	District	5 & 6 (2)
Wang[73]	IDA-ICE	NSGA-II	District	4 & 5 & 6 (3)
Mahbub[74]	EnergyPLAN	NSGA-II	Territory	5 & 6 (2)

(1: energy demand, 2: energy consumption, 3: energy savings, 4: exergy, 5: economic cost, 6: environmental impact, 7: comfort)
**   Particle swarm optimization*
*** Covariance Matrix Adaptation Evolution Strategy & Hybrid Differential Evolution[76]*
**** Queueing Multi-Objective Optimiser[77]*

Finally, Perez et al.[78] developed an optimisation methodology for the design phase of an urban development project and specifically introduces the energy parameter into this approach. A multi-objective optimization procedure was developed to assimilate the specificities inherent in the complex problem of the design of an appropriated district energy concept and to maintain the integrity of the three objectives selected: energy, economic and environmental performance. The procedure was developed based on an innovative optimization framework that is multi-level and uses the NSGA-II genetic algorithm. The diversification and intensification of the results obtained using NSGA-II are appropriate. Moreover, the reduction in computational time is highly advantageous and is even essential when performing the optimization for a district composed of more than a hundred thermal zones. Its integration into the planning process is perfectly suited to support decision-making.

[75] K. Deb, A. Pratap, S. Agarwal, T. Meyarivan, A fast and elitist multiobjective genetic algorithm: NSGA-II, IEEE Transaction on Evolutionary Computation (2002) 182-197
[76] J. Kämpf, D. Robinson, A hybrid CMA-ES and HDE optimisation algorithm with application to solar energy potential, Applied Soft Computing 9 (2009) 738-745
[77] G.B. Leyland, Multi-objective optimization applied to industrial energy problems, PhD thesis, Ecole Polytechnique Fédérale de Lausanne (2002)
[78] N. Perez, P. Riederer, Ch. Inard, Development of a multiobjective optimization procedure dedicated to the design of district energy concept, Energy & Buildings 178 (2018) 11–25

5.3 OPTIMISATION OF BUILDING AND DISTRICT ENERGY SYSTEM OPERATION

5.3.1 CLASSIC CONTROL MECANISMS AND RECENT DEVELOPMENTS

In modern buildings, HVAC systems as well as lighting/shading systems control the internal conditions such as temperature, humidity, pollutants or illuminance. The systems have to guarantee comfortable and healthy conditions for the occupants in the rooms and, at the same time, reduce energy consumption without creating uncomfortable conditions for the occupants.

The control of the systems is generally represented by a control loop similar to that shown in *Figure **91***.

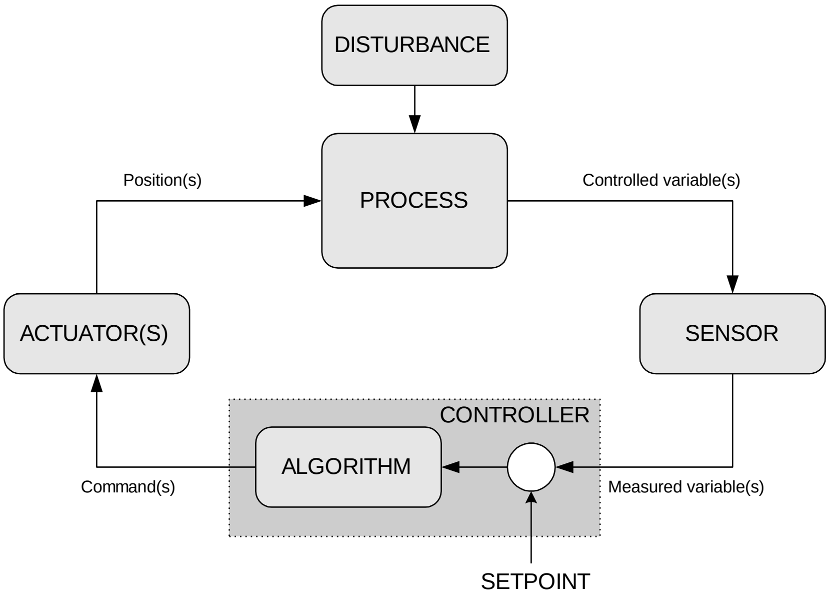

Figure 91 : General layout of feedback control loop

The control loop includes a controller, an actuator, the process to be controlled, disturbances of the process and a sensor measuring the controlled variable(s).

The variables measured by the sensor are compared with a set point value. An algorithm outputs a command signal that is transferred via the actuator to the process, disturbed by conditions outside the process. In addition to open loop commands, different closed-loop algorithms can be used[79,80]:

- On/Off controllers
- P controllers (proportional)
- PI controllers (proportional-integral)
- PID controllers (proportional-integral-differential)
- Fuzzy controllers

The set points of these low-level controllers are either constant or programmed as for night setback issues for example. In more innovative controllers that are mainly based on model predictive control, setpoints will be optimised in order to optimise cost functions that depend on one or several KPI's.

In the case of building related systems, the process can be observed on different levels of the HVAC system (cf. *Figure 92*):

- Control on the room level (e.g. control of the terminal unit of a Variable Air Volume (VAV) system): The conditions (e.g. temperature) in the rooms or groups of rooms (building zones) are controlled. The process can either be thermal, flow or lighting phenomena in

[79] ASHRAE Handbook of Fundamentals, SI Edition, American Society of Heating, Refrigerating and Air Conditioning Engineers, 1997
[80] KNABE G., Gebäudeautomation, Verlag für Bauwesen, Berlin/München, 1992

the rooms. The sensor is placed somewhere in the room and measures conditions as for example temperature or humidity. The actuator is for example a valve, interacting on the hot water flow rate through a radiator.

- Control central unit (e.g. control of the central Air-Handling-Unit of a VAV system): The central part of a HVAC system, for example a VAV system, provides the air needed for the conditioning of the zones, distributed to the terminal units of the building zones. Different controllers act on fans, valves, pumps or dampers, installed in the AHU.
- Supervisory control (supervision of the two previous groups): Depending on superior criteria (e.g. total building energy consumption or time dependent tariffs), this controller has the possibility of interaction on control signals from the two first levels.

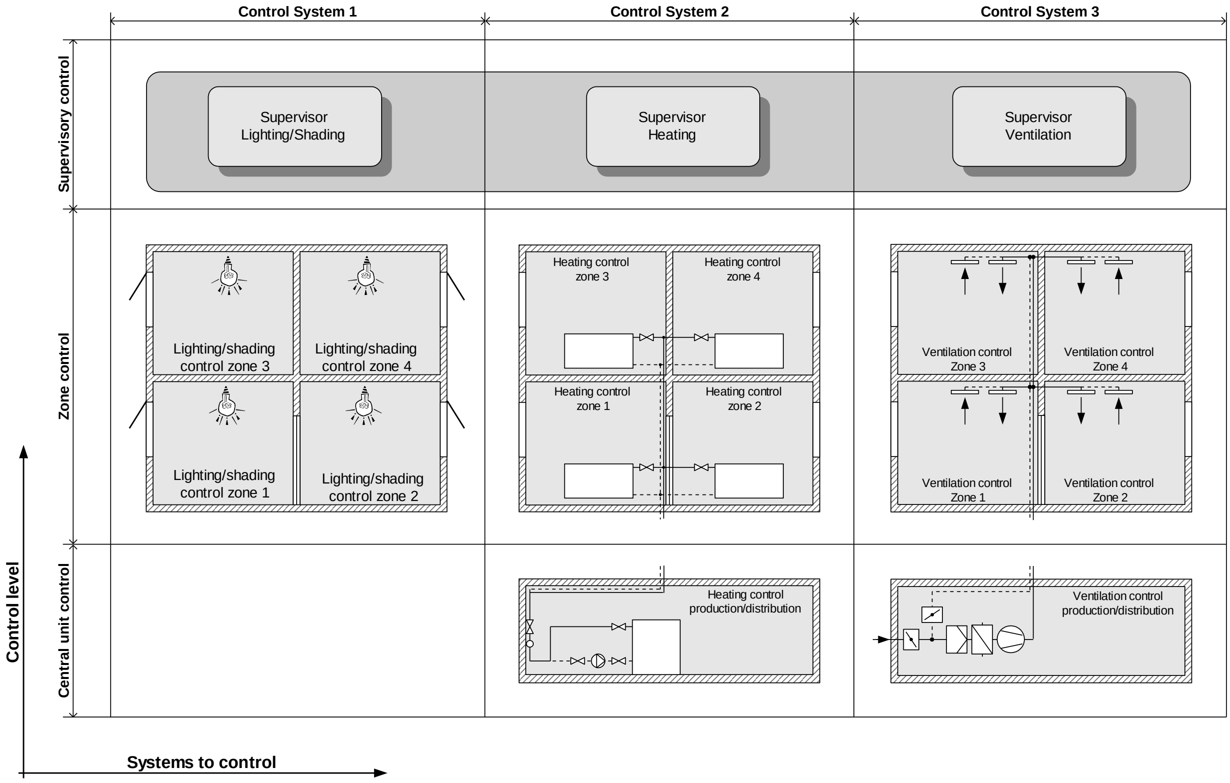

Figure 92 : Example for different levels of building control

The trend in the development of HVAC controls changes from optimisation of individual control to the aspects of total building control (e.g. Building Energy Management Systems BEMS) and even at district level.

This trend tends to combine the integrated control of independent systems controlling different phenomena. In a European research project INTECOM[81], integrated HVAC-shading-lighting control is developed. Supplementary control interactions are so added between the different systems. To reach this goal, more advanced control as described in the next paragraph is needed.

[81] HUSAUNNDEE A., Integrated control of HVAC system, lighting and blind in a building zone, Clima2000 conference, Napoli, Italy, 15-18 September 2001

5.3.2 ADVANCED CONTROL AND OPTIMISATION OF BUILDING AND DISTRICT ENERGY SYSTEMS

New, dynamic control methods have appeared in the literature in the 80s', but their application had been limited due to the calculation power of microcontrollers and computers. In 1988, Hartman[82] highlights the need to consider building inertia for the optimal control of occupant comfort. The author defines two main objectives for this need: anticipate meteorological conditions and/or internal gains to minimise energy consumption and adapt continuously the operation of systems to variable conditions to maximise thermal comfort. The author also states that poor performances are not due to a wrong conception but to a control which assumed steady state conditions in the building.

Several researchers have later developed dynamic control applications based on predictive methods[83,84]. These developments target the minimisation of a cost function that considers occupant comfort and energy consumption over a certain time horizon. To do so, future weather conditions and building response to internal and external perturbations have to be predicted.

This work is based on a general development of Model Predictive Control (MPC) since the 1980s. Initially used for process control in chemical plant sand oil refineries, is has then be used also on the energy field as in the papers cited above.

In general, model predictive control is based on the transient numerical modelling of system or process behaviour in order to predict the system behaviour over a certain time (prediction) horizon exposed to a series of control signals. The necessary models for prediction can either be based on physical (linear or non-linear) modelling of system behaviour or on black box models (for example polynomial models, neural network models etc.). In most cases, the necessary parameters of these models are fitted or identified (or trained) based on available measurement of variables in the process. To do so, the available measurement data is generally split into two periods in order to ensure the validity of the model by training on the first period and then validating on the second period (determination of model uncertainty).

Once the model built (this can be only once in the beginning or on a regular base, for example daily, weekly or monthly), optimisation methods allow then to find the best fit of control signals over the prediction time horizon. This "optimal" control scenario is applied over a certain control horizon until the next prediction/optimisation horizon is started (*Figure **93***).

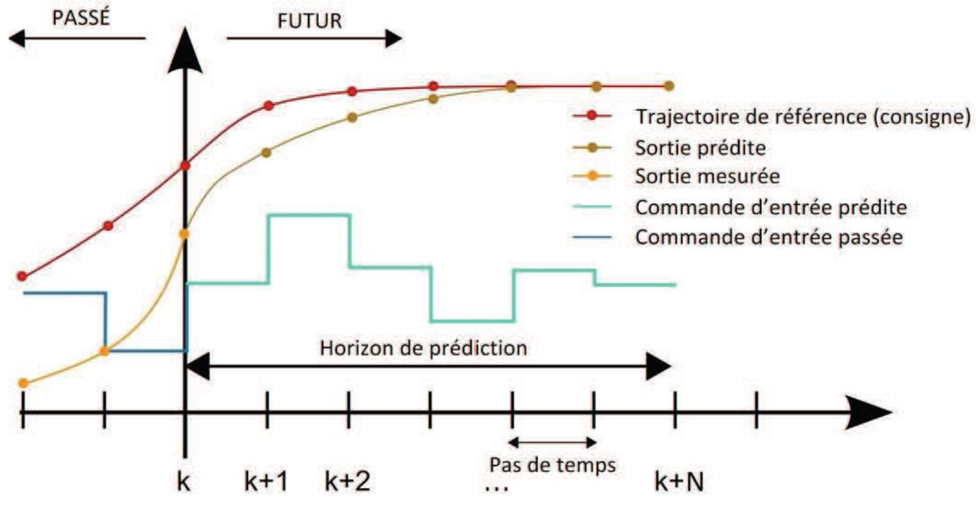

Figure 93 : Principle of predictive control (source: Salque[85])

[82] T.B. Hartman, « Dynamic control : Fundamentals and considerations », ASHRAE Transactions 97, vol I, pp. 599-609, 1988.

[83] P. Parent, « Optimal control theory applied to dwelling heating system », IRCOSE, Agence française pour la maitrise de l'énergie, 1987.

[84] J.C. Visier, V. Paillassa, A. Marti, M.H. Foucard, « La commande optimale : un outil d'aide à la définition de stratégies de gestion », Journées RCT 93 (Régulation – Commande – Télégestion), Sophia Antipolis, pp. 97-107, 1993.

[85] Tristan Salque, Amélioration des performances de PAC géothermiques par couplage de mesures in-situ et de méthodes numériques inverses, CSTB / Mines Paristech, October 2013 (co-director)

The steps in the operation are thus:

- Measurement of key system variables (temperatures, flow rates, powers etc.) at step k,
- Calculation of predictions of environment variables until the end of the time horizon k+N,
- Definition of the “optimal” trajectory of the set point (e.g. room temperature set point),
- Calculation of the optimal control series for the horizon minimising the cost function,
- The optimal control series is applied for the following j time steps (with j from 1 to N),
- The procedure is repeated after these j steps (floating prediction horizon).

While many varieties may exist in the modelling part of prediction of boundary conditions and prediction models for control itself as well as the type of optimisation method, almost any MPC method follows the above steps.

The advantages of such predictive controls are as follow:

- Constraints of all controlled variables can be ensured (multi-variable and multi-criteria optimisation),
- Excessive variations of control signals can be avoided, the control output is thus smoother,
- In case of measurable and predictable perturbances the system automatically adapts,
- If operating properly, the prediction and optimisation allows to obtain “better” operation resulting for example in lower operation costs, better occupant comfort.

The advantages are thus various. However, even to date, the application is still far behind the potential that these methods can bring.

The reasons may be one of the following:

- Low confidence in such “theoretical” and global methods (the user must fully trust the MPC),
- Complexity of necessary hard-and software,
- In many cases, the high complexity of building and configuring the necessary controller (adapt to real system architecture and specificities).

A first change is visible with “intelligent” room thermostats. Based on cheap and wireless (also called “smart”) measurement solutions (in general with the development of IOT solutions), to date the cost of necessary measurement equipment for MPC can almost be neglected. While wired sensors would have been necessary which are cost expensive and not feasible in many cases.

This trend of multiplying IoT and low-cost measurement solutions since the last decade will definitively allow MPC to take a much higher market share.

Additionally, it will allow integrated control solutions (lighting, heating, ventilation etc.) to optimise an energy system in a holistic approach.

CHAPTER III

SELECTION OF APPROPRIATE SIMULATION MODELS / TOOLS

The simulation of buildings and/or systems is a huge field of research and development. After a first part with some general comments that illustrate the large field of applications and objectives, the example of a methodology is shown in the second part for the development of a thermal zone model for the use case of controller tests. Different types of models are briefly described and a table at the end shows the advantages and disadvantages of model choices. However, even today, with the increasing number of simulation fields and objectives, it is difficult to choose at each simulation project, the best fit of the model with project objectives. In many cases, models which are already "in store" are used because they are well managed and directly available.

In the third part, a simple methodology for the selection of the appropriate level of detail and type of model is given.

1. VARIETY OF SIMULATION SPECIFICITIES RELATED TO BUILDINGS, DISTRICTS AND ENERGY SYSTEMS

1.1 SIMULATION OBJECTIVES

Numerical simulation in the scope of this report is mainly applied for two key issues which are design and operation. Both are discussed hereunder:

- Design issues (including renovation cases):

  Design issues can have different aims. Some examples are:
  - Building passive optimisation (envelope and masks),
  - Better building energy system conception,
  - Optimisation of ventilation systems and scenarios,
  - Building visual comfort optimisation (not dealt with in this report),
  - Outdoor comfort optimisation (micro-climate analysis),
- Operation issues (a list of examples):
  - Development (simulation) and test (emulation) of innovative control algorithms for building and district energy systems,
  - Development and test of ventilation control (e.g. hybrid ventilation),
  - Development of innovative control algorithms for building visual comfort,

There are many other simulation topics, but it is obvious that type and level of detail of the appropriated models for these different issues and problems will differ from case to case.

1.2 PERFORMANCE INDICATORS

Also, depending on the necessary key performance indicators, the type of required model may change. For example, for thermal comfort indicators, other model outputs are necessary as for a simple analysis of energy consumption.

Key performance indicators have already been discussed previously, but some key indicators are presented again to illustrate this point:

- Energy demand (the building envelope and air model is sufficient),
- Energy consumption (systems have to be added and depending on the type of system and specificities, the type of system models may vary),
- Auxiliaries consumption (as stated in Chapter I, auxiliaries are often neglected, but represent in many cases very high energy consumptions),
- Thermal Comfort (temperatures, humidity, comfort criteria as PMV/PPD etc.): thermal comfort is often reduced to temperatures. This is mainly a “plan B” solution since the calculation of real comfort requires air velocities and humidity, which is often not considered in the models),
- Visual comfort: This requires again, depending on the complexity of building and bling control different models,

All these factors show that to find for each problem, modelling object and simulation objective, the type of models required is in theory a very difficult question. And in many cases, the choice is made by user tool knowledge and available time for modelling. While research projects allow to spend the necessary time for decision and modelling (if necessary), in practice, modelling is carried out without balancing all these question of fitness for purpose of the used models.

1.3 BUILDING GEOMETRIES AND CONFIGURATIONS

Besides all the previous constraints, the big variety of building and system architectures and complexity add a second point of difficulty.

The variety of system architecture have already been discussed in Chapter I. On the other hand, building projects in case of new buildings or renovated ones, bring additional complexity. While in many cases the building type can be reduced to a wall structure with added isolation, modern building construction but also renovations can bring innovative concepts that are still today difficult to model, at least with the standard tools that are used in most cases. And even if they are useable for the phenomena to be modelled, modelling choices and parameters, that are often based on the experience of the modeller, can have an impact on the quality of results.

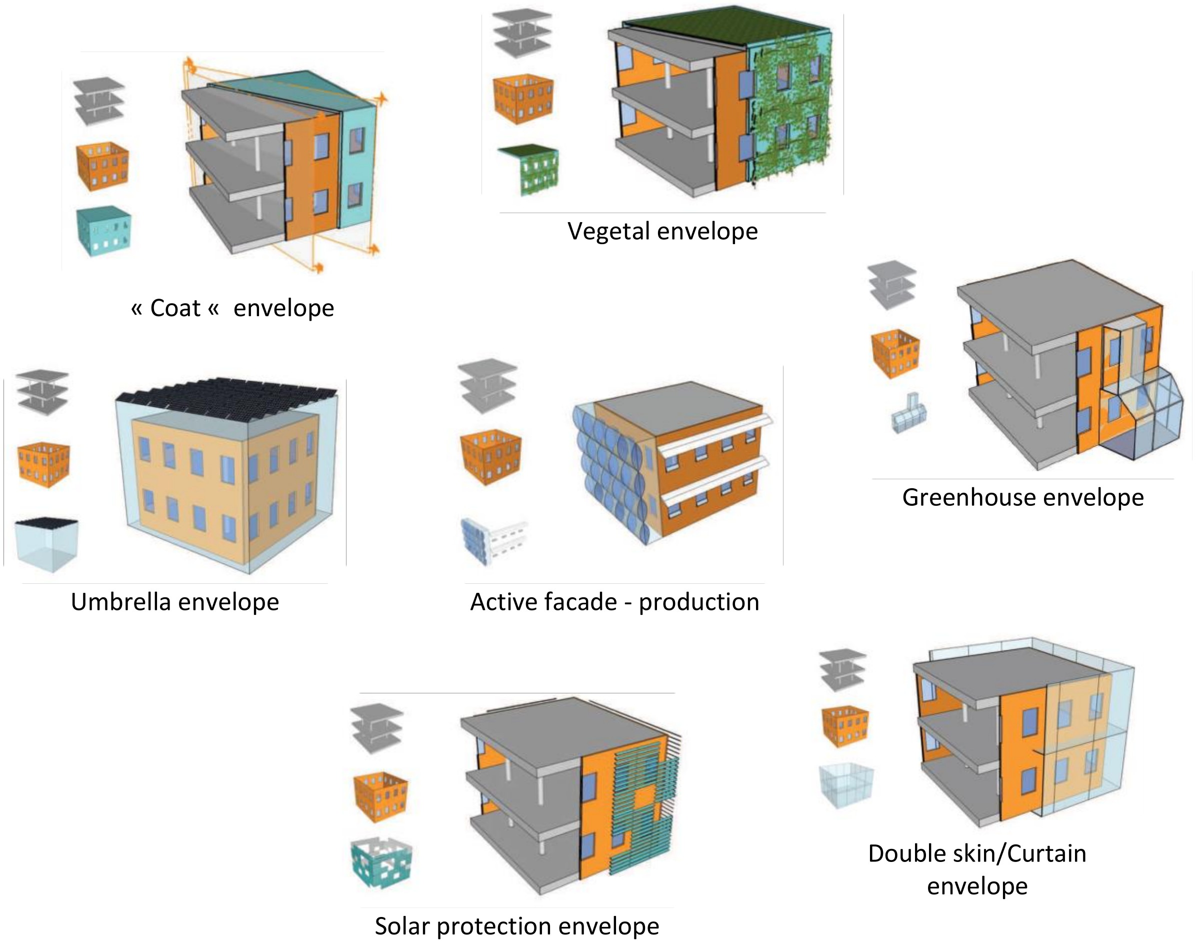

Figure 94 : Different types of innovative façade envelope types (source: unknown)

*Figure **94*** shows some examples of non-typical envelopes. Each of them brings its specific difficulties in modelling them, especially if the simulation objective switches from design to control issues.

These difficulties are related to ventilation (mainly natural), radiation (transmission and reflection) and humidity (condensation and evaporation) phenomena.

1.4 SYSTEM TYPES AND SYSTEM COMPONENTS

1.4.1 SYSTEM TYPES AND SYSTEM COMPONENTS

As already shown in Chapter I about system topologies, the variety of components and systems is large. It is thus very difficult to define appropriate levels of detail on such a large topic which can cover air-or water-based systems or electrical systems and all this with a great number of variants.

The main question in system modelling is probably the level of detail to choose for the model. This can be as a global, simplified model or, the other extreme, the combination of all physical components as a macro-model. Then, again, choices between steady-state and transient models as well as spatial discretisation aspects have to be carried out.

However, what can be mentioned besides these aspects, is that the appropriate use of the model includes at the same time a coherent choice between simulation time steps and the use of transient models. It does not make sense to use very detailed, transient models if the time step does not allow to catch the time constants of the system.

1.4.2 ILLUSTRATION WITH THE EXAMPLE OF A GROUND SOURCE HEAT PUMP

An example of reasoning about these choices is given hereunder for the case of a ground source heat pump as illustrated in *Figure **95***.

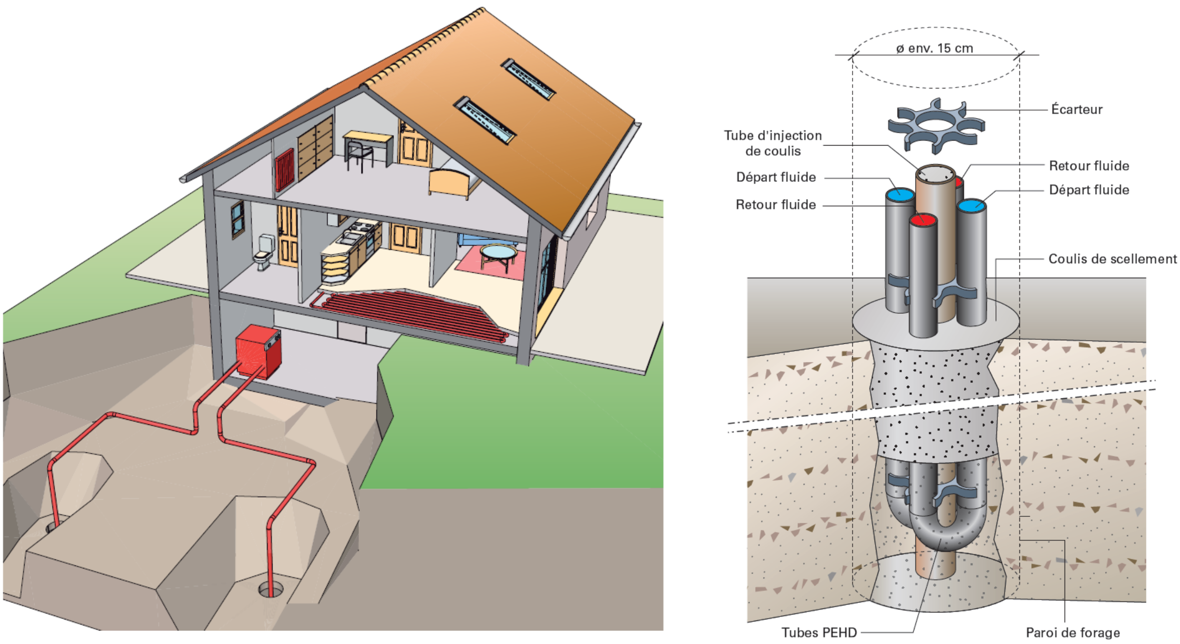

Figure 95 : Building with ground source heat pump (left) and borehole heat exchanger (right)

To build an « accurate » model, without having defined the details of the system (e.g. control laws as on/off or modulating heat pump) and without knowing the objectives of the study, is not possible. For example, most geothermal heat pumps are oparating with on/off control. The length of the cycles of such a heat pump depends strongly on the sizing of the heat pump related to that of the boreholes. Generally it should not be too short to guarantee a sufficient life time of the compressor of the heat pump. An anti short cycle mecanism exists in all heat pump controllers with about 3-5 minutes as default value. Field test have shown that in some cases this short cycle length can be achieved since the heat pump power is too big compared to the length of the borehole and its capacity to pump heat from the ground.

A complete model of a ground source heat pump energy system can be divided into the following parts :

- Building model (we assume here the assembly of models including emission and distribution) : The building model is discussed in the other sections and not detailed here. However it must be mentioned that its level of detail has to be in accordance with the phenomena represented in the two other system parts. Since the system contains a heat pump, the key information, besides the correct modelling of heating or cooling demand, is the correct modelling of heating or cooling supply temperatures (constant, heating law, etc.) which has a huge impact on energy efficiency and consumption.

- Water-water heat pump model : The heat pump model is typically a polynomial model based on operational data from catalogue or measurement. Detailed models with component based description are not appropriated, in most cases, since the availability of parameters, modelling efforts and simulation time does not allow for this solution.

- Borehole heat exchanger model : This is the core model of the complete system model since is represents the source temperature for the heat pump. An error in the difference between cold source (borehole return temperature) and heat sink (building water distribution at supply) will lead to wrong performances and this potential errors in the conclusions of the simulation results analysis.

  The borehole heat exchanger model again can be sub-divided into :

  - Ground model around the borehole
  - Borehole filling
  - Borehole pipes

  It has to be mentioned that, very often, the borehole filling and pipes are represented in a simplified way. This is done in most cases via the « borehole resistance » which assumes a thermal resistance between the fluid and the border of the drilling. Partenay[86] summarises these different approaches in a good overview.

  Besides models based on analytical solutions of heat transfer in the ground, lumped, two-dimensional and three-dimensional models are currently used for the modelling of the borehole and the activated ground around the drilling. *Figure **96*** illustrates these 3 types of numerical modelling approaches.

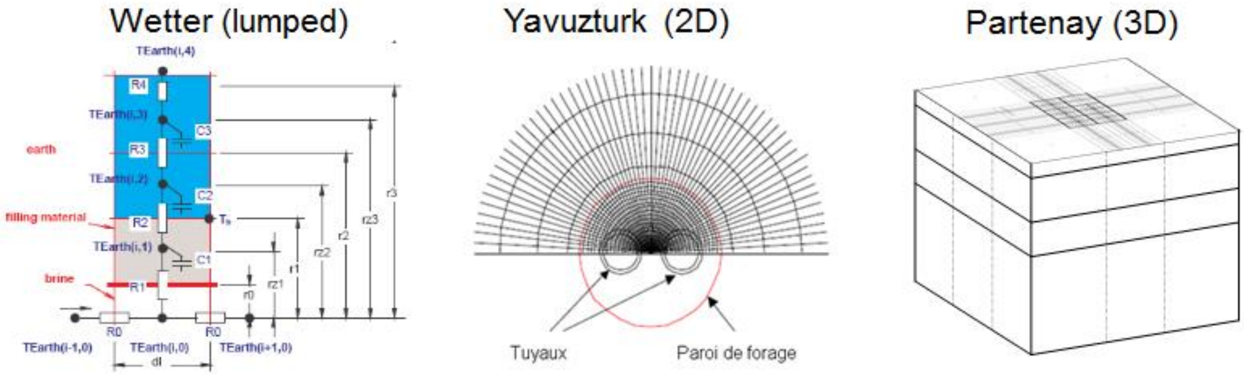

Figure 96 : Borehole heat exchanger modelling approaches (lumped[87], 2D[88] and 3D)

The error of the resulting model is thus reoresented by three sources : ground modelling, drilling thermal model and pipe model.

*Figure **97*** shows the example of the validation of a 2D rectangular mesh model by comparison with the analytical solution as reference. It can be clearly seen that the choice of a finer mesh (bottom) guarantees a better fit with the reference as the larger mesh (top of figure).

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[86] Vincent Partenay, Thèse de doctorat, "Développement d'une méthodologie d'évaluation des performances de systèmes de pompes à chaleurs", CSTB / Ecole doctorale de l'Université de Savoie, October 2010

[87] Wetter M, Huber A, TRNSYS Type 451; Vertical Borehole Heat Exchanger EWS Model, Version 3.1 –Model description and implementing into TRNSYS, Transsolar GmbH, Stuttgart,Germany, 1997

[88] Yavuzturk, C : Modeling of vertical ground loop heat exchangers for ground source heat pump systems. Thèse de doctorat, Oklahoma State University, 1999

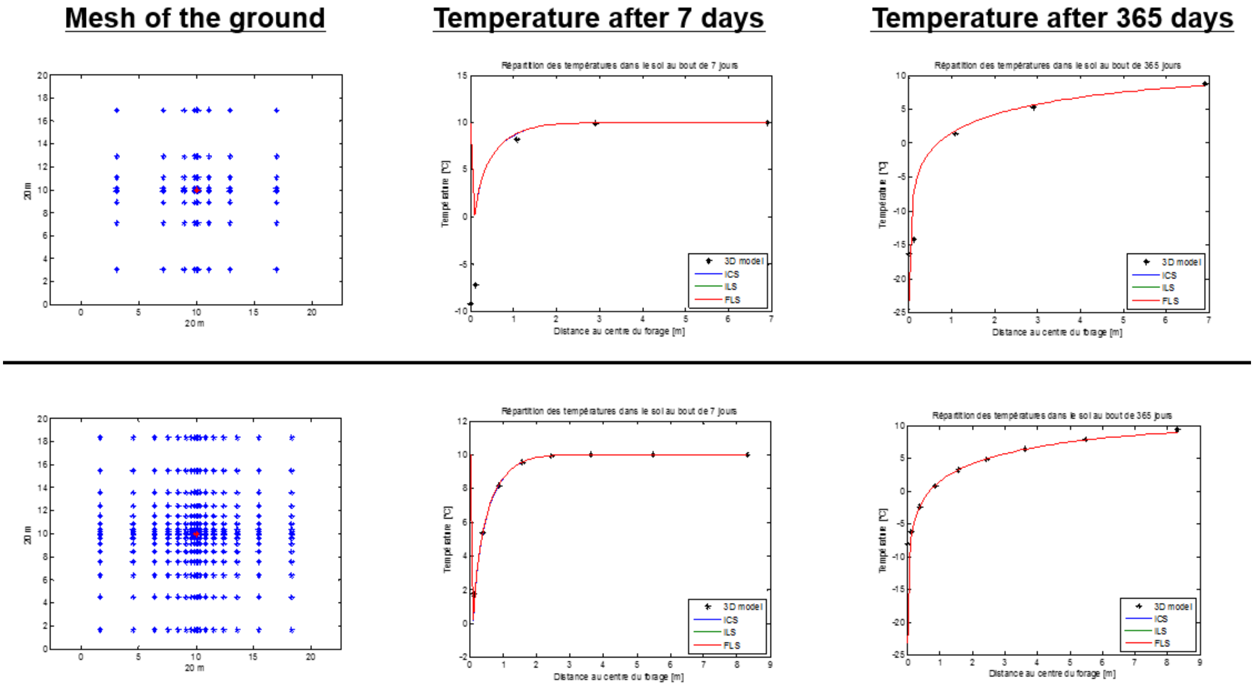

Figure 97 : Borehole heat exchanger modelling of surrounding ground (2D model)

When the drilling and pipe model is analysed, it depends on how this part is modelled. While the lumped model (and many others) are based on the thermal borehole resistance (thus a steady state model that do not consider transients of the drilling radius), the 2D and 3D models shown in *Figure* ***96*** sub-discretisize the drilling radius and are able to better characterise transient effects at small time horizonts (short cycles etc.).

An example of a detailed representation of the borehole drilling including piping is the the model developed by Partenay[86]. It includes a meshed borehole drilling with a nodal pipe model dividing the pipes into several subvolumes. Again, the pipe model can be modelled in different ways, from a steady state nodal model, a transient nodal model up to a transient plug flow model (which gives best results).

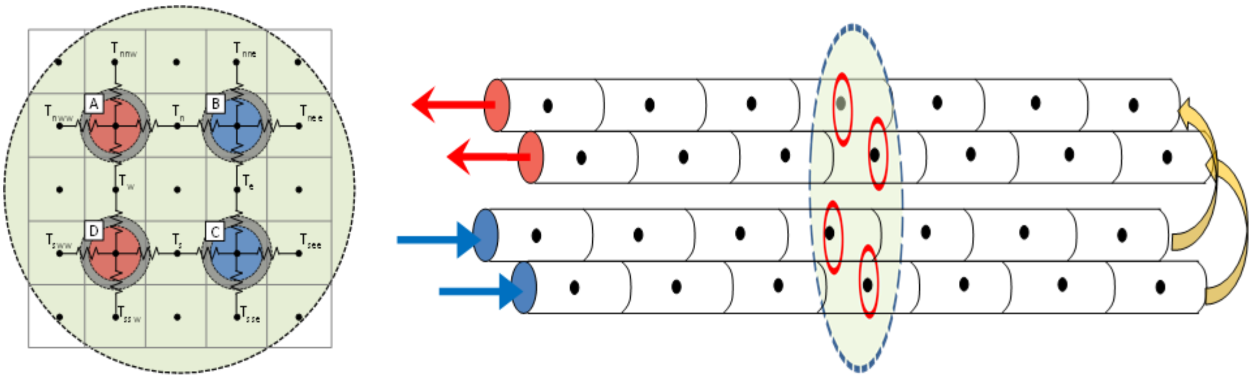

Figure 98 : Borehole heat exchanger modelling of central (drilling) part

The impact of the choice of the pipe model is shown in the example of a pipe with a step in the inlet temperature, in *Figure* ***99***. Three model types are compared with the result that, if the time step is above 120 seconds, all three models would give the same result. In most cases the flow rate is always on its nominal value (on/off control of heat pump). However, for modulating heat pumps of multi-stage compressors, the flow rate can be modulated. In this case, the travel time of the fluid passing the geothermal heat exchanger can be 3-4 times higher. The results will thus be affected by the fluid delay up to almost half an hour. If the time step, for example for control issues is below this value, the modeller has to be careful.

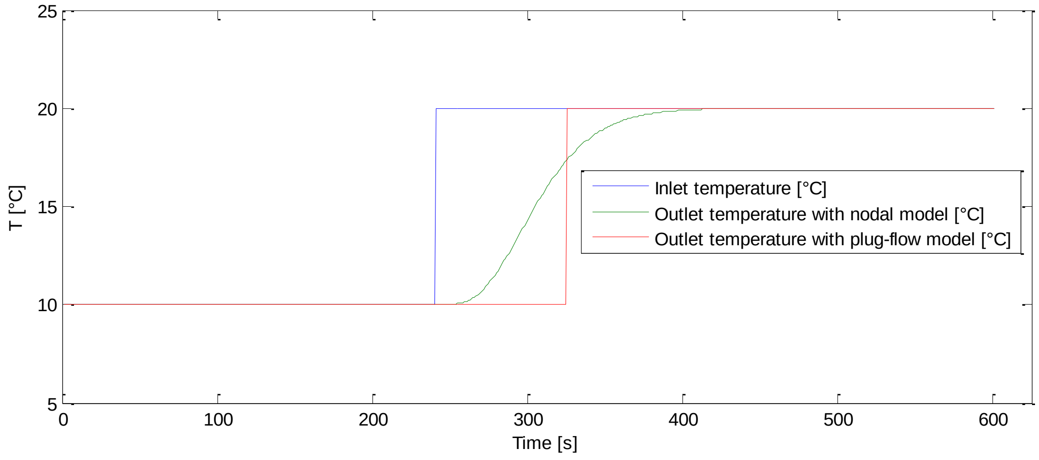

Figure 99 : Calculation of outlet temperature of a tube using nodal transient and plug-flow models

Finally, with all these sub-levels integrated in one geothermal borehole model, Partenay[86] has shown a significant impact of the modelling approach on the quality of results in the simulation. The comparison of a cyclic injection of heat (constant value) into the ground, between measurement and different levels of detail of the model (steady state, transient), as shown in *Figure **100***, has shown differences in temperature distribution, but also in the energy calculated by the models.

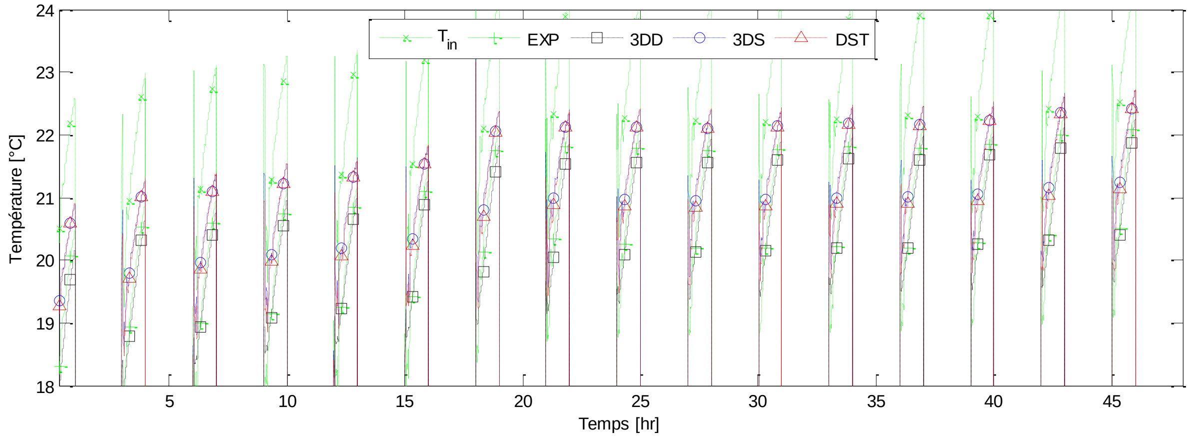

Figure 100 : Cyclic injection of heat into a borehole heat exchanger (comparison between measurement and different modelling approaches)

The difference observed in this comparison rises up to 37% for the case of a steady state model (*Table **6***).

Table 6 : Differences of energy storage in a borehole compared to measurement

(nomenclature: 3DD: 3D dynamic, 3DS: 3D steady state and DST, TRNSYS borehole model)

	Measurement	**3DD**	**3DS**	**DST**
Energy injected during 48h [kWh]	23.3	24.1	14.6	15.9
Relative error [%]	-	-3.4	37.3	31.9

Partenay also gives a very interesting example for the case of the simulation of a thermal response test, in order to compare different modelling approaches. While the complete test of 48 hours (*Figure **101*** on the left hand) seems to indicate that all 3 types of modelling match very well with the measurement data, a zoom on the first hours of the test indicates differences in the results. Due to the fact that thermal inertia is not represented in the steady state drilling models, parts of the energy « stored » in the ground are not considered by the model. The transient model however fits very well with measurement (right hand of figure with the difference between each simulation and the experimental data). This means that the smaller the cycles of the heat pump are, the better the simulation model has to reproduce time constants in the global system. On the other hand, if the heat pump is modulating, the necessary model that fits with results can be much more simplified.

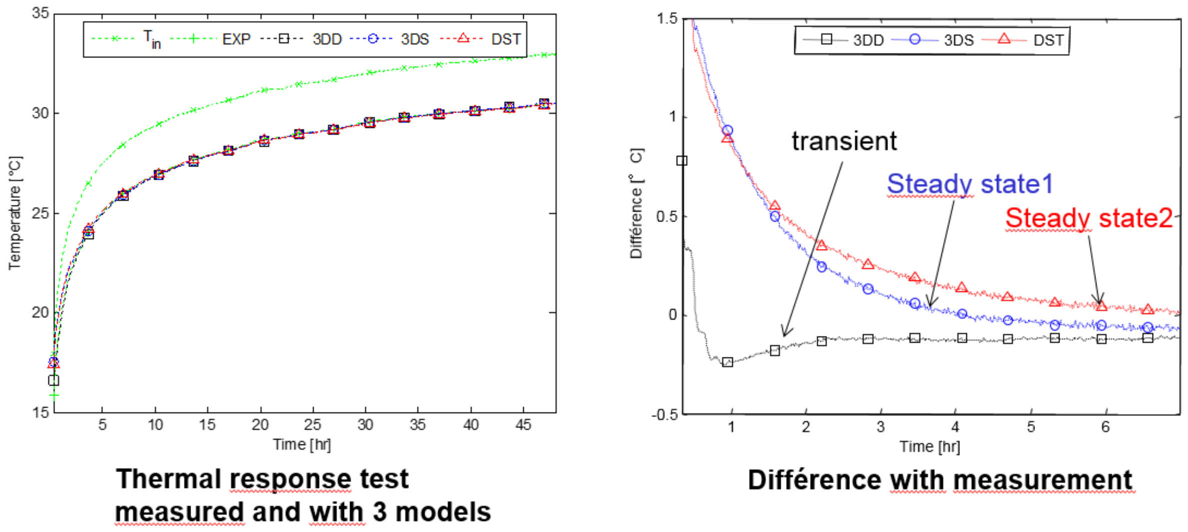

Figure 101 : Measurement and simulation of a thermal response test

As shown above, it is very difficult to provide a generic method on how to define the appropriate level of detail and characteristics of a model of a ground source heat pump system. In many cases, this must be analysed case by case and regarding the simulation objectives. The appropriate choices require thus a certain level of expertise of the modeller.

1.4.3 CONCLUSION ON SYSTEMS

As shown in this paragraph, many modelling choices are possible for a “simple” system to be simulated. While the choices are rather simple (or better “less dangerous”) if all parts of the system are modulating in order to achieve a smooth control of components (making the transients less important), the use of other control modes, especially on/off control or cycles due to binary decisions (night set back, modulation at low loads that tends to on/off etc.), can lead to significant errors as has been shown in *Table **6***.

It has to be mentioned that the example that has been presented is only one of many possible system combinations. Each other system might have other particular specificities that have to be checked in the modelling procedure.

In general it can be stated for systems (but also for any other part such as the building) that if thermal inertia or quick changes are important, the modeller has to be very careful in the selection of the appropriate models and modelling choices. This is particilarly true for controller studies (generally with small time steps), but can mostly be neglected in design simulations with larger time steps.

2. EXAMPLE OF MODEL CHOICE AND DEVELOPMENT OF ROOM AND BUILDING MODELLING FOR THE USE CASE OF CONTROLLER TESTS

2.1 MAIN CATEGORIES OF ROOM AND BUILDING MODELS

This section is mainly oriented to the modelling of room internal air for two reasons: the phenomena are very complex, and the variety of available models and modelling approaches is vast. Conduction in walls and radiation are assumed to present a much higher accuracy and are thus only briefly described, but a similar approach for analysing the adequacy between the simulation objective and the appropriate modelling method can be carried out. This section details thus a methodology related to the zone air convection as an example.

Room models exist with different levels of complexity: from simple “well mixed” models with one air node representing the whole (mixed) air volume of the room, to complex computational fluid dynamic (CFD) models solving the equations of conservation of mass, momentum and energy.

The models can be divided into five main groups:

- Well-mixed models (model of convection)
- CFD models (model of convection)
- Zonal models (model of convection)
- Lumped parameter models (model of room including envelope)
- Model using identification (convection model or room model)

The simple well-mixed models on the one hand are commonly used to study the energy consumption in buildings (TRNSYS[89], Energy Plus[90], Clarke[91]).

CFD models, on the other hand, such as Phoenics[92] or Fluent[93], are used for comfort studies and the prediction of airflow in rooms as they provide detailed information about the conditions in the room. Since CFD calculations are very time consuming, they are mostly used for steady state problems, even nowadays.

Zonal models represent an intermediate type of model, between well-mixed models and CFD models. They divide the room air into a reduced number of air sub-volumes. Although they have mainly been developed for the study of comfort and thus for steady state cases, they have also been used for the simulation of transient cases (During[94], Musy[95]).

For control purposes, mostly lumped parameter models are used (Laret[96], Haves[97]). Only in some rare cases, zonal models or, very rarely, CFD models with several simplifications have been used (Peng[98]). But these cases are limited to very specific cases. They are not generic and can hardly be reused for other zones or emitters.

All of the before mentioned air models have to be coupled with a model of the room envelopes (conduction) and that of the thermal radiation inside room (and the ingoing one).

The following types of envelope models are typically used:

- Nodal wall models,

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[89] TRNSYS, A transient Simulation Program. Solar Energy laboratory of the University of Wisconsin; Madison, USA, 1996

[90] https://energyplus.net

[91] CLARKE J.A., Energy simulation in building design, Adam Hilger Ltd, Bristol (UK), 1985

[92] PHOENICS, Reference manuals, CHAM Company, UK 1991

[93] FLUENT User’s Guide, Version 5.3 (1998), Fluent Inc., Lebanon – NH, USA

[94] DURING H., Consommations énergétiques et confort thermique des locaux chauffés: approche par les modèles zonaux, Thèse de Doctorat, INSA Lyon, 1994

[95] MUSY, Génération automatique de modèles zonaux pour l’étude du comportement thermo-aéraulique des bâtiments, Thèse de Doctorat, Université La Rochelle, 1999

[96] LARET, Contribution au développement de modèles mathématiques du comportement thermique transitoire de structures d’habitation, Thèse de Doctorat, Université de Liège, 1980

[97] HAVES Ph., Norford L.K., DeSimone M., A standard simulation test bed for the evaluation of control algorithms and strategies, ASHRAE Transactions, 1998, Vol. 104, Part 1

[98] PENG, X., Modelling of indoor thermal conditions for comfort control in buildings, PhD thesis, Delft, University of Technology, 1996

- Lumped parameter wall models (identical to the most simplified nodal wall model),
- Finite difference models,
- Transfer function models.

Most commercialised simulation tools are based on the two latter modelling approaches. Whatever approach used, since the phenomena are well known and rather simple (1 to 3-dimensional conduction), the difficulty is rather to select the appropriate choice of the model than the complexity of phenomena itself (as for natural convection). Also, depending on the models of all other phenomena (mainly air circulation in rooms or unsymmetrical radiation inside the room), the main issue is to divide the envelope into several envelope elements (mainly represented as 1-D models) as for example floor, walls (external and internal) and roof. Depending on the room air model the envelope conduction models should be sub-divided into several ones in order to be homogeneous with the number of cells of the air model.

On the other hand, heat exchange by long wave radiation can either be modelled by using:

- Mean radiant temperature node,
- Star temperature node (TRNSYS),
- Walton's method[99],
- Other radiation models[100]

Outdoor short-wave radiation from diffuse and direct is generally calculated using radiation processors that project the radiation on the various orientations of envelopes while considering (or not) solar masks from ground, vegetation and other buildings. Solar transmission into the building or the rooms is calculated by window models estimating the amount of short-wave radiation passing the window which is exposed to transmission, absorption and reflection). Depending on the model used, either constant values are considered or angle dependent functions that allow to correctly model the phenomena. Again, these questions are very well known and do not represent a particular difficulty other than the choice of the best suitable model type. Also, complex envelop cases as shown in the introduction of this chapter are more a problem of applying the appropriate level of detail of the model as the phenomena themselves.

The modelling of the envelope and radiation has been subject of various studies. They are thus not treated here in detail. Only in the case of lumped parameter models the envelope modelling is shown here since convection, radiation and conduction are coupled in one single model.

In the following sections the different types of convection models are presented.

2.2 MODELS OF ROOM CONVECTION

2.2.1 WELL-MIXED MODELS

This type is frequently used for the study of energy consumption in buildings. The air in the room is considered to be perfectly mixed in temperature and all other properties as for example humidity or pollutants as well. *Figure **102*** (left) shows the heat exchanges in the well-mixed air model.

The phenomena of heat exchange in the case of the well-mixed model are:

- external air supply (fresh air, inter-zonal air exchange, air conditioning system)
- Convective heat exchange at internal surfaces (walls, floor, ceiling)
- Convective heat exchange at internal heat sources (emitters, other heat sources as occupation, electric equipment, …)

[99] WALTON G.N., A new algorithm for radiant exchange in room load calculations, ASHRAE Transactions, Vol. 86:2, pp. 190-208, 1980
[100] ÖZISIK M.N., Heat Transfer - A basic approach, McGraw-Hill Publishing Company, ISBN 0-07-047982-8, 1985

Any heat exchange is assumed to take place between the boundary conditions and the mean temperature node in the room. *Figure **102*** (right) shows the corresponding electrical representation of the example with one capacitor representing the average room air state.

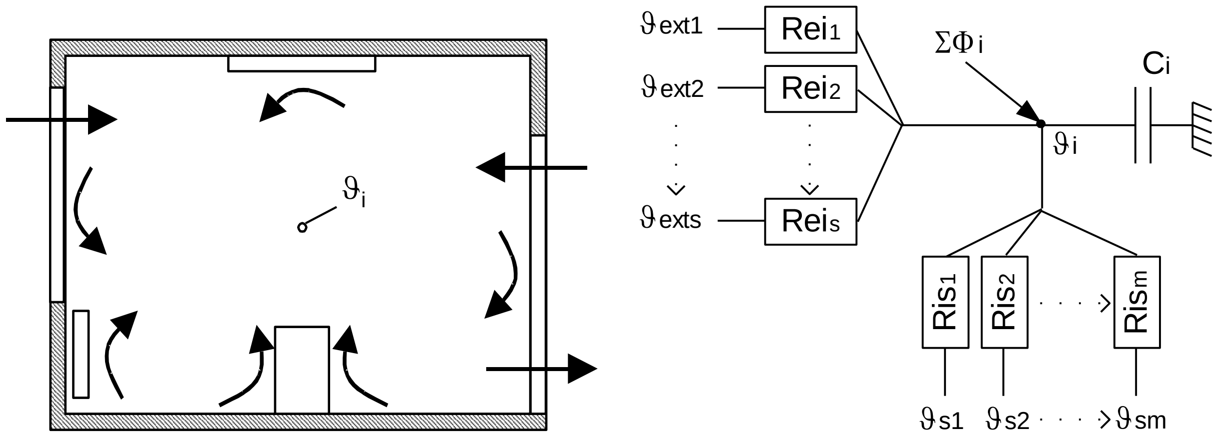

Figure 102 : Heat exchanges in the well mixed model (left) and electrical representation (right)

The system is described by the differential equation of energy conservation:

$$\rho\, V_i\, C_p\, \frac{d\,\vartheta_i}{d\,t} = \sum_{1}^{m} \Phi_{conv} + \sum_{1}^{s} \Phi_{j,i} - \sum_{1}^{s} \Phi_{i,j} + \sum_{1}^{q} \Phi_{Gains} \qquad (1)$$

where m is the number of internal surfaces, s the number of sources of air exchange and q the number of convective heat sources in the zone.

Due to the simplification of homogeneous conditions, no information about temperature distribution throughout the zone is available in this type of model.

2.2.2 COMPUTATIONAL FLUID MODELS

The detailed description of this type of model would require an entire chapter (or report). Since it is not directly in the scope of this report (analysis of system performances), only a short overview is given here.

Using computational fluid models, the room air is divided into a large number of finite elements or volumes. In each of the cells the equations of mass, momentum and energy are solved in order to obtain the conditions throughout the room. Due to the high number of cells, the computational effort is very high and fast simulations or even real-time simulations are, to date, almost impossible for three-dimensional cases.

Beausoleil[101,102] has undertaken first steps for the integration and coupling of CFD to building simulation environments. One zone of the building is there simulated in detail while the detail in all other zones is kept on a low level. Ratnam[103] applies a "quasi-transient" CFD model to the transient study of a control loop. Due to the large calculation time this kind of model is unusable in many cases. Peng[98] carried out CFD simulations for the generation of a simplified CFD model with fixed flow fields.

CFD models need the use of a turbulence model. The choice of this type of model is, even for specialists, still difficult, and depends on the case treated. Various simulations have been carried out in order to recommend the use of turbulence models for specific cases of HVAC systems. The key problem in the use of these models in buildings is natural convection.

[101] BEAUSOLEIL-MORRISON I., Modelling mixed convection heat transfer at internal building surfaces, Building Simulation 99 conference, Kyoto, Japan, September 1999
[102] BEAUSOLEIL-MORRISON I., Further developments in the conflation of CFD and building simulation, BS2001 conference, Rio de Janeiro, Brazil, 13-15 August 2001
[103] RATNAM E., Campbell Th., Bradley R. Advanced feedback control of indoor air quality using real-time computational fluid dynamics, ASHRAE Transactions, 1998, Vol. 104, Part 1

2.2.3 ZONAL MODELS

In zonal models, the internal zone air volume is divided in several sub-volumes (Musy[95]). Contrarily to CFD models, only the equations of conservation of mass and of energy are solved. Navier-Stokes equations are not considered. The airflow between the sub-volumes is calculated by correlation and/or other simplified methods (pressure calculation).

This type of model has been developed in order to characterise the comfort in a zone while keeping the model as simple as possible. The main purpose is to represent the conditions at the occupant zone of the room. *Figure **103*** illustrates heat and mass exchange between the sub-volumes and boundary conditions.

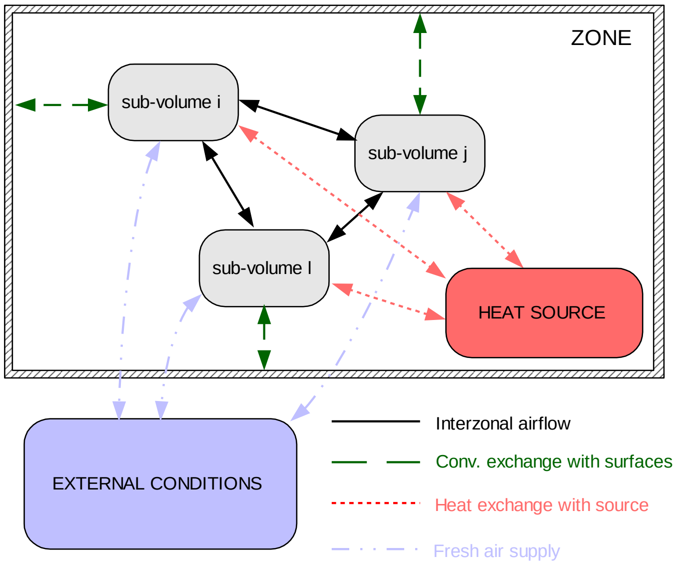

Figure 103 : Principle of a zonal model

The following heat and mass transfers appear in a zonal model:

- Airflow between sub-volume i and sub-volume j
- Convective heat exchange of sub-volume i with adjacent surface A_k
- Airflow between sub-volume i and external conditions (fresh air supply or ventilation)
- Heat source in sub-volume i

Flow rates between volumes are obtained from correlations, the equations of momentum have thus not to be solved. The correlations can be of one of the following types:

- Correlation for the flow rate in plumes and jets
- Correlation for the flow rate in boundary layers (free convection)
- Correlation for the flow rates between air volumes due to temperature differences

The heat balance on one air sub-volume is:

$$m_i c_p \frac{d\vartheta_i}{dt} = \sum_{j=1}^{l} \dot{m}_{j,i} c_p \vartheta_j - \sum_{j=1}^{l} \dot{m}_{i,j} c_p \vartheta_i + \sum_{k=1}^{m} h_{i,k} A_{i,k} (\vartheta_{A,k} - \vartheta_i) + \sum_{r=1}^{s} \dot{m}_{ext;r,i} c_p \vartheta_{ext,r} - \sum_{r=1}^{s} \dot{m}_{ext;i,r} c_p \vartheta_i + \sum_{p=1}^{q} \Phi_p \qquad (2)$$

where i is the number of sub-volumes, m is the number of internal surfaces, s the number of sources of external air exchange and q the number of convective heat sources in the zone.

One of the weaknesses of the zonal model approach is that the principal airflow pattern in the zone has to be known in order to guarantee qualitatively accurate results.

Several authors have developed zonal models for a room equipped with a convective heat source, such as a convector or a radiator, below a cold window. Lebrun[104] proposed first, to divide the air volume in the room into several air sub-volumes, depending on their flow phenomena. Horwarth[105], after analysing experimentally the main convective phenomena in a room heated by a radiator, the plume of the radiator and the boundary layer at the external wall, developed a zonal model with an upper zone and a lower zone, working in transient conditions. The boundary layers at all walls have been assumed as natural convection cases.

Laret[96] developed an analytical model, based on steady state conditions, able to calculate the temperature profile at the centre of the room. This model has also been extended, after some simplifications, to the transient case.

Inard[106] developed a model for a room with a convector or a radiator including the plume and boundary layer phenomena in free convection. The occupant zone is modelled with three zones.

Ngendekumana[107] developed a model using the principle of heat exchangers in order to calculate the heat transfer at the walls. He also included a re-circulation in the upper part of the room.

During[94] studied the use of zonal models for transient conditions. He increased the number of air sub-volumes to 12. The transient analysis was, in his case, focussed on long time periods (simulation of several days). Short time dynamics, important in controller studies, have not been treated. The dynamic phenomena studied in this case were thus mainly the dynamics of the envelope elements. A second, similar model for the case of a heated floor has also been developed.

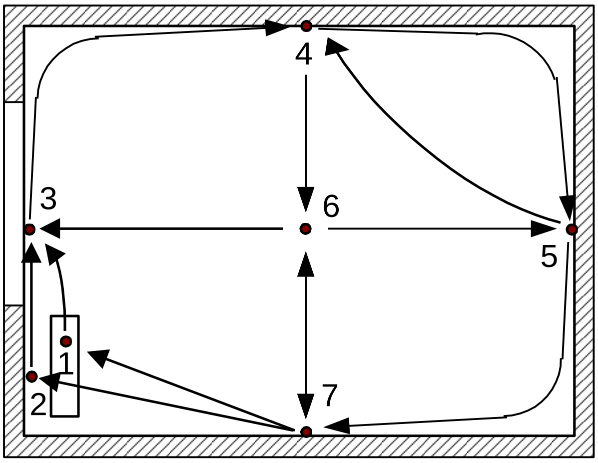

Figure 104 : Zone with radiator/convector Lebrun[104]

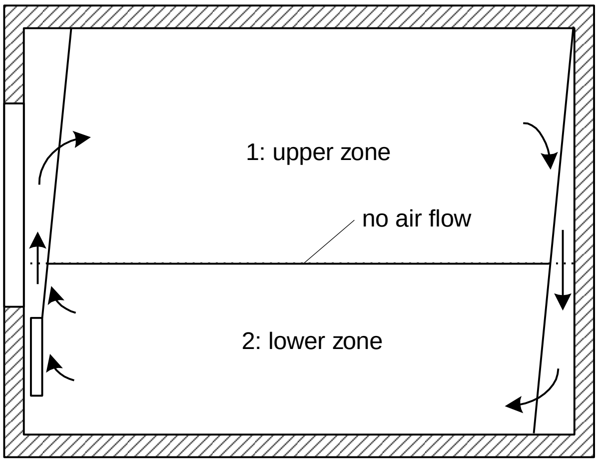

Figure 105 : Zone with radiator (Horwarth[105])

[104] LEBRUN J., Exigences physiologiques et modalités physiques de la climatisation par source statique concentrée, PhD thesis, University of Liège, Belgium, 1970
[105] HORWARTH A. T., Temperature distributions and air movements in rooms with a convective heat source, PhD, University of Manchester, 1980, 226 p.

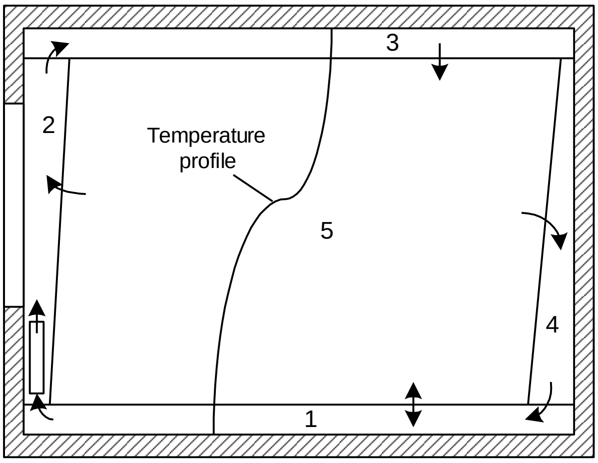

Figure 106 : Zone with heater (Laret[96])

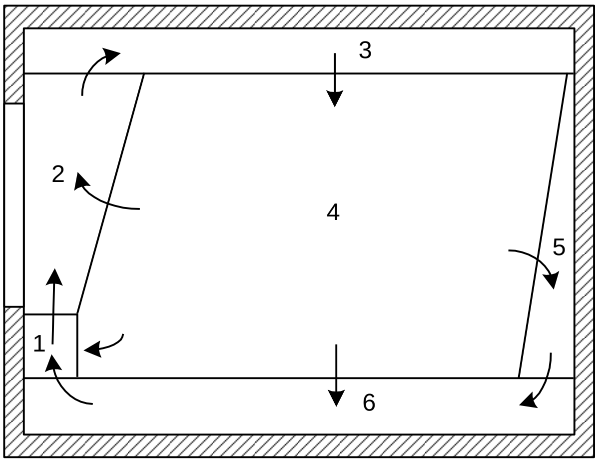

Figure 107 : Zone with convector/radiator (Inard[106])

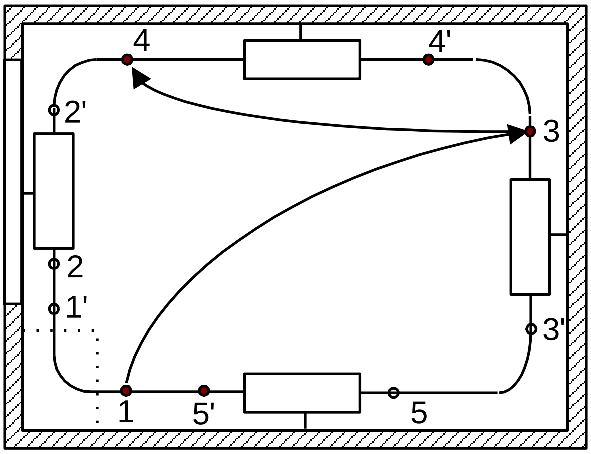

Figure 108 : Zone with convector/radiator (Ngendekumana[107])

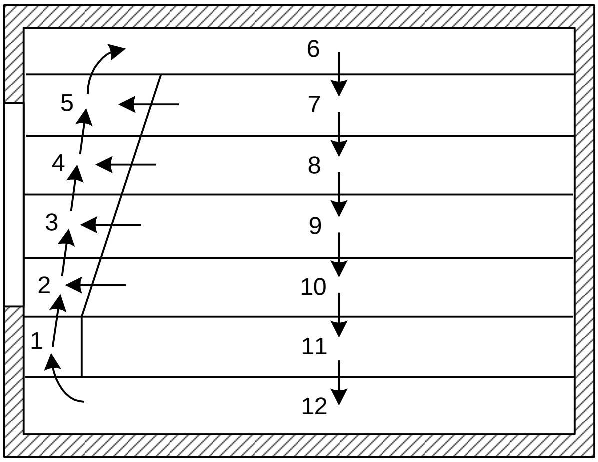

Figure 109 : Zone with radiator/convector (During[108])

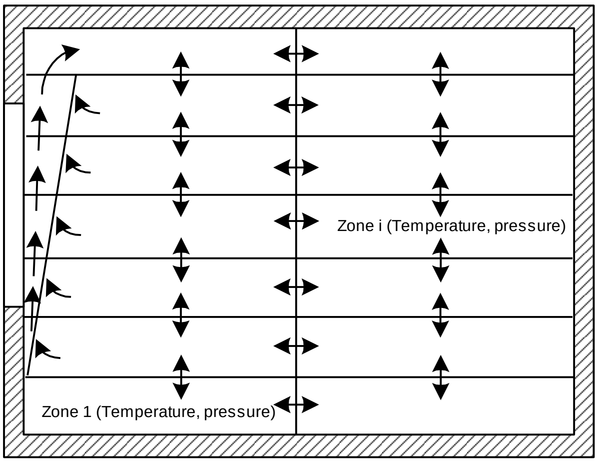

Figure 110 : General zonal model (based on pressure laws and correlations) (since 1985)

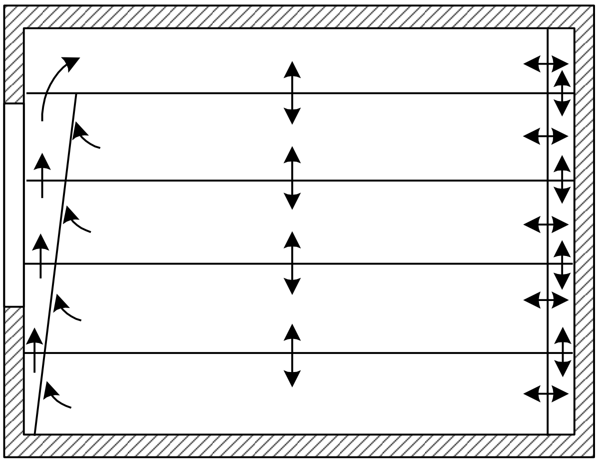

Figure 111 : General zone model of Togari[109]

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[106] INARD C., Contribution à l'étude du couplage thermique entre un émetteur de chaleur et un local, Thèse de Doctorat, INSA Lyon, 1988, 440 p.

[107] NGENDAKUMANA, Modélisation simplifiée du comportement thermique d'un bâtiment et vérification expérimentale, Thèse de Doctorat, Université de Liège, 1988, 210 p.

[108] DURING H., Consommations énergétiques et confort thermique des locaux chauffés : approche par les modèles zonaux, Thèse de Doctorat, INSA Lyon, 1994

[109] TOGARI S., Arai Y., Miura K., A simplified model for predicting vertical temperature distribution in a large space, ASHRAE Transactions: Research, Vol. 3630, pp 84-98, 1993

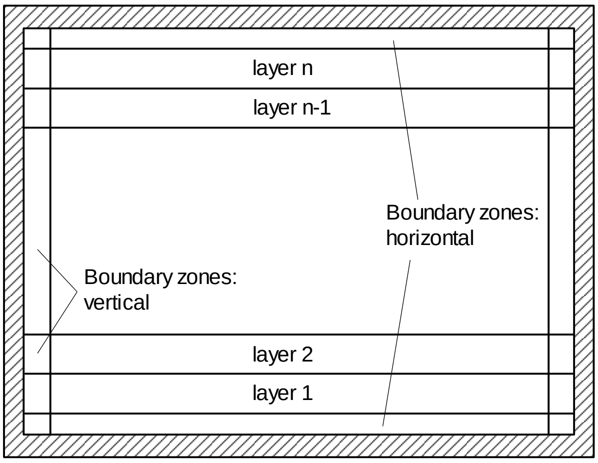


Figure 112 : Zone with natural convection ([Hutter81])

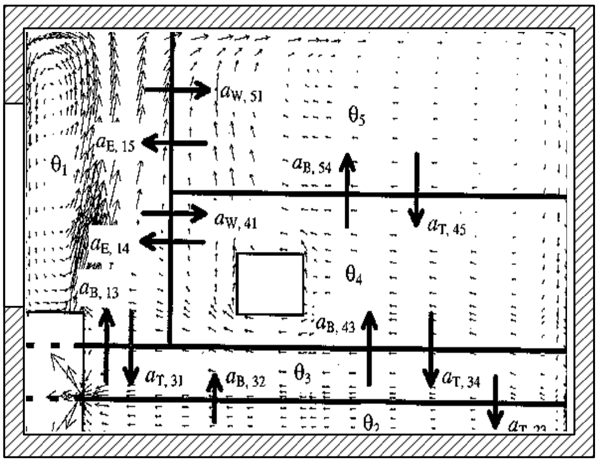


Figure 113 : Zone with fan coil unit and heat source (Peng[110])

Fauconnier[111] developed a zonal model where the mass transfer between the zones is obtained from correlations based on pressure differences. Wurtz[112] and Musy[95] continued this work and developed models with flexible zones as shown in *Figure **110***.

A model presented by Togary[109], similar to Inards[106] model and with higher number of zones, is extended to the use for different emitters or ventilation (*Figure **111***). It can be used also for air conditioning with divers jets and also in transient conditions.

Hutter[113] presented a zonal model for natural convection. This model uses a variable number of horizontal air layers (*Figure **112***) and represents also the zones of natural convection near the walls.

Peng[110] developed a first zonal model for control studies for a fan coil application based on pre-simulations in CFD for controller studies (*Figure **113***). However, since the sensor was, in his case, placed at the air extraction of the fan coil unit, it was not necessary to model convective phenomena around the sensor (wall jet). The main assumption in his modelling is that the airflow in the zone does not change and is only a function of the fan speed of the fan coil.

The zonal model principle has been more and more generalised. But all of these models have been optimised in order to represent well the conditions at the centre of the zone. The modelling of thermal effects near walls was of lower importance. The boundary layers at the wall have thus all been represented by expression for free convection. Either correlation of vertical flat plates has been used or correlation obtained in test rooms with heated or cooled surfaces. The results of these approaches are in good agreement if the boundary layers are one of the main engines of the airflow in the room. This is the case for high temperature differences between room air and the surfaces. On the other hand, phenomena of negative buoyancy are more difficult to handle. Measurements carried out by Riederer[114] allowed to characterise the phenomena in the air volumes near the internal walls illustrating that in many cases negative buoyancy governs the flow near the internal walls.

[110] PENG, X., Modelling of indoor thermal conditions for comfort control in buildings, PhD thesis, Delft, University of Technology, 1996

[111] FAUCONNIER et al., Simulation thermique détaillé des bâtiments : Présentation du modèle BILGA, Rapport de recherche UTI/CEBTP E51.84, january 1985

[112] WURTZ, Etienne, Modélisation tridimensionnelle des transferts thermiques et aérauliques dans le bâtiment en environnement orienté objet, PhD thesis, Ecole Nationale des Ponts et Chaussées, Paris, 1995

[113] HUTTER E., Etude du comportement thermique des galéries couvertes par simulation en régime varié avec prise en compte de la stratification d'air, Thèse de Doctorat, Université de Paris VII, 1981, 207 p.

[114] RIEDERER P., Thermal room modelling adapted to the test of HVAC control systems, PhD thesis, Ecole des Mines de Paris / Technische Hochschule Dresden, 2002

2.2.4 SIMPLIFIED MODELS USING ADDITIONAL IDENTIFICATION OR CORRELATION

This model type is typical for an application on the field of control studies. By identification based on measurement data sets, the necessary phenomena can be modelled. The system can then be represented as a state space model with the parameters obtained by identification with experimental results.

This concept could be interesting due to the possibility to represent the observed phenomena while keeping the model at a minimum level of detail. Maalej[115], for example, presents correlations for temperature stratification in rooms for different heat sources. Correlation or identification could also be used to represent differences between sensor and centre temperature.

However, identification or black box models have the disadvantage that they are only valid within the range of conditions they are based on. Extrapolation outside this range given by the identification process is risky compared to physical models.

2.3 MODELS OF ENVELOPE CONDUCTION

There are four basic types of wall models:

- Lumped parameter model: they have the advantage of a low number of parameters. A set of a few parameters describes the system. A lumped parameter model can integrate all layers of one envelope element (e.g. wall), all elements of the envelope of a room or the whole room model (convection, conduction and radiation in a room). The latter is currently used to simulate rooms in controller studies. In the same way, one or more envelope elements can be modelled as a lumped parameter model. This modelling permits fast simulations since the system is reduced to a fist order system. The model can be described as by thermal-electrical analogy. Several authors (Laret[96], Roux[116]) studied this type of model and found acceptable agreement with more detailed models.
- Nodal wall model: the wall is divided into n equivalent sub-layers of a wall, each characterised by a thermal capacitance. The capacitances connected with resistances equivalent to the inverse of the thermal conductivity. The nodal model is equivalent to the finite difference model with second order approximation (Roux[116]).
- Finite difference/volume/element model: it is based on the spatial (1, 2 or 3D) and temporal discretisation of the equation of conduction. The model can be used in one or more-dimensional representation (Özisik[100]).
- Transfer-Function models: the coefficients of the transfer function are calculated in a “pre-processing” program. The model is currently used in simulation programs for the study of energy consumption (TRNSYS[117]).

2.4 MODELS OF LONG WAVE RADIATION

There are different types of long wave radiation models that are only described briefly since their detail of modelling has a lower importance on the studied problem as the modelling of convective phenomena. Three main types are:

- Models using a mean radiant temperature node:

  All radiative heat exchange between the internal room surfaces and external radiation is calculated using a fictitious mean radiant temperature node. Due to the simplification using a mean temperature node, an error is introduced depending on the temperature differences

[115] MAALEJ J., Emetteurs de chaleur dans les bâtiments : comportement thermique et étude des performances, Thèse de Doctorat, Université de Valenciennes, 1994

[116] ROUX J.J., Proposition de modèles simplifiés pour l'étude du comportement thermique des bâtiments, Thèse de Doctorat, INSA Lyon, 1984, 201 p.

[117] TRNSYS, A transient Simulation Program. Solar Energy laboratory of the University of Wisconsin; Madison, USA, 1996

between the surfaces. The error can be neglected for small temperature differences. The heat balance uses a simplified (constant) radiative heat transfer coefficient.

- Models using the mean radiant temperature nodes of all surfaces surrounding the treated surface ([Walton80]):

  The second model type uses different fictitious radiant temperature nodes. For each surface element, the mean radiant temperature of all other surfaces exchanging long wave radiation with this element is calculated. Solar radiation and radiation from equipment has to be injected to the different radiant temperature nodes. This model represents an improvement of the first model using only one mean radiant temperature since it considers only the temperatures of all other surfaces for the balance at the concerned surface. A simplified radiant heat transfer coefficient is used in the heat balance on each surface.

- Models using view factors:

  The view factors between the different internal surfaces are calculated. The view factors are then introduced into the heat balances of each surface element. Özisik[100] lists some methods of radiation modelling based on view factor theory.

2.5 LUMPED PARAMETER ROOM AND BUILDING MODELS

This model type "lumps" a number of phenomena and parameters together, in order to obtain a model, as simple as possible, able to represent the key phenomena in a room. This can be the room air that is generally treated as well-mixed or the different layers of a wall or even different walls or surfaces. *Figure **114*** shows two examples of very basic lumped parameter models representing the air temperature ϑ_i, a resultant temperature ϑ_s (mix between mean radiant and air temperature) and a wall temperature ϑ_w (Riederer[118], RT2012[119]).

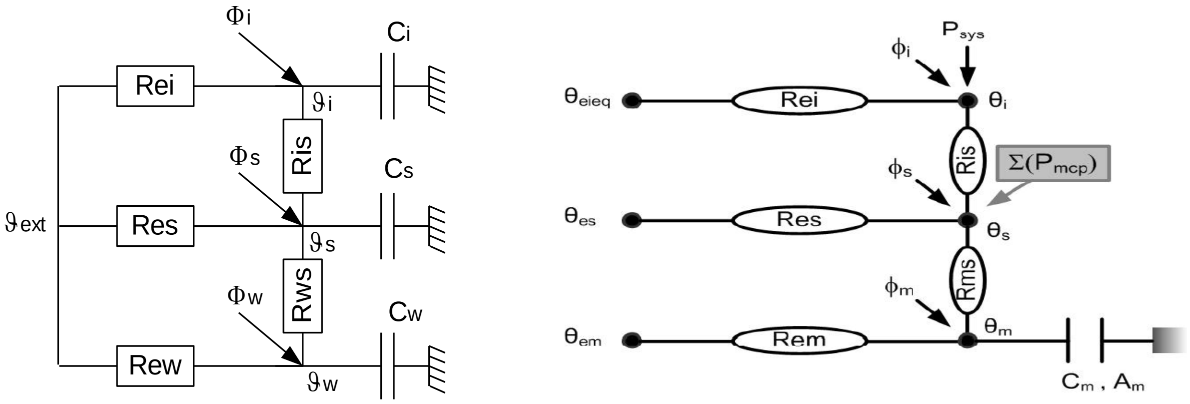


Figure 114 : Examples for lumped parameter models (left: R5C3, right R5C1)

Laret[96] developed a model representing only a resultant temperature in the zone. This results in a very simple model structure and the elimination of non-relevant outputs of a model. On the other hand, the use of these models is limited since they only represent the minimum of information.

To illustrate the variety of possible lumped models, three room models of different complexity that have been developed for the Dimosim simulation platform[120] are shown in *Figure **115*** (the most simple level of detail), *Figure **116*** (average level of detail) and *Figure **117*** (detailed level of detail).

[118] RIEDERER P., Marchio D., Gruber P., Visier J.C., Lahrech R., Husaunndee A., Building zone modelling adapted to the study of temperature control systems, ASHRAE/CIBSE conference 2000, Dublin, Ireland
[119] RT2012, https://www.cohesion-territoires.gouv.fr/rt2012
[120] Dimosim platform, https://thermoss.eu/dimosim/

It can clearly be seen, that "lumped" parameters models can have a broad range of level of detail. While the first one corresponds to a very simple model, it has very limited capabilities of adaptation to specific phenomena such as adjacent zones (walls, floor or ceiling) and can thus only be used for standard cases. The average level of detail has been developed to overcome these limitations it can be connected to the ground with a simple floor model. Also, an additional thermal mass has been added to better represent thermal inertia. However, it still does not provide the possibility to parameter separate characteristics of walls and ceiling/roof. Therefore, the detailed model has been developed as a final step. This model, developed as a modular model, allows to represent several individual envelope elements (n walls, aggregated or not, floor and ceiling). It also includes thermal bridges, inner inertia and adjacent walls.

From the point of view of necessary parameters to set up the model, the difference in the number of parameters is not very important since even the simple model is based on a pre-processor to aggregate several envelope elements into a single one. If the model shall be used for model identification (real time control), of course, the simple model is far more appropriated and useable as the detailed one.

Simulation time will differ with the level of detail, but the experience is that even for the simulation of several hundreds or thousands of buildings, even the detailed model still allows to achieve very fast simulations.

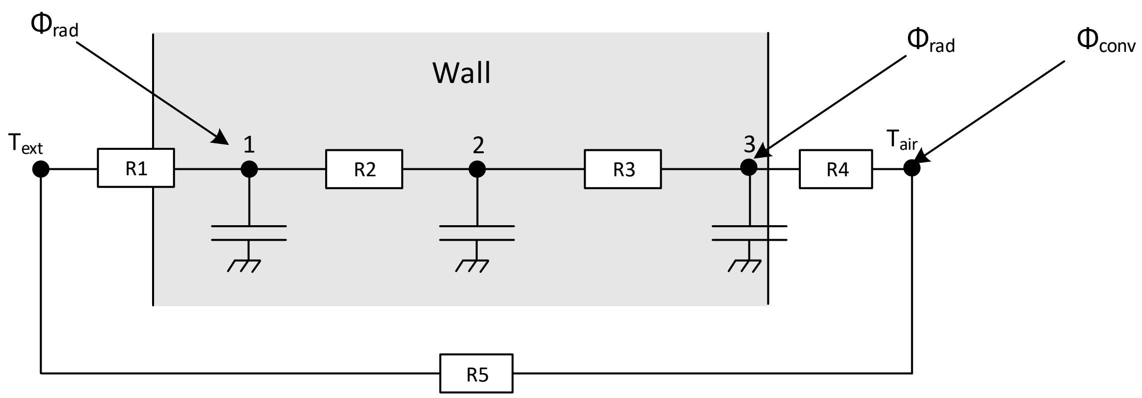


Figure 115 : Simplified Thermal R-C model used in the DIMOSIM v0

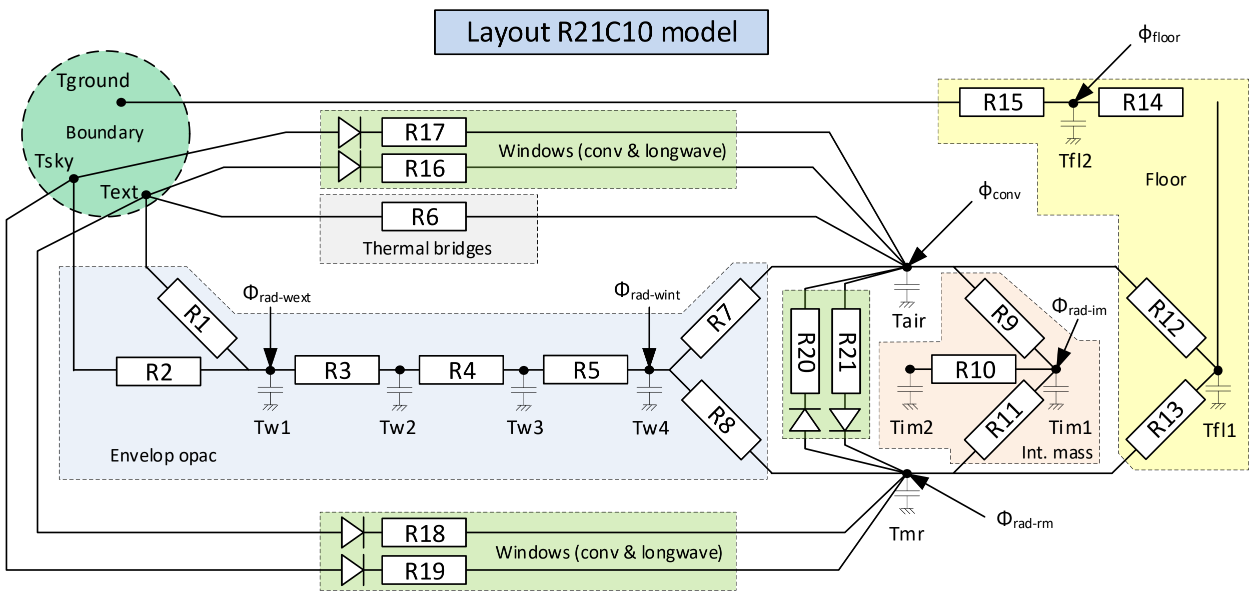


Figure 116 : Average thermal R-C model used in DIMOSIM v1

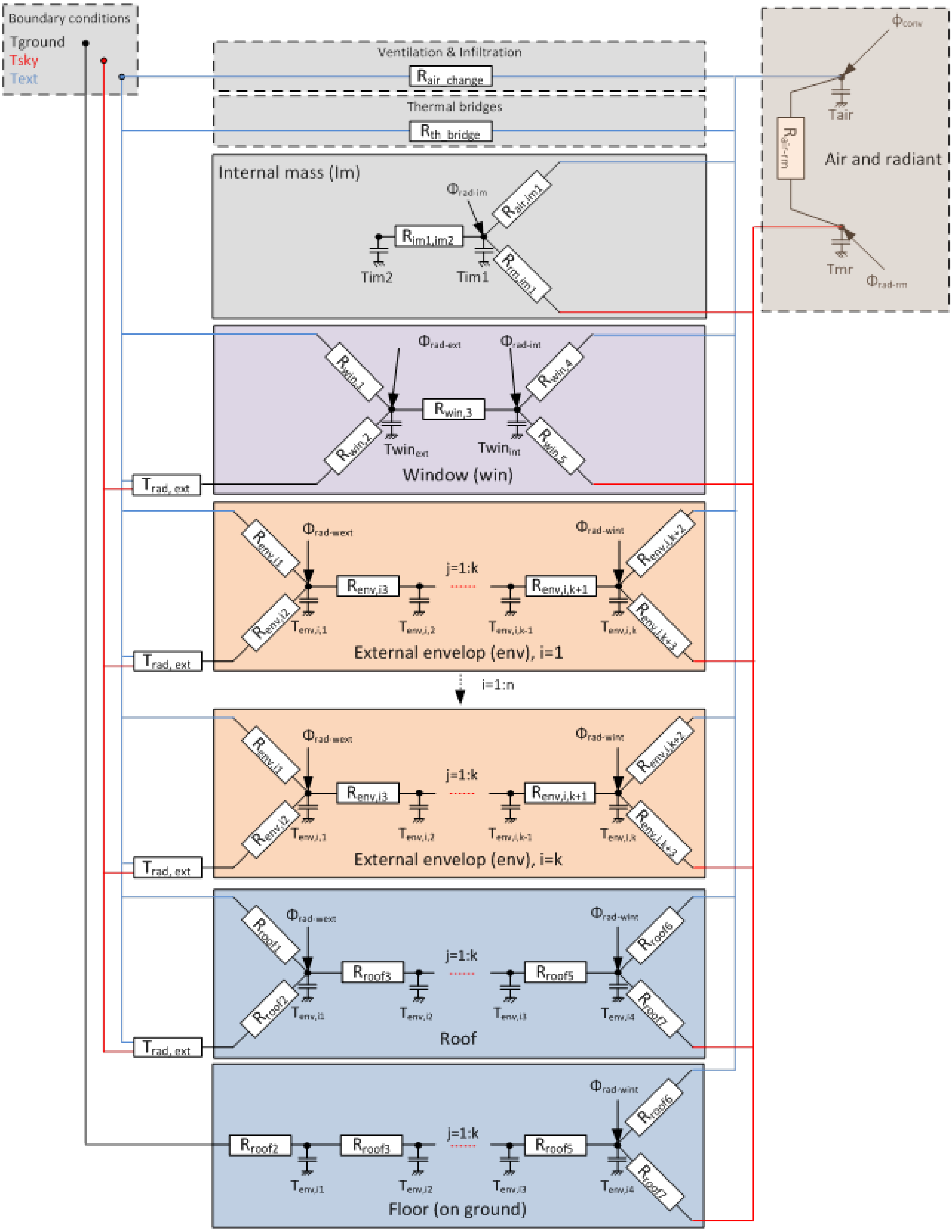


Figure 117 : Detailed thermal R-C model used in DIMOSIM v2

In other words, all three models can have their typical use cases. But it has to be mentioned that if one wants to be sure not to miss important parameters, the detailed model will probably be the most secure choice.

On the other hand, if very few details are known about the building (in case of city simulation for example), the simple model will be more sufficient in most cases.

2.6 CONCLUSION ON ROOM MODELS

A large variety of convective models have been developed and are used. The most used model in system design is the well-mixed zone model.

Detailed CFD models are mainly used for the design of zone emitters and placement of air diffusers in larger zones. However, these models are characterised by large simulation times and are mainly used for steady state calculation of instantaneous pictures of air flows in rooms. Their use for transients with simulation periods higher than 1 week is generally not done.

The zonal modelling approach consists in an intermediate level of detail and allows to refine results within the zone while still allowing the simulation of larger periods, even yearly simulations.

Radiation models and conduction models of different complexities have also been listed. For standard cases their choice is significantly less impacting than the choice of the convective model.

Lumped parameter models have been developed in a large variety of details, from only 1 capacitor to a higher number. The border to detailed models gets thus flue.

2.7 CONCLUSION ON MODEL CRITERIA OF ROOM MODELS

The “best” room model should be a good mixture of low simulation time, accuracy and detail related to the simulation objective(s).

For controller studies in rooms (which was the objective in this paragraph), zonal models have been found to match this specification. The room model has to be based on simple and available parameters while the validity and the robustness of the model is guaranteed.

The model has to represent the conditions at possible positions of the controller sensor: at the centre of the room, in the jet trajectory of an emitter and in a boundary layer of natural convection. A sensor model will then use the corresponding temperature around the controller sensor.

An example of judgement of the ability of different room models to answer the particular question of controller studies is carried out using qualitative classification in Table 7.

The values in this table are estimated regarding the possibilities of the different model types.

While the well-mixed model is characterised by good results in the upper part of the table (general characteristics, parameter setting and validity), it is not able to predict most of the interesting outputs offered by the CFD models. CFD models on the other hand, assuming perfect knowledge of their use, obtain good results in the model outputs but have bad results in the upper part, general characteristics, parameters and validity.

Identification models (improved well-mixed) are interesting from the point of view of their general characteristics since they are simple and offer fast simulation runs. Also, the outputs of interest could probably be well predicted. However, to represent convective phenomena around the controller sensors (negatively buoyant wall jet), especially if room geometry changes, will bring this type of model into serious trouble.

Zonal models can be seen as a good compromise in all three main groups of criteria. While they allow real time simulation, even with a longer simulation time as simple models, they are, depending on the correlations used, also valid for other room geometry and uses. Most of the outputs of interest can be predicted with acceptable accuracy.

Table 7: Criteria for the development of the zone model

		Model types			
Groups of criteria	Specific criteria	**Well mixed**	**Improved well mixed**	**Zonal**	**CFD**
General characteristics	Possibility of real time simulation	YES	YES	YES	?
	Calculation time	++	++	+	--
	User level	Low	Low	Intermediate	Very high
Model Parameters	Low number of parameters	++	+	+	--
	Low user level for parameterisation	++	+	+	--
	Complexity and coherence of initial and boundary conditions	++	++	o	--
Model Outputs Performance Assessment	Mean room air temperature	o	o	+	++
	Mean radiant temperature at occupant zone	Depends on wall modelling			
	Horiz. temperature variation at occupant zone	n.a.	+	+	++
	Vert. temperature variation at occupant zone	n.a.	+	+	++
	Air velocities at occupant zone	n.a.	-	o	++
Model Outputs Sensor measurement	Horiz. temperature variation at sensor positions	n.a.	-	o	++
	Vert. temperature variation at sensor positions	n.a.	o	+	++
	Air velocities at sensor positions	n.a.	o	o	++
	Mean radiant temperature at sensor positions	Depends on wall modelling			
Validity	Validity for different zone type (heavy/light)	Depends on wall modelling			
	Validity for different geometry	?	?	?	++
	Validity for different zone use	?	?	?	++
++ very good + good o satisfying - sufficient -- not sufficient n.a. not available					

2.8 OUTDOOR CONDITIONS

If one or more buildings or even a complete city shall be modelled and simulated, several phenomena can significantly affect the quality of results. The reason is of different nature and has to be analysed before starting the modelling procedure of the object itself. Note that many simulation objectives do not necessarily require the consideration of all these aspects.

It has to be mentioned that in the past, this part, except direct solar masks from other buildings or ground topology, has mostly been neglected. In recent developments, especially in the context of urban heat island, additional models that represent neighbourhood, city or even regional scales have been developed.

The next paragraphs will summarise these phenomena, related to the scale on which they are mainly observed and considered (some of them can be at different scales), starting from the building up to the city or region.

2.8.1 BUILDING SCALE

On the building scale, mainly solar radiation, especially masks caused by other buildings, ground topology and vegetation can be considered. If the building is located in a flat, rural area without vegetation around, the building can be simulated "as is", by considering the typical (or real) weather files.

However, if the building is located close to other objects (vegetation, ground topology or other buildings), these obstacles should be considered as solar shading. The shading will diminish especially direct solar radiation, depending on sun position (solar angle and azimuth) related to the solar masks. The masks are typically considered by generating a table with angle of view (0-360°) and height of obstacles (0-90°). They can be estimated from a site visit, measured using appropriated tools (typically used during the feasibility study of solar thermal and photovoltaic projects) or calculated from geometrical data of all relevant objects.

Some tools, mainly up from neighbourhood level, allow the direct calculation of these masks since information of other buildings and ground is available. *Figure* ***118*** illustrates the result of such a calculation with the height of mask on the right hand.

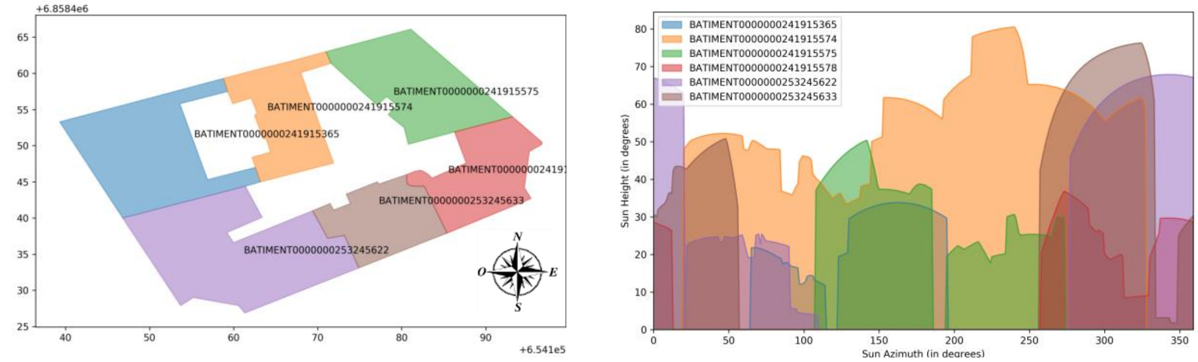


Figure 118 : Detection of adjacencies and masks in a small neighbourhood (left: top view, right: height of masks)

Figure ***119*** illustrated the impact of the consideration of solar masks for an arbitrarily chosen building in a local context. While the two plots on top of the figure show solar radiation on the external envelope as a carpet plot over a whole year once for considering shading (left) and one without (right). The left figure on the bottom indicates, on the same axes, the difference between both versions (with and without considering) indicating an annual difference of about 11% in solar gains. Typical values of this difference vary in between 0 and 30% with the latter being a building in a narrow street canyon with rather high buildings. Finally, the figure on the bottom right illustrates again mask height but this time with all sun courses over a whole year.

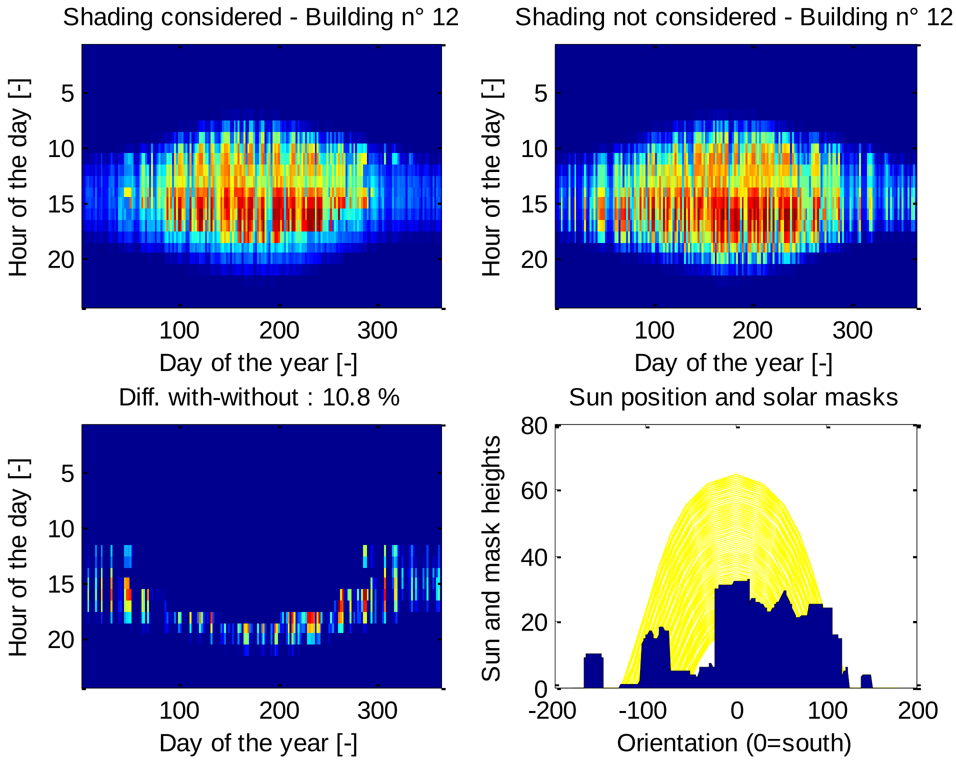


Figure 119 : Solar mask calculation and impact (example of the centre of a building)

Depending on the objective of the simulation, it can be crucial to consider this phenomenon (e.g., switch on of lighting in the afternoon impacting internal gains and consumptions but also solar gains at low sun positions).

2.8.2 NEIGHBOURHOOD SCALE

On the neighbourhood scale, solar masks as shown in the previous paragraph are of course also impacting results.

Other phenomena on this scale are related to microclimatic issues. These are of different nature:

- latent phenomena: Latent phenomena are especially important when the building or neighbourhood is located close to vegetation or latent sources (lakes, river, sea). The presence or not of such latent sources will definitively affect simulation results since outdoor air humidity and temperature are impacted. This has an impact on results related to air exchange between outdoor and indoor conditions (infiltration and especially mechanical ventilation or air handling units). The study of green envelopes does of course require the consideration of latent effects, inside the envelope but also on the microclimate.
- temperature-related phenomena with two separate aspects, related to:
    - Radiation : besides masks, the long wave radiation is affected on this scale due to long wave radiation exchange between buildings. Of course, this exchange depends on the location and distance of buildings. View factors allow to calculate these heat exchanges. *Figure **120*** left illustrates radiative calculations using Solene[121].
    - Air temperature: the outdoor temperature is affected locally since the segments of external envelopes are exposed (or not) to solar radiation and long wave radiation. This will affect the air temperature around the buildings and thus dry-bulb temperature of the standard simulation weather conditions. Different approaches have been applied to consider these effects. Either CFD calculations

[121] F. Miguet, Paramètres physiques des ambiances architecturales : Un modèle numérique pour la simulation de la lumière naturelle dans le projet urbain. PhD thesis, University of Nantes, France, 2000

(Envimeth[122]) or zonal models have been developed (Envibate[123]). While CFD tools allow the detailed calculation of outdoor air temperatures, it is still restricted to short simulation periods (typical or extreme days), zonal models have been developed too allow anual calculations and to analyse at the same time impacts on yearly energy consumptions.

- Air flow and pressure related phenomena:

  The air flow around buildings and air pressure on facades impact mainly the air exchange between outdoor and indoor conditions through infiltration (and to some extent also ventilation) as well as heat exchange at the external surfaces of the envelope (convective heat exchange coefficients will vary with air velocity). *Figure **120*** (right) illustrates air velocities around the buildings of a neighbourhood (reference Quic-urb) that can be used for improving calculations of infiltration. For buildings with high air permeability the impact can be significant for building zones with different orientations since pressure differences betweeen these facades will drive the amount of infiltration.

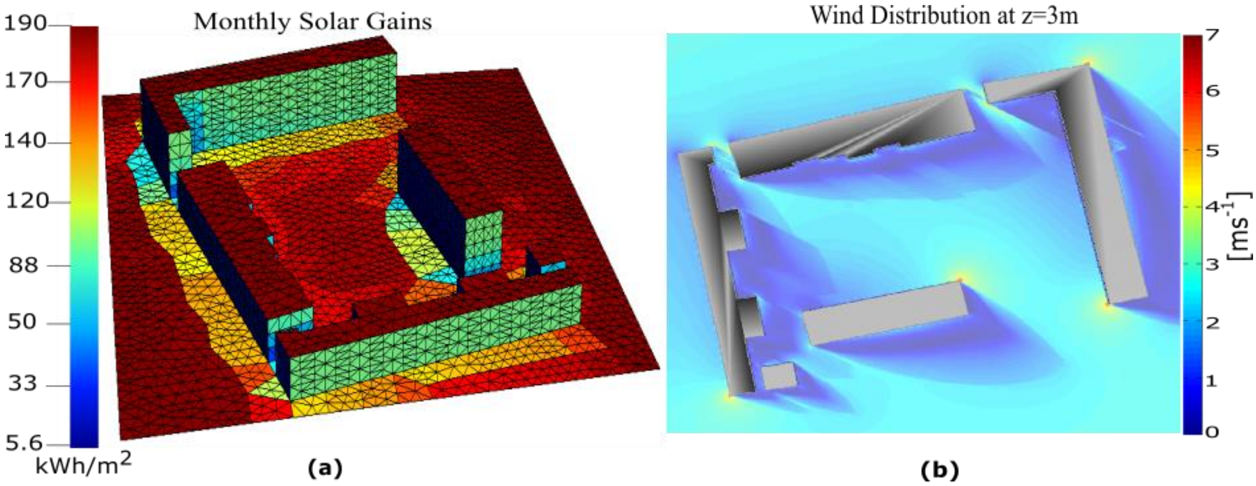


Figure 120 : Detailed received solar gains (a) and airflow distribution (b) in a neighbourhood

However, it has to be mentioned that in most cases, buildings with high permeability are often also those buildings that are badly insulated. The impact of the consideration or not is thus not obvious.

Starting from the Envibate tool, Kyriakodios[124] has coupled this tool to Dimosim to study the impact of considering the microclimate in a neighbourhood on comfort and energy consumption in a wholistic approach.

2.8.3 CITY SCALE

The last scale in this chapter covers the scale of a city. Energy-related processes throughout the city will heat up the temperature with maximum temperatures in the densest areas. *Figure **121*** illustrates the impact with almost no impact at the border of the city (the standard weather file is thus sufficient to set the boundary conditions of such a simulation) and a maximum impact for downtown areas.

On this last scale, local phenomena cannot be considered in detail. It is sufficient to model with archetype objects the heat (sensible and latent) gains from city objects in order to estimate the temperature increase due to the city. *Figure **122*** shows the heat balance on the city area allowing to simulate the temperature increase. Tools as Urban Weather Generator[125] are widely used for this purpose.

[122] https://www.envi-met.com/
[123] A. Gros, Modélisation de la demande énergétique des bâtiments à l'échelle d'un quartier. Phd thesis, University of La Rochelle, 2013
[124] Georgios Kyriakodis, Development of a coupled simulation tool for urban building energy demand, district energy systems and microclimate modelling, CSTB/Université de la Rochelle, August 2020
[125] Bruno Bueno, Leslie Norford, Julia Hidalgo & Grégoire Pigeon (2013) The urban weather generator, Journal of Building Performance Simulation, 6:4, 269-281, DOI: 10.1080/19401493.2012.718797

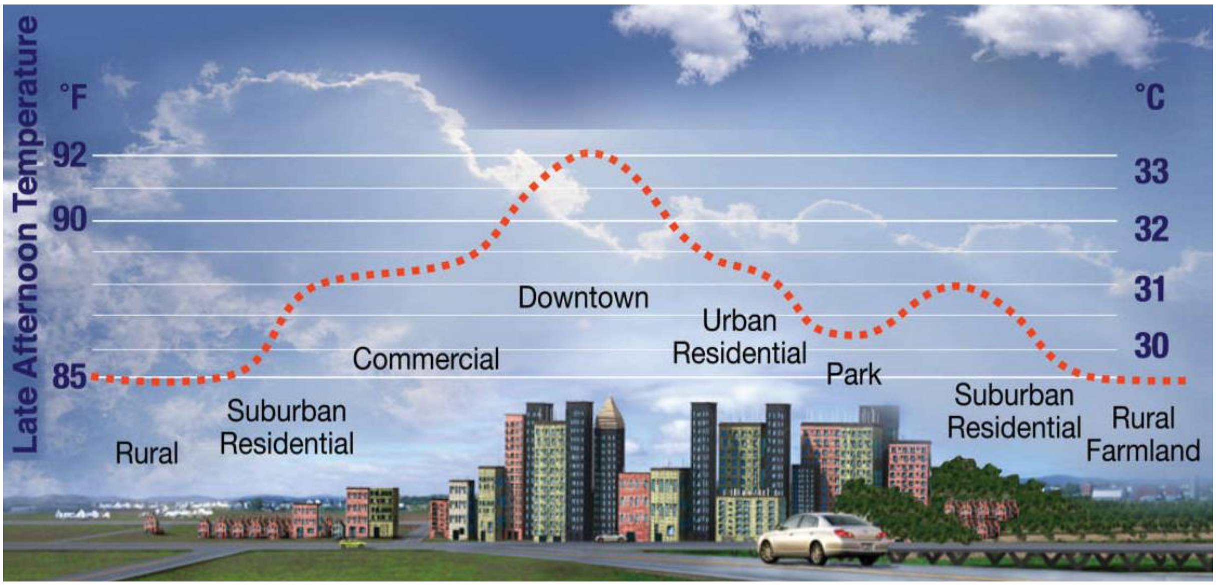
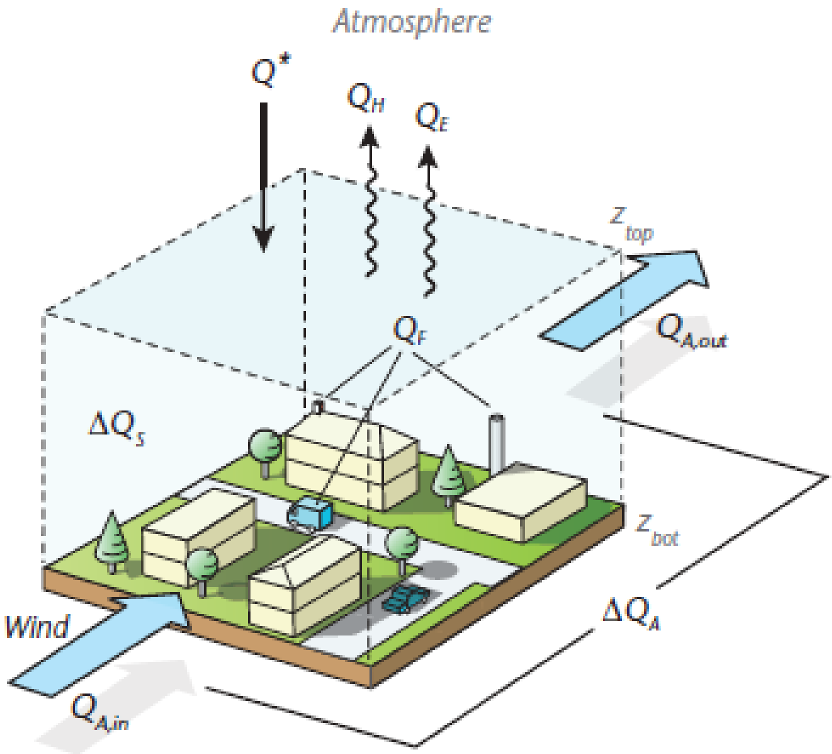


Figure 121 : Temperature distribution over a city, (adapted from: ebook of Abstracts from the 5th International Conference on Countermeasures to Urban Heat Islands, Hyderabad, 2019)

Important phenomena on this scale are sensible heat gains from buildings and processes. These processes are related to buildings (industry etc.) but also heat gains from transportation.

Latent heat exchange also takes place with evaporation/condensation at water surfaces (lakes, rivers, sea) but also with vegetation.



$$Q^* + Q_F = Q_H + Q_E + \Delta Q_S + \Delta Q_A$$

Figure 122 : Energy balance on the neighbourhood/city scale [126]

[126] T. R. Oke, G. Mills, A. Christen, and J. A. Voogt, Urban climates. Cambridge University Press, 2017

2.8.4 WEATHER CONDITIONS CONSIDERING FUTURE CLIMATE SCENARIOS

In recent research (Meteonorm[21], Jentsch[127]), methodologies for building weather files for the future periods have been and are still being analysed and built. This last aspect will also affect results of energy related simulation of buildings and their systems.

The methodologies are not described here in detail but especially for buildings and energy systems with a high lifetime (e.g., district heating and cooling networks, geothermal, …) these future scenarios will have a significant impact on energy consumptions.

2.9 OCCUPANTS AND EQUIPMENT

As for the previous paragraph, the development of models of occupants and equipment is not in the scope of this work since it is an entire research topic itself. For the simulation of energy systems, it has nevertheless a major impact and is currently and will be topic of future research. This paragraph summarises different aspects and the approaches that have been developed to model them.

Considering occupants and equipment in energy system related simulations is linked to two main aspects:

- Heat gains (sensible and latent):

  Any occupant emits heat due to his physical activity. Depending on this activity the heat gain to the building zone can vary between about 115 W (seated at rest) and 440 W (heavy work) as described in CIBSE Guide A, Section 6 (total heat gains, sensible plus latent). During the day, all occupants change their activity several times (*Figure **123*** bottom). Equipment is also launched either by occupants or from programmed schedules and are thus not constant with time.

  In the past, heat gains from occupants and equipment have, in most cases, been modelled as using typical occupant profiles with hourly and seasonal variations, as deterministic profiles. However, the real stochastic behaviour of occupant presence and activity has only been introduced in more recent developments (No-Mass[128]). These profiles have been validated against measurement in housing and office buildings and results show a huge variation in heat gains, depending on many parameters (Gay[129]).

  It is thus, on the one hand, important to consider these aspects in simulations, but on the other hand this brings additional difficulties since the choice of an occupant model will also affect results (e.g., impact of the type of occupants on the analysis of an energy system).

- Occupant actions:

  Occupant actions are meant in this paragraph as the response of an occupant to disturbances, mainly temperature and humidity change, but also illuminance (and more in general, any aspect of occupant comfort). Typical actions are set point changes (heating and/or cooling), blind control (both for heat gains but also illuminance control) or window opening (hygienic and thermal comfort related).

  These actions are even more difficult to model than heat gains (and also with a much higher impact on simulation results), since occupant actions depend on a large variety of parameters such as age, sex, social status, climate and many more. For example, while one

[127] M. F. Jentsch, P. A. James, L. Bourikas, and A. S. Bahaj, "Transforming existing weather data for worldwide locations to enable energy and building performance simulation under future climates," Renewable Energy, vol. 55, pp. 514 – 524, 2013
[128] Chapman J, Siebers PO & Robinson D (2018) On the multi-agent stochastic simulation of occupants in buildings. Journal of Building Performance Simulation, 11(5), 604-621
[129] Low carbon district –Energy and behaviour modelling, C. Gay, P. Schetelat, Proceedings of the 4th Workshop organised by the EEB Data Models Community ICT for Sustainable Places. Nice, France, 9th-11th September, 2013

occupant will increase the set point for the heating system when he feels uncomfortable, another occupant might only put on additional clothing to be comfortable. As a result, in one case the heating system has to react to guarantee comfortable conditions, in the other one the occupant will adapt to the changing conditions. Obviously, this type of actions exists for many other phenomena such as window opening, blind positioning, or others. In many cases there will also take place a negotiation between several occupants to take decisions.

The resulting profiles and actions are non-deterministic, against the traditional approach in system simulation to use deterministic models.

This field of research is huge and the development of appropriate and validated models is an enormous and challenging field of work.

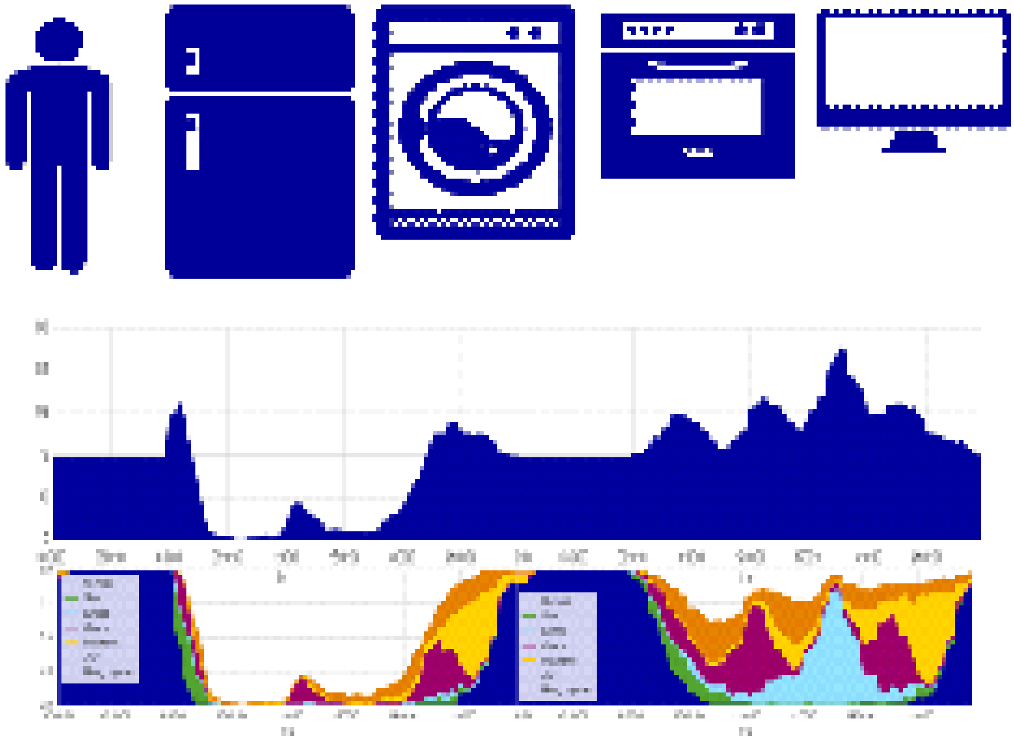


Figure 123 : Example of occupant and equipment activity (bottom) and resulting heat gains (middle)

The objective in this report is only to point out the necessity to decide whether a deterministic or stochastic model suit better to the simulation objectives. And this decision is not an easy task since occupants' actions have to be modelled. In most cases the most ensuring variant would be a parametric study for different occupant behaviours, but this will not be possible in emulation tests that run in real time. A single model approach has thus to be chosen for these cases.

In the recent past, simulations of energy systems related to the energy flexibility are increasing. In these cases, especially on the building level, stochastic methods seem to be more appropriate since the reflect better the realistic behaviour of occupants and the real impact of flexibility actions.

For the evaluation of the performance of an energy system on the other hand, deterministic approaches seem more suitable.

3. GENERAL CONSIDERATIONS FOR AN APPROPRIATE MODEL CHOICE FOR SIMULATION AND EMULATION

As shown in the previous paragraphs of this chapter, the modelling of an energy system in buildings or districts requires many decisions on the modelling approach and the necessity for the choice of “appropriate” models that fit with the simulation objectives. Besides, the modeller has to ensure the quality of the results by using validated models or tools, for the specific simulation objective, or by validating them for this purpose.

In almost all cases, decisions are taken following previous experiences, other simulation studies and easily available models in the selected tools. This approach is “normal”, since the effort to ensure completely the adequacy between the simulation objectives, the energy system and the chosen modelling approach would be extremely high.

Recently, Garreau et al[130] presented a first phase in the development of a method for parsimonious modelling, applied to the simulation of district energy simulation. The author showed a first application to solar shading calculation which shall, in a second phase, be extended to other phenomena. The method is divided into 7 steps that allow to generalise the approach also to other phenomena and objectives:

- Step 1: Literature review and selection of models
- Step 2: Definition of key comparison indicators (KCI)
- Step 3: Selection of representative districts
- Step 4: Definition of model selection criteria
- Step 5: Simulation and analysis
- Step 6: Sensitivity and uncertainty analysis
- Step 7: Concatenation of sub-families

Although the method has been presented for districts, it could be adapted and generalised to a single building, any energy system and with different objectives.

However, it remains still an open question on how to fix a threshold that allows to select the minimum level of detail of the model(s) that allows to ensure the “correct” results. This last point could be analysed easily using brute force in comparing all combinations of models on a given project with given objectives. The most detailed modelling represents the reference results and a threshold on the final KPI’s (and not intermediate results) could give an explicit answer. But this would again explode the necessary effort for a simulation study.

The general tendency today is to use tools and models with probably a too high level of detail compared to the quality and availability of input data. This choice is obviously better than to use models with low level of detail. However, in some cases, the use of too detailed models might lead to less accurate results since some influent parameters could be missing for the input. The only way to get on the safe side is to apply a sensitivity analysis in order to present a range of results instead of a single result.

[130] Urban-Scale Energy Simulation: A Development Of A Novel Method For Parsimonious Modelling – The Example Of Solar Shading Model Calculation, Enora Garreau, Thomas Berthou, Bruno Duplessis, Vincent Partenay, Dominique Marchio. BS2019, Sep 2019, Rome, Italy. hal-02393146

CHAPTER IV

APPLICATIONS OF NUMERICAL SIMULATION AND EMULATION FOR THE IMPROVEMENT OF THE PERFORMANCES OF ENERGY SYSTEMS

This chapter presents examples of projects or studies that illustrate the use of modelling and simulation related to conception and operation of energy systems in buildings and districts as well on their application to develop emulation test methods.

These examples shall illustrate the variety of use where modelling and simulation can be useful.

1. CONCEPTION OF BUILDINGS AND DISTRICTS INCLUDING THEIR ENERGY SYSTEM

1.1 IMPROVEMENT OF ENERGY EFFICIENCY OF HYDRONIC NETWORKS: OPTIMISATION OF DESIGN

This work has been done in the frame of a PHD[131]. It shows an application with thermo-hydronic modelling approaches.

1.1.1 PROJECT OBJECTIVES

Hydronic networks allow to easily distribute energy within a building or a district for heating, cooling or DHW services. However, if the conception, installation and commissioning are not carried out correctly, the energy cannot be delivered as it planned. The main questions related to the quality of energy delivery are the correction conception of network layout and related sizing issues (e.g., tube sections, pump and valve choices etc.) and, in the commissioning phase the correct balancing of the hydronic network. In this work, numerical simulation has been applied to analyse the impact of good and bad choices and methods on the quality of heating and cooling supply as well as on energy consumption.

Key performance criteria used:

In this study, several criteria have been applied which are occupant thermal comfort, final energy consumptions as well as investment and operation costs.

1.1.2 DETAILS ON MODELLING APPROACH AND CHOICE

Model needs and specifications:

The models that were necessary to allow the correct analysis had to include the following characteristics:

- thermo-hydronic behaviour (pressure and temperature calculation within the networks)
- thermal transients for control strategies (detailed models with a nodal approach that allow to represent fluid delays and time constants have been applied)
- pressure calculation to solve real flow through the networks

Model selection:

No method, intuitive choice and validation

Model validation:

1) Inter-model comparison for individual component models.
2) Experimental validation on a test bench for complete network model validation

[131] Nicolas Couillaud. Amélioration de l'efficacité énergétique des réseaux hydrauliques : optimisation de la conception, PhD thesis, CSTB/Université de Marle-la Vallée, December 2006

1.1.3 KEY RESULTS

The aim of this work was to evaluate different hydronic balancing methods and variable speed pump control strategies. The assessment criteria used are thermal comfort of occupants, energy consumption, global costs and quality of control strategies.

The development of the simulator of hydronic networks, systems and buildings has been based on the SIMBAD Building and HVAC Toolbox in Matlab/Simulink environment. These models as well as the whole model assembly have been successfully compared with experimental data from a real network (*Figure **124***) in order to validate the tool.

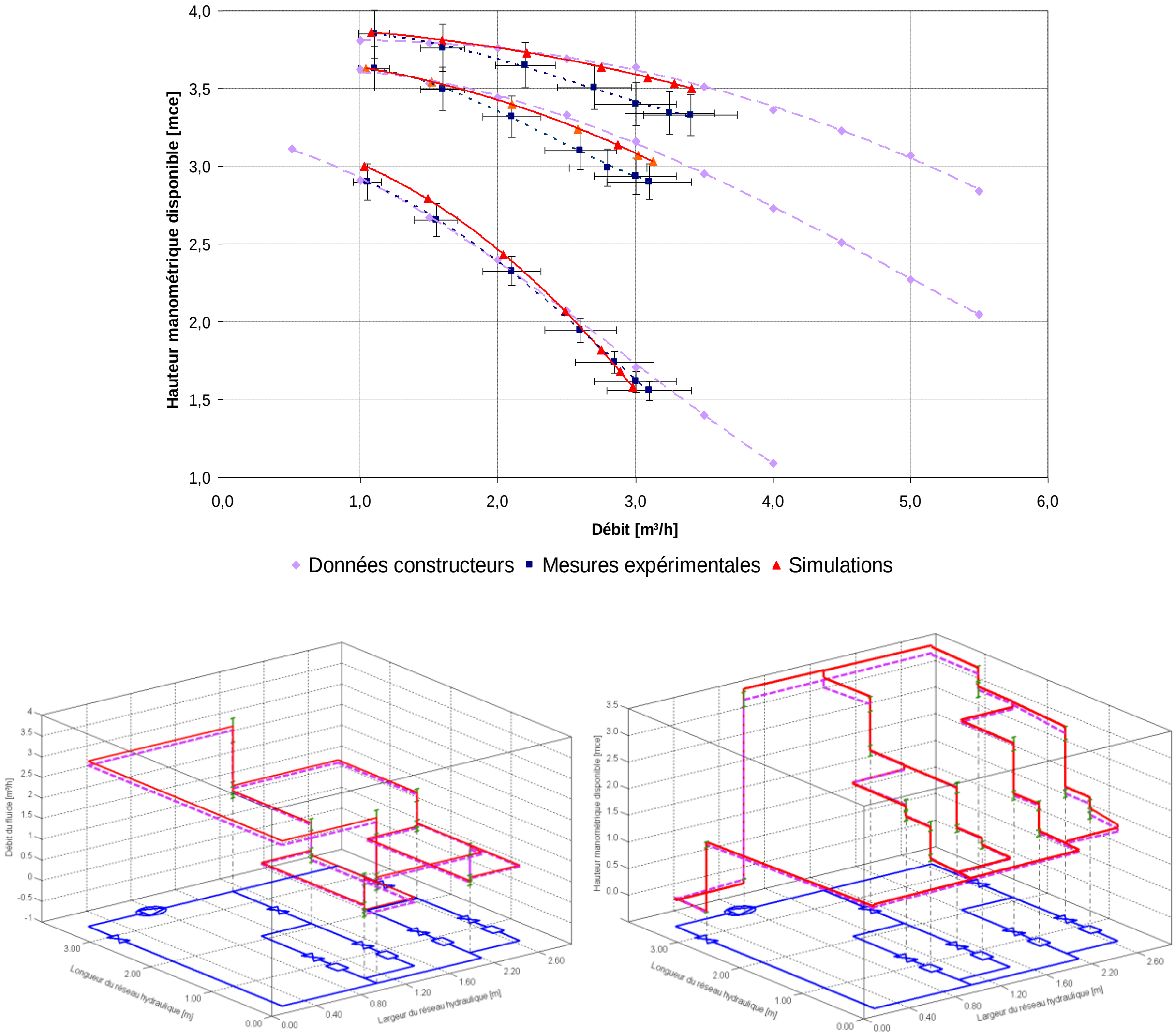


Figure 124 : Validation of network model against measurement (top: pump model; left: flow rates; right: pressure)

In the main part of the work, an installation of a tertiary building located in Trappes, France has been analysed. Annual simulations have allowed to evaluate the impact of hydronic balancing and pump control algorithms in terms of thermal comfort, global cost, energy consumptions and quality of control. An optimisation of the design is also proposed and analysed according to the same criteria (*Figure **125***). The complete procedure has been simulated in order to ensure the correction operation of the method. Besides giving advice for the application of the method in practice, it has also been fully implemented in the SIMBAD toolbox.

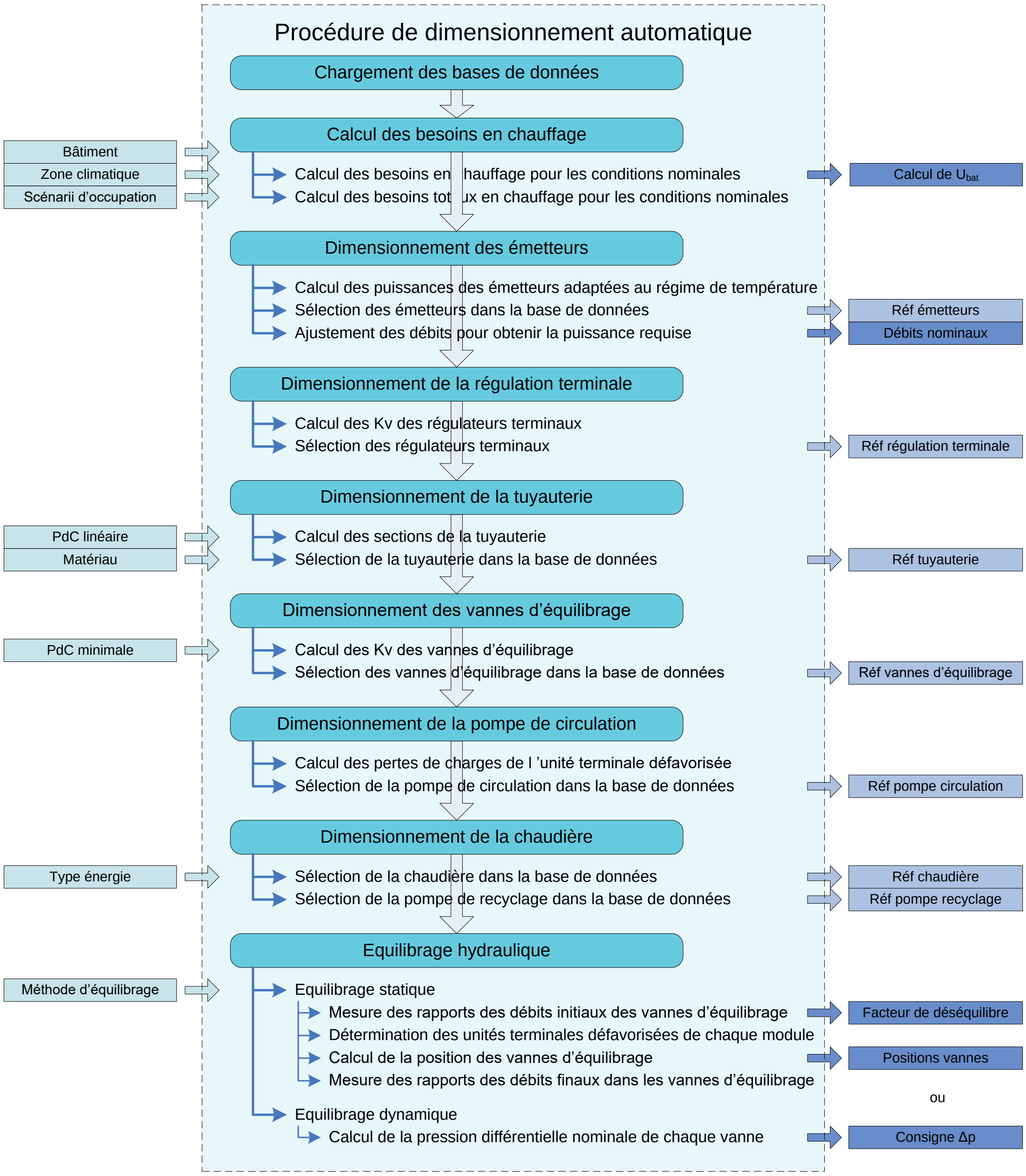


Figure 125 : Generic procedure for network conception, sizing and balancing (validated using numerical simulation)

This work highlighted the importance of hydronic balancing to improve thermal comfort in buildings zones by admitting an increase of the global cost compared to an unbalanced heating system. The use of variable speed pumps reduces significantly energy consumption of circulation pumps. The optimisation of the design allows to reduce the unbalance of small hydronic networks without decreasing thermal comfort. The components of hydronic balancing are then reserved to balance the small hydronic networks between them.

1.2 OPTIMISED DESIGN OF LOW ENERGY BUILDINGS

This work has been carried out in the frame of a PhD project[132]. It has been chosen here since it gives an additional use of numerical simulation: to build reference results for the construction of a meta model.

1.2.1 PROJECT OBJECTIVES

This work allowed to develop a methodology that can be used for the optimal design of low energy buildings. The methodology consists of combining a numerical simulation tool and the design of experiments method (DOE) to develop polynomial models that allow the evaluation of the energy efficiency and summer thermal comfort of buildings. The advantage of using polynomial models is that numerical simulation tools with long calculation time can be avoided. Instead, the use of polynomial models guarantees to find appropriate solutions to reach a low energy building level. The methodology is used to improve the energy efficiency of a small office building, called Beethoven, in order to get to a low energy building with respect to the French climate context.

Key performance criteria used:

Energy consumption, thermal comfort, costs

1.2.2 DETAILS ON MODELLING APPROACH AND CHOICE

Model needs and specifications:

Since the aim was to generate a meta model of a building including its energy systems, a rather detailed modelling approach has been adopted for the reference tool. The SIMBAD Toolbox with transient system models has been chosen. A time step of 5 minutes has been used to catch control related phenomena.

Model selection:

No method, intuitive choice.

Model validation:

Inter model comparison for newly implemented or developed models.

1.2.3 KEY RESULTS

In a first step of this work, the SIMBAD toolbox model library has been enlarged with component models for low energy buildings. These models have been compared with those available in other tools.

Typical French office building characteristics as well as possible system configurations have been constructed after a preliminary analysis. These reference characteristics were then considered as reference configuration to evaluate the energy efficiency improvements of the low energy office building using the developed methodology. The study has been carried out on eight climate zones defined by the French thermal regulation. The eight zones have then been reduced to 3 representative zones that have been judged sufficient for the next steps.

The key part of this work deals with the development of the most suitable meta model using DOE. The potential and limits of the design of experiments method to model the building energy efficiency and thermal comfort via polynomial models are discussed.

[132] Fadi Chlela, Développement d'une méthodologie de conception de bâtiments à basse consommation d'énergie, PhD thesis, CSTB / Université de la Rochelle, février 2008

An application strategy of the design of experiments method in the framework of low energy building numerical design studies is then presented.

Finally, the meta models are used to optimize the office building envelope and HVAC systems characteristics in order to get to a low energy building with respect to the guidelines of the French label Effinergie and the German label Passivhaus. The low energy office is compared to the reference configuration in terms of energy consumption, summer thermal comfort and CO2 emissions.

The main advantage of the developed methodology is the simplification of the parametric study to find out solutions to improve the energy efficiency of buildings, by performing graphical diagrams for solutions selection. The methodology results show satisfying agreement with the numerical simulation results. Thus, it could be used to develop design tools for low energy buildings.

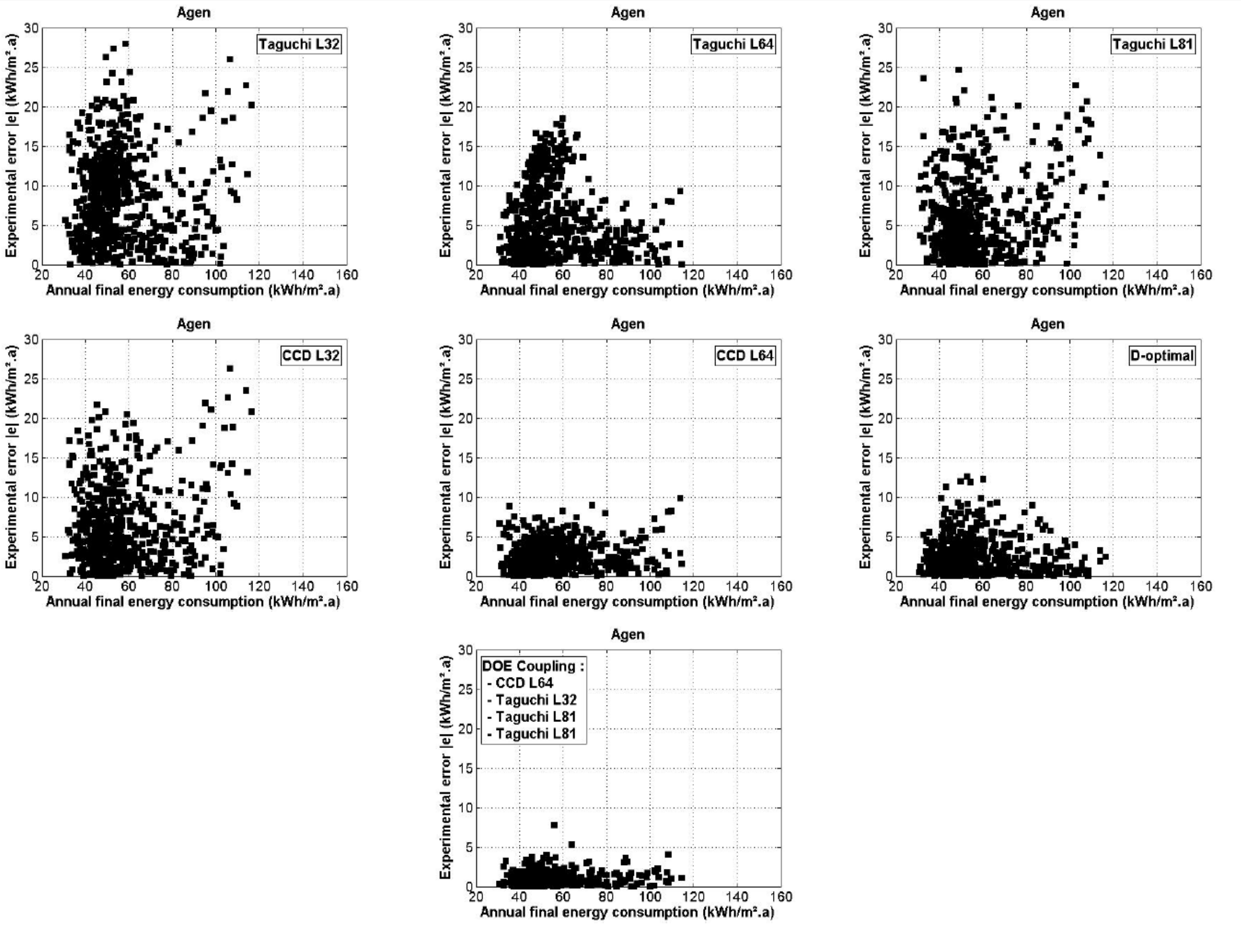


Figure 126 : Absolute errors using different approaches of the final annual energy consumption for the city of Agen

1.3 OPTIMISATION OF HEAT PUMP PERFORMANCES BY INJECTION OF IMPROVED BOREHOLE FILLINGS

This study has been carried out within the European Messib project[133] and has been published in a paper[134].

1.3.1 PROJECT OBJECTIVES

The European Messib project has dealt with several energy storage technologies. One of these technologies was related to underground heat storage. While this type of storage is relatively well known, an innovative approach has been developed and tested in the frame of this project. The idea was to use an improved borehole filling (called CFM, conductive fluid matrix) to decrease the thermal resistance between the water in the pipes and the ground.

When the borehole is filled, depending on ground characteristics (mainly porosity), the borehole filling penetrates sidewards into the ground. In the project, the CFM was injected with higher pressure in order to facilitate the penetration of the highly conductive filling into the ground (*Figure* ***127***).

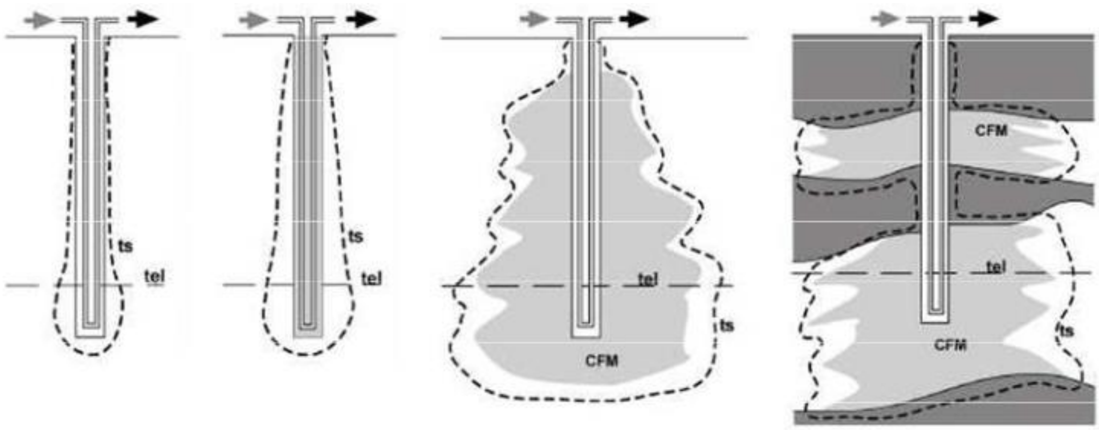


Figure 127 : Messib solution for underground energy storage (left 1-2: state of the art; right 3-4: Messib CFM)

While the solution has been studied in measurement campaigns, a numerical study was necessary to extrapolate results to other buildings, climates, ground characteristics and injection radius of CFM.

Key performance criteria used:

Energy consumption and heat pump performances (heating season, cooling season and annual).

1.3.2 DETAILS ON MODELLING APPROACH AND CHOICE

Model needs and specifications:

The SIMBAD toolbox has been used for this numerical study using a transient, 3-D finite-difference model of the borehole or borehole field. This model has allowed to simulate thermal behaviour in the ground for different CFM injection radius and ground types.

The discretisation of the model is automatically refined around the boreholes in order to correctly represent heat exchange and transient behaviour of borehole drilling and ground.

Only conductive phenomena have been modelled since the CFM matrix is assumed to fill the ground porosity and block underground water flow.

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[133] Multi-source Energy Storage System Integrated in Buildings (MESSIB), NMP2-LA-2008-211624, Grant Agreement Number 211624, coordinator: ACCIONA, 2008, 48 months

[134] S. Pincemin, V. Partenay, P. Riederer (2011). Optimisation des performances d'un champ de sonde par injection de coulis à haute performance thermique. Congrès Français de Thermique 2001, Société Française de Thermique SFT, 2011

Model selection:

For the underground storage, mainly based on the project requirements: 3-D transient model. All other models (building and system) have been chosen as state of the art of available modelling techniques.

Model validation:

The building and system models from the SIMBAD toolbox have been validated in several projects. The 3-D borehole field model has been developed and validated against measurement and by inter model comparison, in a separate PhD project[135].

1.3.3 KEY RESULTS

As stated before, the study has covered several key parameters: 8 climatic zones, 3 ground conductivities and 3 different injection radiuses.

*Figure **128*** clearly illustrates the impact of CFM injection for low ground conductivities (1W/m/K). In these cases, an injection radius of 1-2 meters is sufficient to improve system performances. In the case of higher ground conductivities and injection radius, the additional gain is negligible.

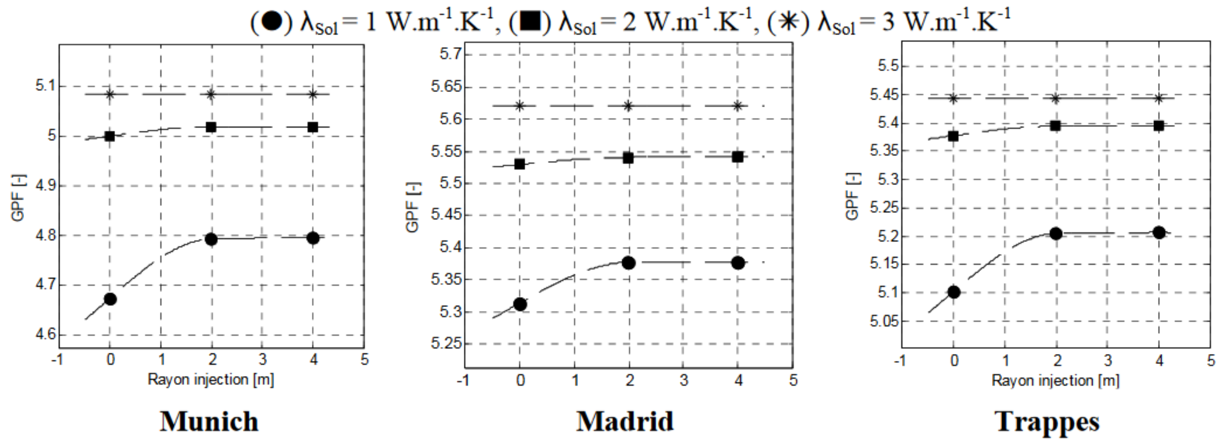

Figure 128 : Global performance factor of CFM injection depending on ground conductivity and injection radius

*Table **8*** quantifies the simulated gain by CFM injection. It is in between 1-4% for a CFM conductivity of 3 W/m/K (against 2 for a standard filling). For a CFM conductivity of 5 W/m/K the resulting performance gain is between 2 and 6 % (with a maximum for the low ground conductivity).

Table 8: Impact of CFM injection on global performance factor of heat pump system

		λ_{CFM} [W.m^{-1}.K^{-1}]					
		3			5		
	λ_{Sol} [W.m^{-1}.K^{-1}]	1	2	3	1	2	3
ΔGPF [%]	Munich	3.88	2.26	1.97	6.01	3.25	2.66
	Madrid	2.10	1.14	1.39	3.07	1.99	1.88
	Trappes	3.10	1.95	1.76	4.83	2.79	2.37

[135] Vincent Partenay, Thèse de doctorat, "Développement d'une méthodologie d'évaluation des performances de systèmes de pompes à chaleur", CSTB / Ecole doctorale de l'Université de Savoie, October 2010

1.4 NUMERICAL STUDY OF PERFORMANCES OF WASTEWATER HEAT RECOVERY IN A DISTRICT WITH A HEAT SHARING NETWORK

This work has been carried out in the European H2020 Research project ReUseHeat [136]. The numerical study shows the aspect of validating a choice of conception of a district energy concept. This validation includes a parametric study that allows to ensure the performance and robustness of the solution even if many parameters of the simulation scene are uncertain.

1.4.1 PROJECT OBJECTIVES

The objective of the ReUseHeat project is to study concepts of heat recovery in districts. Different sources have been identified such as heat from metro tunnels, rejected heat in hospitals from cold generation, datacentres as well as heat from sewage. The latter source has been adopted by the City of Nice, France, in the Grand Arenas district (district including the airport of Nice) and simulated using numerical simulation.

The energy system of the Grand Arena district is composed by (*Figure **129*** and *Figure **130***):

- Wastewater as heat source (with a small seasonal temperature variation).
- Very low-temperature network (heat-sharing network),
- Thermo-refrigerating heat pump substations (heating, cooling and DHW production are possible, the network acts as buffer)

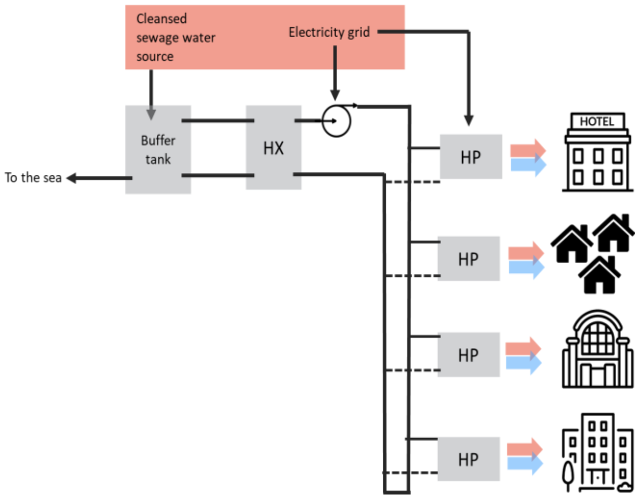

Figure 129 : Energy concept of the Grand Arenas project

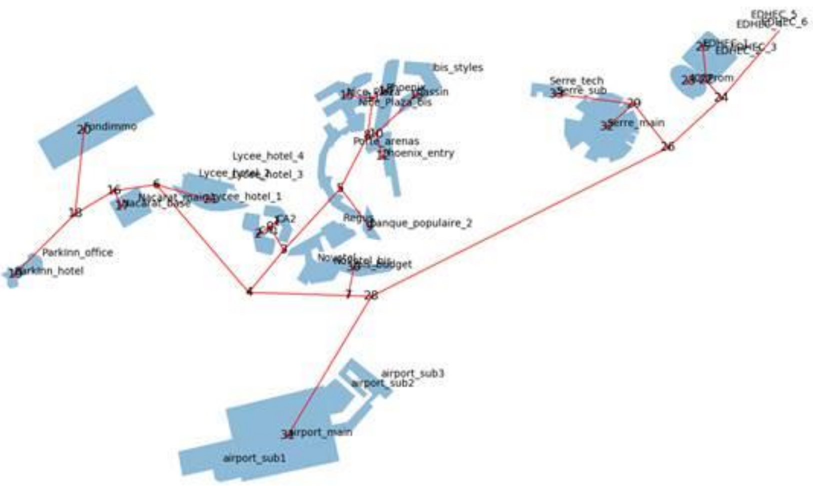

Figure 130 : Buildings and heat sharing network in the Grand Arenas project

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[136] Recovery of Urban Excess Heat (ReUseHeat), Europe (H2020-EE-2016-2017), grant agreement n° 767429, coordinator: IVL Svenska Miljoeinstitutet AB, 2017, 48 months

Key performance criteria used:

Performance criteria in the project have been final and primary energy consumption, occupant comfort as well as CO2 emissions.

1.4.2 DETAILS ON MODELLING APPROACH AND CHOICE

Model needs and specifications:

In this case of simulation, the tool must have the possibility to represent many phenomena of a district level. While it must handle many buildings and potentially building zones including the energy systems on zone and building level, it has also to allow to model the energy network on the district level. Additionally, it is important to consider solar masks and shading from other buildings, especially when the cooling season is analysed. The district simulation tool DIMOSIM[137] has been developed for this purpose and has been used in this project.

Model selection:

The DIMOSIM tool was the only choice possible for this project since it was the only tool able to consider all mentioned phenomena. Some additional models have been implemented (thermo-refrigerating heat pump, sewage temperature and flow model).

Model validation:

While DIMOSIM has been validated for several purposes in other projects (Bestest for building envelope, comparison with measurement data from real buildings and districts, etc.), the specifically built models have been compared against manufacturer data (heat pump) or fitted to measurement (sewage model).

1.4.3 KEY RESULTS

Key results of this study were to allow to provide a range of energy consumptions for heating, cooling and DHW production considering the high number of uncertainties of buildings in the district. Therefore, the following key parameters and ranges around the reference (reference in the sense of the probable value) have been used:

- Internal gains (-25% to +25%)
- U-values of opaque and transparent envelope (-20% to +20%)
- Window to wall area ratio (-10% to +10%)
- 2 different blind control strategies in summer

Figure ***131*** shows an example of result for the load variation in the district.

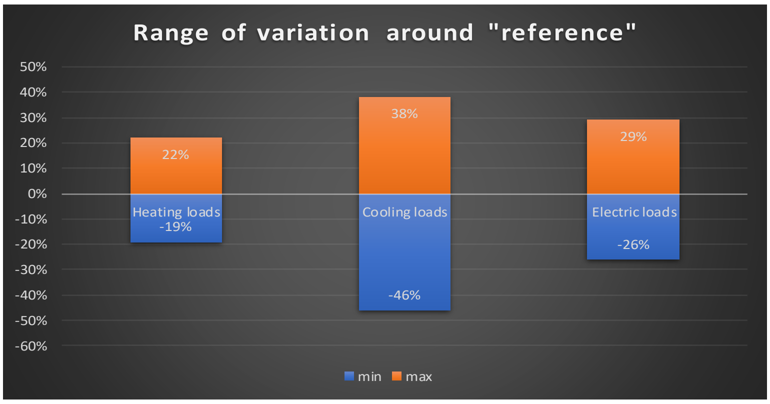

Figure 131 : Simulated variation of loads in the Grand Arenas district

[137] Riederer, P., Partenay, V., Perez, N., Nocito, C., Trigance, R., Guiot, T. (2015), Development of a simulation platform for the evaluation of district energy system performances, Fourteenth International IBPSA Conference, p.2499-2506

The result for the electricity load is plotted for one year in *Figure* ***132***. The scale is normalised to keep confidentiality. It is clearly visible that the given range of possible parameter values results in a high uncertainty of the global energy consumption. This is an interesting input for the local electricity supplier that has to ensure the delivery of electricity. The additional time series data is also interesting for peak load analysis.

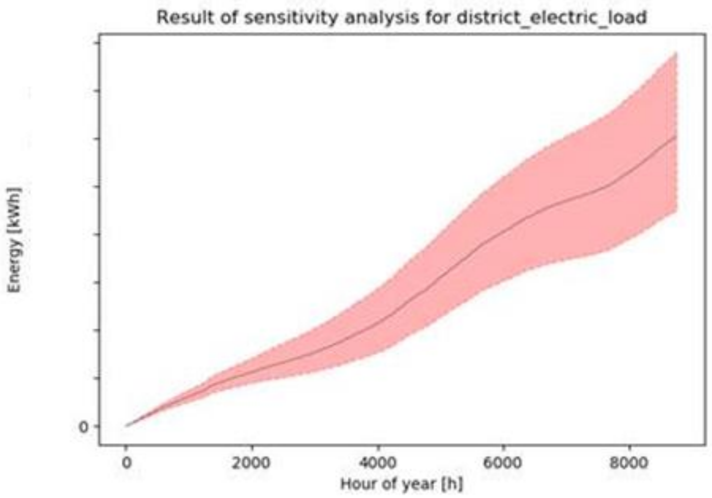

Figure 132 : Impact of parameter uncertainty on loads in the Grand Arenas project

The same analysis can be done for the thermal waste heat source. It is important to know, from the point of sewage treatment, to know resulting temperatures of sewage water for the treatment process or, in case of heat recovery after treatment station, the rejected water temperature to the sea. *Figure* ***133*** shows the minimum, average and maximum thermal power extracted or injected to the sewage water for a one-year period. The corresponding analysis of water temperatures, directly linked to this plot, allows to judge if the water temperature after heat recovery is practicable (e.g., there is a law in France for the maximum rejection temperature of water into the sea).

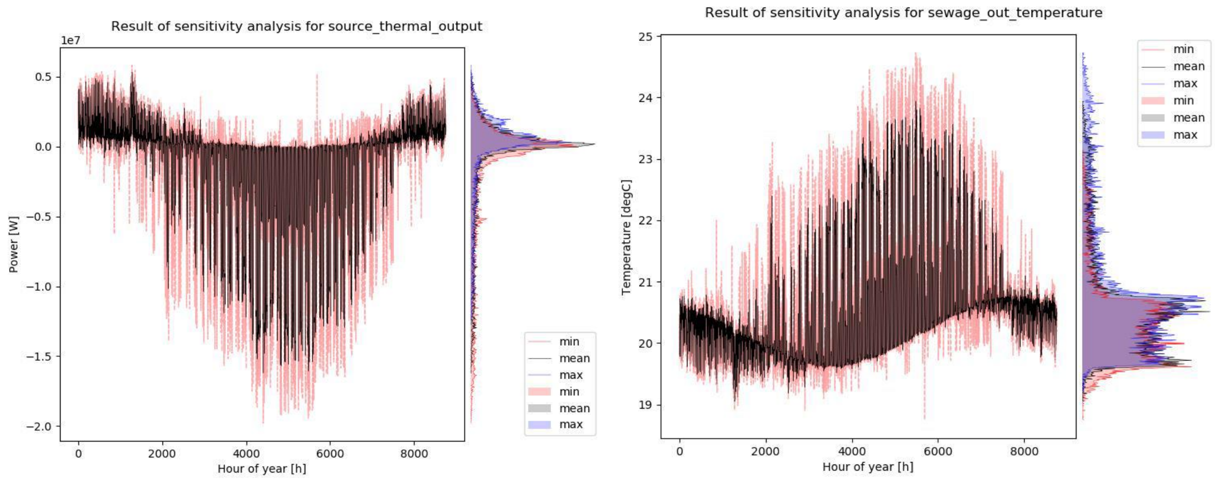

Figure 133 : Evolution of extracted or injected heat from wastewater (left) and temperature variation of wastewater rejected to the sea (right)

This type of simulations delivers thus key results for planners and energy utilities. To date, these actors have not such detailed tools available and work based on ratios. To adapt such a tool for these actors is thus a key in knowledge transfer from research to practice.

1.5 DEVELOPMENT OF A MULTI-OBJECTIVE OPTIMIZATION PROCEDURE DEDICATED TO THE DESIGN OF DISTRICT ENERGY CONCEPT

This work has been carried out in the frame of a PhD on the optimal conception of energy systems in districts[138].

1.5.1 PROJECT OBJECTIVES

The district scale offers significant potential for improving energy efficiency, particularly at the early stages of the design of energy concepts. A transversal approach for the optimisation of the energy concept of districts has been developed in this work. It was undertaken using the DIMOSIM simulation platform, which provides a detailed analysis of a configuration. The energy, economic and environmental aspects were combined to obtain the best overall performance. The multi-objective optimisation procedure is multi-level and includes direct search and the NSGA-II evolutionary algorithm to deal with the specificities of this problem. The search space contains continuous and discrete parameters, it is thus almost infinite, and the objective functions are non-linear. An optimization procedure has been developed to solve this complex problem. A case study on the design of an eco-district shall illustrate the possibilities offered by this type of approach to obtain the best design solutions.

Key performance criteria used:

Performance criteria in this project have been final and primary energy consumption, occupant comfort, CO2 emissions and costs.

1.5.2 DETAILS ON MODELLING APPROACH AND CHOICE

Model needs and specifications:

The DIMOSIM modelling and simulation platform was used in this work to allow the transient simulation of the physical behaviour of a district (i.e., buildings including all components of the energy system). It was developed using a Bottom-Up approach involving the independent and transient modelling of all technological components (e.g., building, emission, production, storage or networks). Furthermore, the adaptable level of detail of each physical model allows a wide range of studies covering construction, refurbishment and management.

Model selection:

The DIMOSIM tool[137] was the only choice possible for this project since it was the only tool able to consider all mentioned phenomena. A building zone model has additionally been implemented.

Model validation:

The implemented building model has been validated against other tools (TRNSYS)

1.5.3 KEY RESULTS

The optimisation of the global energy concept in a district is a very complex problem. A global optimisation strategy (*Figure **134***) has been suggested in this work. The strategy covers at the same time building envelope characteristics, renewable energy potential as well as energy system concepts in a step-by-step approach, facilitating to solve the optimisation problem.

The optimisation has used a multi-criterion objective function based on energy consumption, global costs, global warming potential (CO2).

Once the set of optimal solutions is determined following this approach (*Figure **135***), the selection of the preferential actions can be facilitated by the use of a new multicriteria analysis

[138] Nicolas Perez, Contribution à la conception énergétique de quartiers : simulation, optimisation et aide à la décision, PhD thesis, CSTB/Université de la Rochelle, October 2017

method which was developed within this work. The generalist outranking method, ATLAS (Assistance TooL for Decision Support to Assess and Sort), was developed to assist decision-making by providing a detailed assessment of the different district concepts.

The method has been compared to the brute force results in terms of speed and showed a gain of more than 96%. Without this method, the optimisation on this scale would be very difficult.

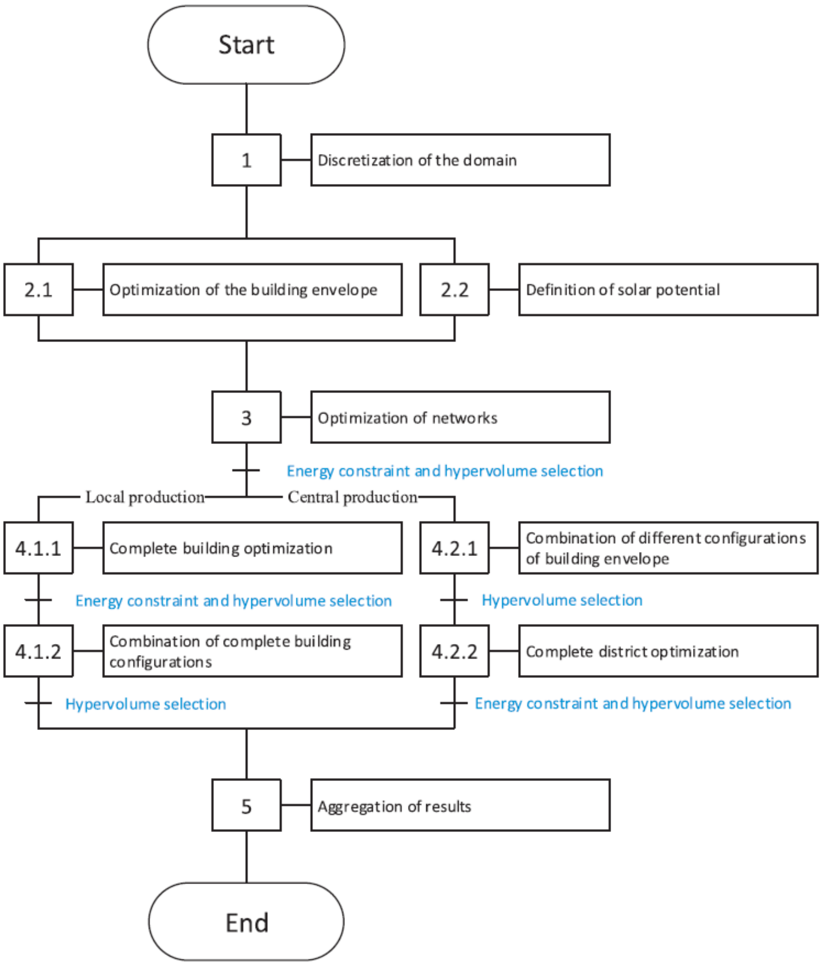

Figure 134 : Global optimisation procedure

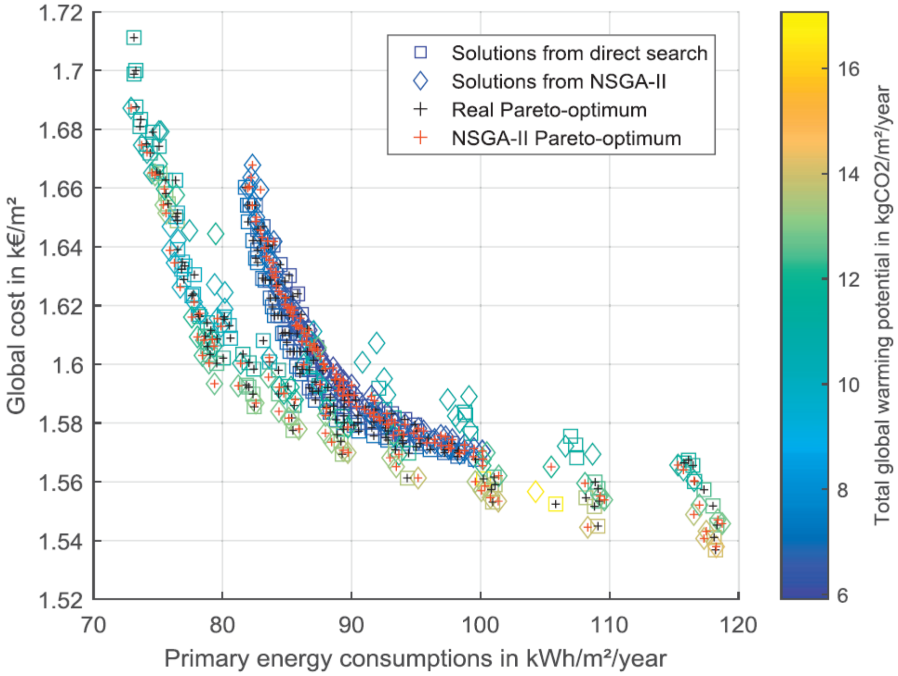

Figure 135 : Aggregated optimisation results after step 5 on a district use case

1.6 TOWARDS THE DEVELOPMENT OF A COUPLED MODEL FOR DISTRICT ENERGY SIMULATION

This work has been carried out in the frame of a PhD[139]. It is highlighted in this part to illustrate the reason and potential of software coupling and co-simulation as described in Chapter II.

1.6.1 PROJECT OBJECTIVES

In the recent past, climate change, combined with urban heat island and microclimate effects has become as serious challenge at the same time for the security of occupants and for the energy consumption in neighbourhoods.

The simulation platform Envibate[140] has been developed in order to provide a tool for the first challenge of thermal comfort and health within districts. It consists in a co-simulation platform of a reduced-order building model, an urban dispersion tool and a thermo-radiative numerical code, combined with a zonal modelling approach for air volumes around the buildings on a neighbourhood or district scale. On the other hand, the DIMOSIM tool[137] provides a powerful tool for energy systems and buildings in districts which allows to perfectly respond to questions of energy consumption and building indoor comfort.

The objective of the project has thus been to provide a global simulation suite, enabling the user to analyse UHI mitigation strategies and evaluate them in terms of health and energy consumption.

<u>Key performance criteria used:</u>

Outdoor occupant comfort, indoor occupant comfort, energy consumption and CO2 emissions.

1.6.2 DETAILS ON MODELLING APPROACH AND CHOICE

<u>Model needs and specifications:</u>

The main part of the PhD has dealt with identifying the most suitable coupling scheme between the tools in terms of accuracy and simulation speed. *Figure **136*** illustrates the coupling layout.

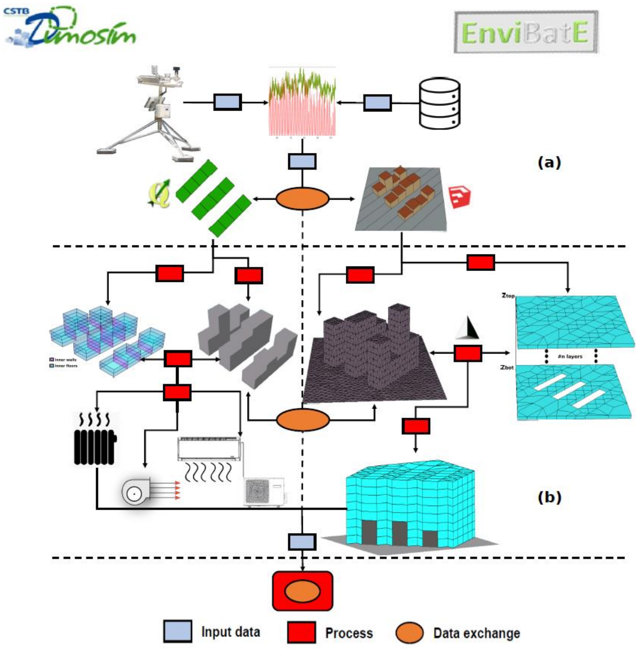

Figure 136 : Global coupling layout of the simulation suite

[139] Georgios Kyriakodis, Development of a coupled simulation tool for urban building energy demand, district energy systems and microclimate modelling, CSTB/Université de la Rochelle, PhD thesis, August 2020

[140] A. Gros, Modélisation de la demande énergétique des bâtiments à l'échelle d'un quartier. Phd thesis, University of La Rochelle, 2013

Model selection:

The work has focussed mainly on coupling of existing models and not on modelling of specific components.

Model validation:

The validation of the coupled simulation suite is for the moment restricted to the validation of individual components. The coupled platform has been validated qualitatively and an experimental validation or validation by tool comparison is planned in an ongoing PhD work.

1.6.3 KEY RESULTS

Different coupling strategies between the microclimate tool Envibate and the energy system tool DIMOSIM have been implemented and compared (online and offline coupling, different interface variables for coupling). An example of coupling is given in *Figure **137***. As shown on the left hand of the figure, the interface variables in this coupling strategy are the outdoor air temperatures (calculated in the Envibate tool) in which the heat fluxes (energy system, ventilation etc.) from the system tool DIMOSIM are injected into. The right-hand side of the figure illustrates the data exchange with synchronous (b) and asynchronous (a) time steps of both tools.

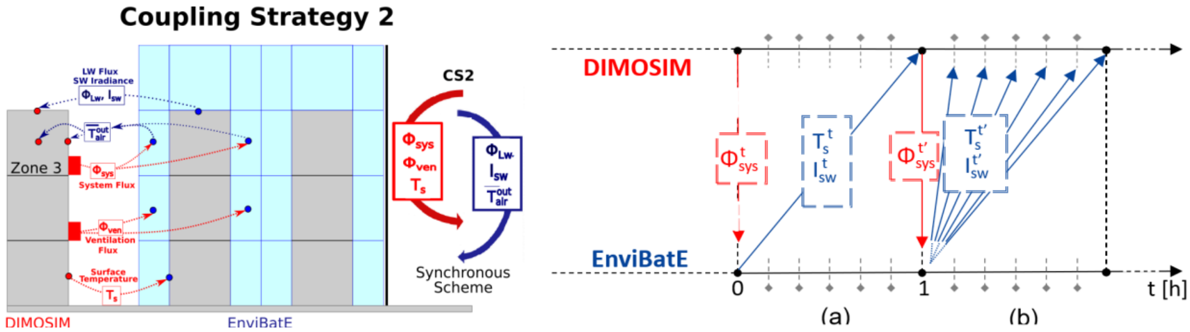

Figure 137 : Example of coupling strategy (left) and synchronisation of data exchange (right)

In terms of results of UHI studies, a large variety of results has been produced. An example is given in *Figure **138*** in which the impact of UHI effects is analysed for individual air conditioning systems (AC) and district cooling network (DEN). This example, for the case of La Rochelle shows more than 25% difference in cooling energy demand when UHI effects are considered.

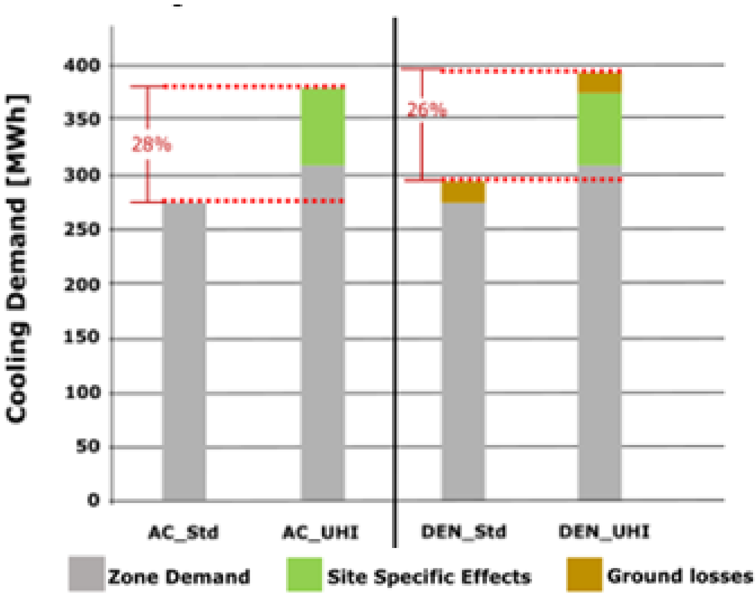

Figure 138 : Impact of UHI and microclimate on cooling demand (Std: Standard; UHI: Urban heat island effects) AC: air conditioners; DEN: District energy network

A very interesting result is shown in *Figure **139***. Is shows very clearly that, for wind speeds above 5 m/s, the air temperature deviation can almost be neglected (but not the radiant temperature!) while the deviation can be significant for low wind speeds, below 2 m/s.

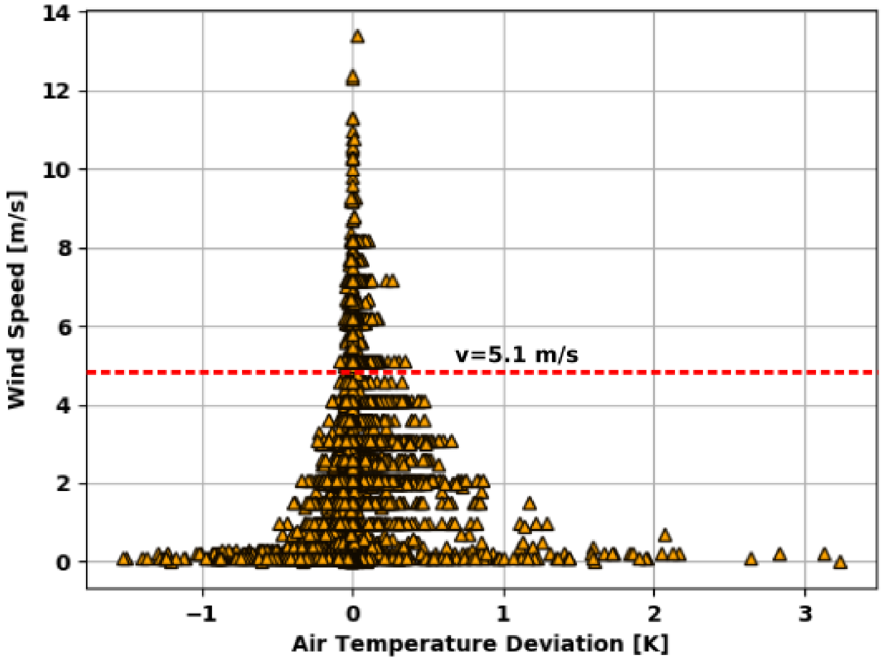

Figure 139 : Impact of wind speed on air temperature deviation in a neighbourhood

*Figure **140*** illustrates the evolution of heating and cooling demand in a district in La Rochelle. Besides a high impact on the scenarios on cooling loads, it clearly shows a different impact on heating loads, i.e., for example the air conditioning standard scenario is characterised by low cooling loads while at the same time it shows higher heating energy demand since the air conditioners reduce the temperature in the canyon.

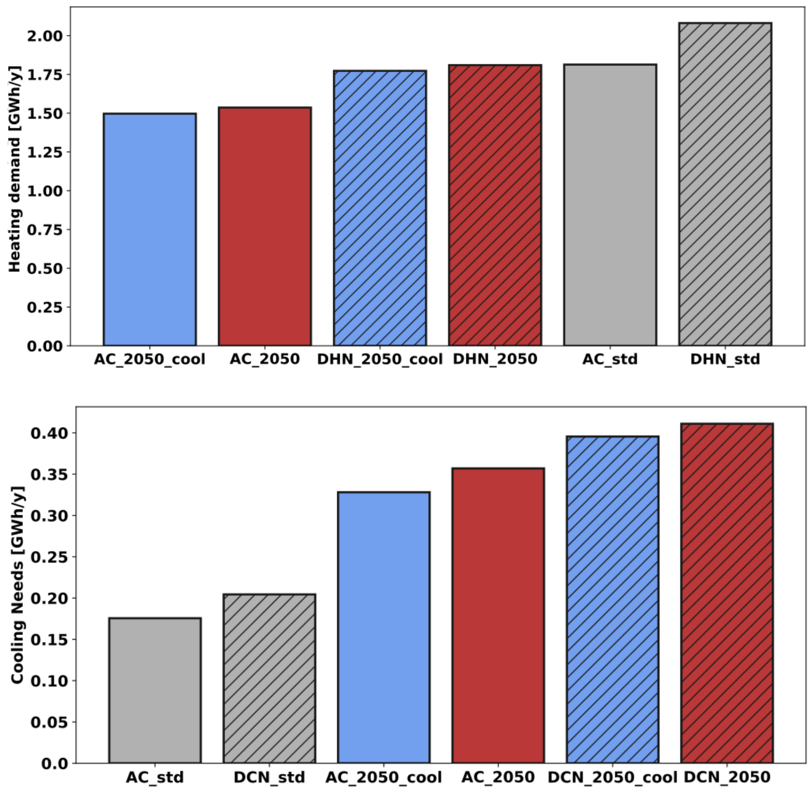

Figure 140 : Comparison of different scenarios implemented (top: heating demand; bottom: cooling demand)

2. CONTROL OF ENERGY SYSTEMS IN BUILDINGS AND DISTRICTS

2.1 IMPROVEMENT OF PERFORMANCES OF GEOTHERMAL HEAT PUMPS USING MODEL PRODICTIVE CONTROL

This work has been carried out in the frame of a PhD[141]. It provides an example of modelling suitable for control studies, in this case with predictive control assisted mainly by artificial network models. It also contains a co-simulation approach since TRNSYS (the building and energy system simulator) has been coupled to Matlab, the latter containing an artificial neural network (ANN) toolbox that has been used to build such a controller.

2.1.1 PROJECT OBJECTIVES

Ground source heat pumps connected to a floor heating system can offer high efficiency for heating and cooling. However, the inertia of the floor heating creates a thermal lag that can lead to discomfort and overconsumptions when conventional, reactive controllers are used. To overcome this problem, a neural predictive controller for single-speed ground source heat pumps systems was developed. The objective of the controller is to minimize the energy consumption and maintain a good comfort level anticipating the thermal behaviour of the building and external disturbances. A new neural network module for the heating power prediction of a single-speed ground source heat pumps system is proposed. The operation of the controller has been tested by simulation and emulation on a typical French dwelling during the month of March. In addition to an increase of comfort, numerical results showed that the predictive controller can provide up to 18% energy savings with the studied building in comparison with conventional controllers.

Key performance criteria used:

Final energy consumption, thermal occupant comfort.

2.1.2 DETAILS ON MODELLING APPROACH AND CHOICE

Model needs and specifications:

This study has focussed on a building equipped with a hydronic floor heating system. The best available model available to the authors at the date of the work was the built-in floor heating module in the Type 56 of the TRNSYS simulation environment[89]. The complete building and system model have therefore been chosen in TRNSYS. On the other hand, the ANN predictive model has been developed in Matlab environment, with its neural network toolbox. The modelling structure of the global project is shown in *Figure* ***141***.

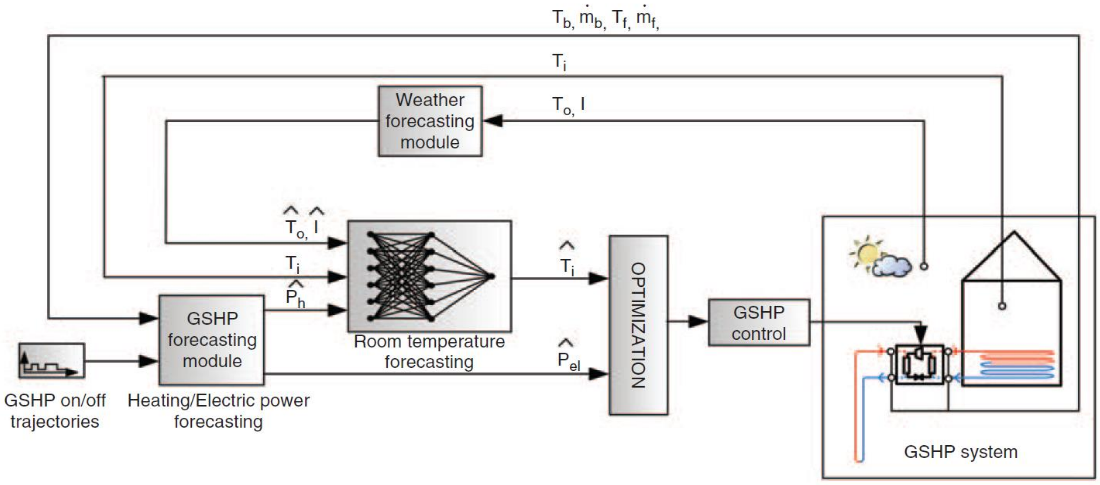

Figure 141 : Layout of the predictive controller linked to the energy system to be controlled

[141] Tristan Salque, Amélioration des performances de PAC géothermiques par couplage de mesures in-situ et de méthodes numériques inverses, PhD thesis, CSTB / Mines Paristech, October 2013

Model selection:

The most detailed models for building, floor heating and heat pump have been chosen since the simulation had to handle a control study with low time steps (15 minutes).

Model validation:

All models from the TRNSYS environment have been extensively validated by the TRNSYS simulation community. ANN prediction models have been validated against detailed models.

2.1.3 KEY RESULTS

To develop the method, a predictive controller for GSHP is elaborated. The controller is based on artificial neural networks used for the prediction of weather data and indoor temperature. A new module for the prediction of floor heating and boreholes fluid temperatures is also proposed. An example of validation of the neural network models is shown in *Figure **142***.

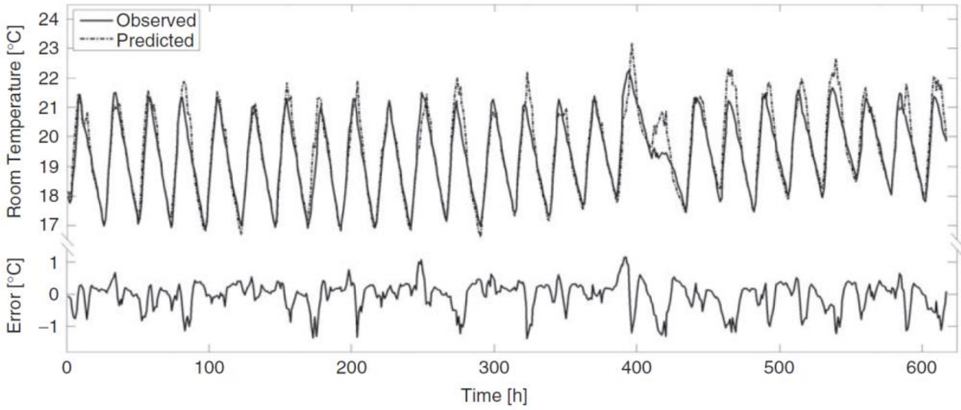

Figure 142 : Validation results of the global prediction model for the month of march (6 hours prediction horizon)

The ANN controller has then been compared with a close loop (CL) controller and a compensated open loop controller (COL) in two simulation cases, one with fixed set point and one with night set back (*Figure **143***).

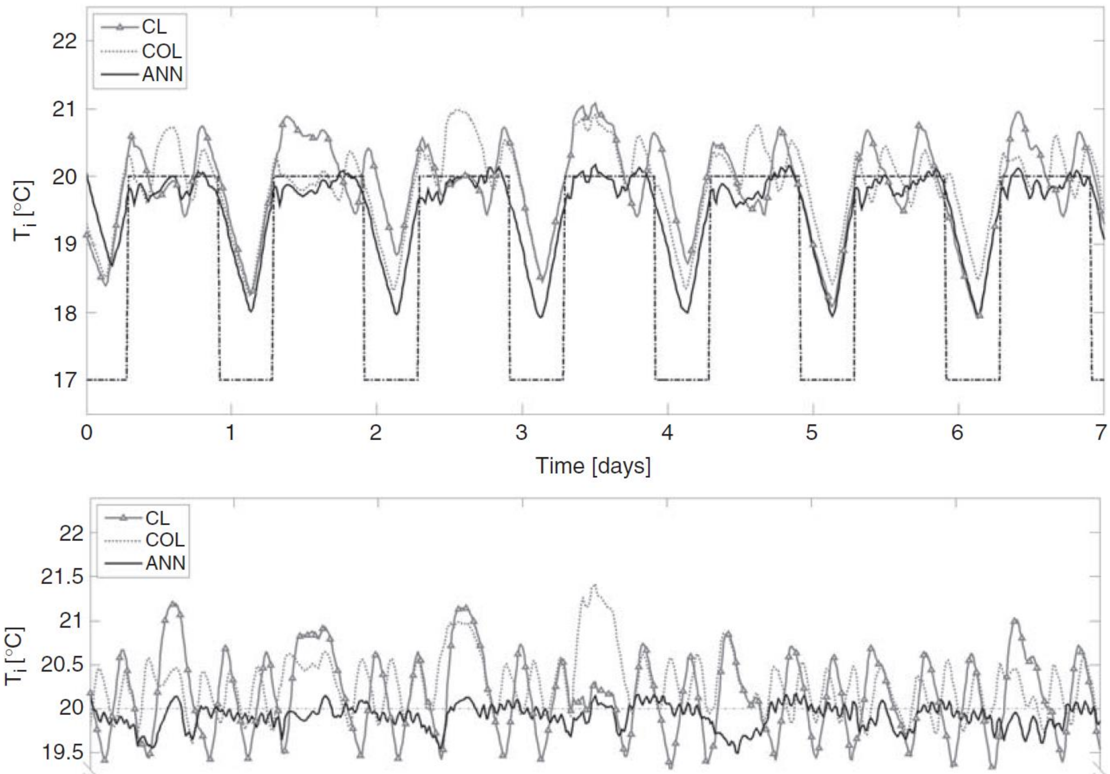

Figure 143 : ANN against typical open and closed loop controllers (top: scheduling; bottom: constant set point)

Even if the case with night set back is not typical for floor heating characterised by high thermal inertia, the ANN controller performs better in both cases. Overshoot of room temperature is reduced by factor of more than 2.

The predictive controller is tested by simulation and later emulation over a heating season for various climates and types of single-family house. The developed controller gives better results in terms of both, occupant comfort and energy consumption. According to the reference case, the energy savings vary between 6%-17% and 5-18% for fixed set point and night set back respectively. *Table **9*** summarises one of the simulation cases. Typical overheating of conventional controllers in the morning when solar radiation heats up the building rooms is almost completely avoided with the predictive controller (4 or 3 hours against 40/30 or 22/12 hours for fixed set point and night set back).

However, the average duration of heat pump cycles is reduced from 1.7 / 2.5 hours to 0.5 hours and from 3.1/2.1 hours to 0.8 hours (for fixed set point and night set back scenarios respectively), which has a negative impact on the lifetime of the heat pump compressor.

Table 9: Comparison of ANN and conventional controllers - March (top: fixed set point; bottom: night set back)

	Maximal overshoot (°C)	Maximal under-shoot (°C)	Over-heating duration $T_i > 21°C$	Under-heating duration $T_i < 19°C$	Average GSHP cycle duration (h)	Heating energy (kWh)	Compressor elec. energy (kWh)	Total elec. energy (kWh)	ANN total energy gain (%)
CL	2.17	0.74	40 h	0 h	2.5	1020	242	272	6
COL	2.15	0.52	30 h	0 h	1.7	999	237	309	17
ANN	1.11	0.78	4 h	0 h	0.5	981	227	256	-

	Maximal overshoot (°C)	Maximal under-shoot (°C)	Over-heating duration $T_i > 21°C$	Under-heating duration $T_i < 19°C$	Average GSHP cycle duration	Heating energy (kWh)	Compressor elec. energy (kWh)	Total elec. energy (kWh)	ANN total energy gain (%)
CL	2.28	0.80	22 h	0 h	3.1	976	230	259	5
COL	1.83	0.59	15 h	0 h	2.1	972	227	300	18
ANN	1.08	0.72	3 h	0 h	0.8	945	217	245	–

ANN: artificial neural networks; CL: closed loop; COP: compensated open loop

The number of compressor cycles is also illustrated in *Figure **144***. The price to pay for this ANN controller to perform better in terms of comfort and energy consumption lies in the number of cycles and, eventually, a reduced lifetime of the heat pump compressor.

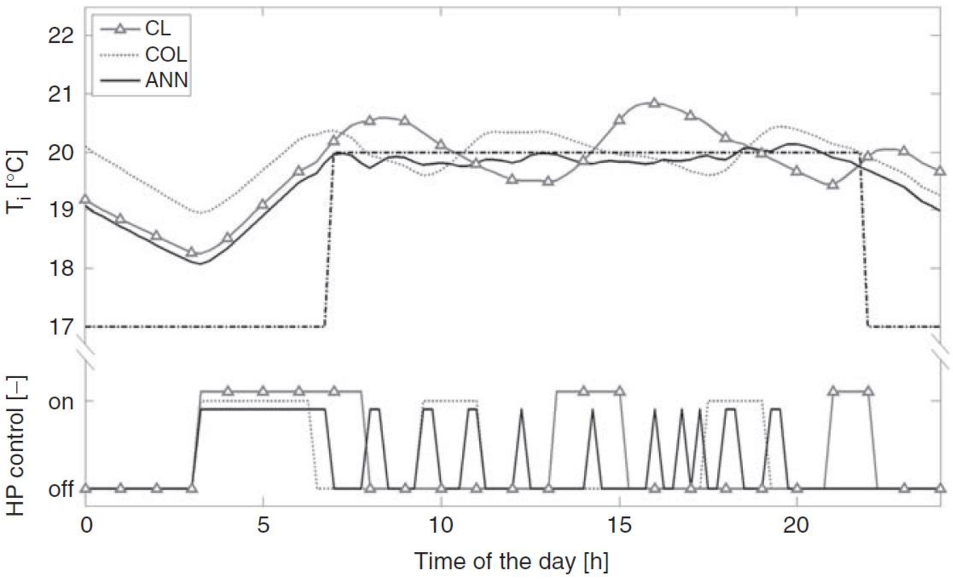

Figure 144 : Comparison of control strategies during one representative day in March

2.2 DEVELOPMENT AND EVALUATION OF ADVANCED CONTROL STRATEGIES FOR DISTRICT ENERGY SYSTEMS

This work has been object of the PhD[142]. The topic is interesting for this report since it illustrates the development, implementation of predictive models as well as the appropriate selection and use of a simulation environment for testing these advanced control strategies. Contrarily to the previous work presented, this work aims in developing a generic solution for optimising building or district energy management. It is thus thought more generic as the previous development.

2.2.1 PROJECT OBJECTIVES

The objective of this work was to develop a generic methodology for the optimisation of energy systems in buildings and districts. The methodology contains prediction models, implemented as a library of models, in a generic methodology for optimising energy systems.

Key performance criteria used:

Occupant comfort, energy costs and energy consumption.

2.2.2 DETAILS ON MODELLING APPROACH AND CHOICE

Model needs and specifications:

The generic optimisation method does not fix a type of model that has to be chosen. In this first stage of development, the use of physical models has been preferred since it allows to implement a complete methodology and the associated functionalities.

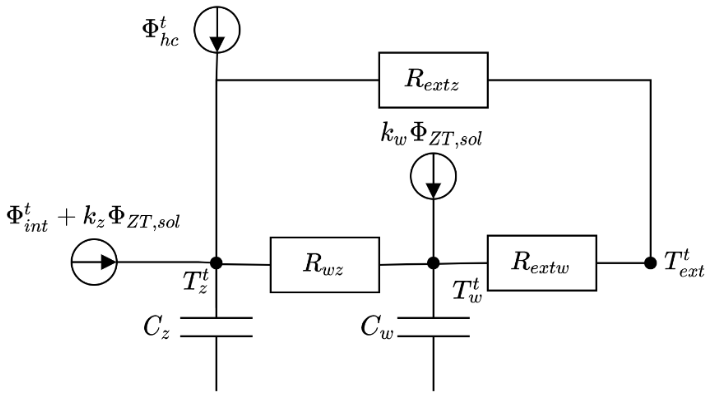

Figure 145 : Lumped parameter model for thermal zones implemented in the optimisation method

In fact, the use of physical models with states needs the identification of initial states as well as their update at each optimisation step. Since generally the used model for predictions in an optimisation routine are reduced order models, the states in the model do, in almost all cases, not correspond to real, measurable states. For example, the state of a wall temperature in a lumped zone model cannot be measured (and thus updated) since it corresponds to a virtual temperature that does not exist in practice. As a conclusion, reduced order physical models have been chosen for the prediction, but in many cases the use of black box models might be a better choice (see previous application).

Model selection:

As stated above, the choice of physical models has been preferred in this first development due to development issues. The modelling detail has been chosen arbitrarily in this case since the objective was mainly to develop a generic methodology for energy system operation optimisation. If this methodology is then used for real applications, the choice of modelling details is a key point for calculating optimal operation scenarios.

[142] Mathieu Brugeron, Méthodologie d'évaluation de produits ou algorithmes de gestion avancée au niveau du quartier, PhD thesis, CSTB/Université de Grenoble, June 2021

Model validation:

The reduced order models have been compared to detailed physical models. These models are widely used since the early beginning of computer simulation, the main aspect was in the development of a suitable calibration method that allows to identify the key parameters and initial states at the beginning of each new prediction.

2.2.3 KEY RESULTS

The methodology as shown in *Figure **146*** for the configuration phase (top) and the operation phase (bottom) has been implemented and tested. While the configuration phase allows to construct the complete system architecture of the energy system to be optimised from a configuration file (json or geojson), the global model is then applied for each optimisation procedure of a certain horizon (e.g., 6 hours) by delivering measured data from the past.

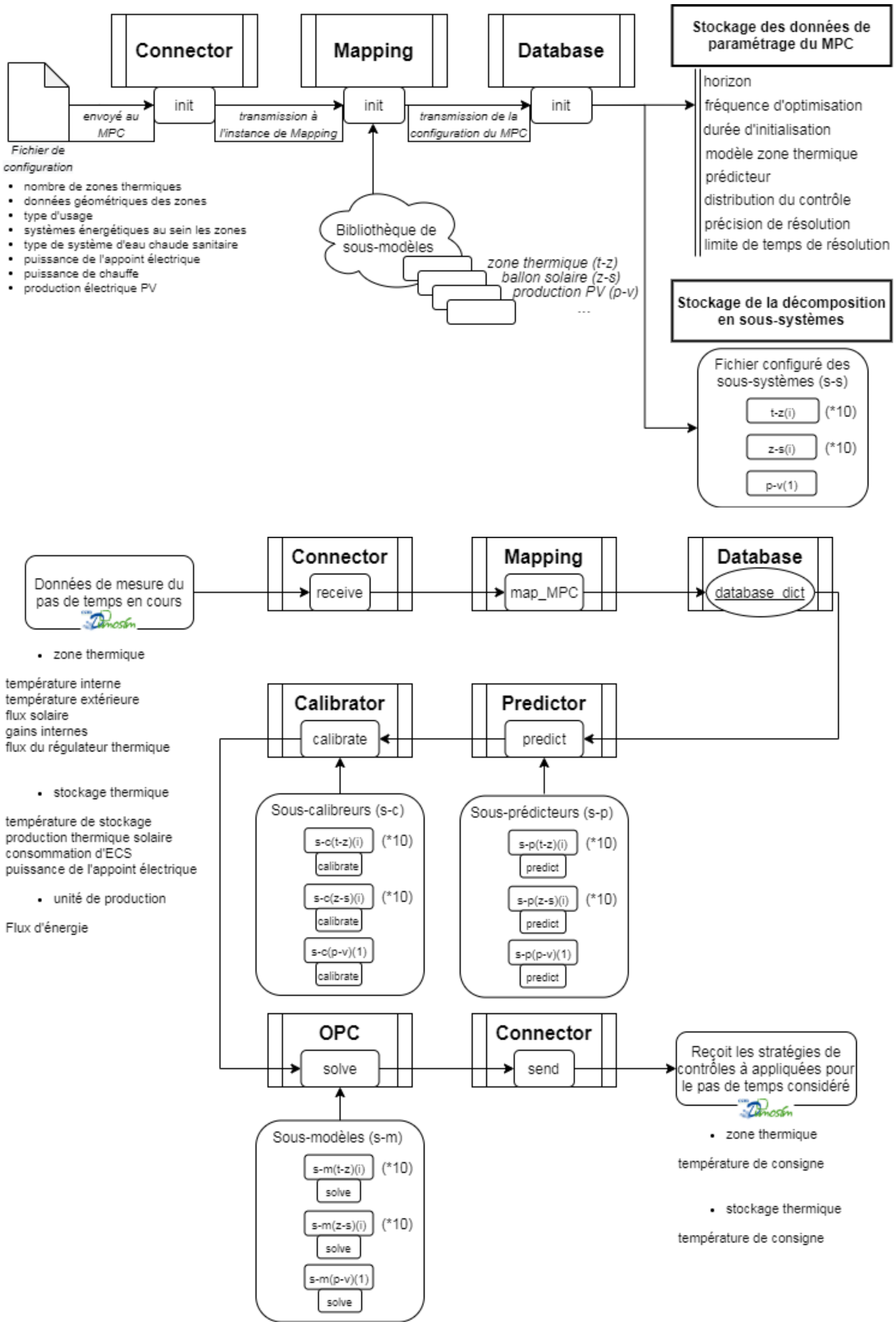

Figure 146 : Flowchart of configuration (top) and operation (bottom) phase of the optimal controller

As the architecture has been constructed in a generic way, the methodology allows to solve centralised and decentralised control strategies, which was one of the project objectives.

An example of application has been simulated on a small neighbourhood with 10 buildings. Each building, with 1 thermal zone, was equipped with an electrical heating system, an electric DHW production with storage and solar photovoltaic panels. The objective was to maximise self-consumption and to minimise energy consumption while ensuring occupant comfort related to space heating and available DHW temperature.

To illustrate the potential of the optimisation methodology, the problem had been solved using both a centralised and a decentralised optimisation strategy. The operation of the tool had so been proved and results could be compared for this simple example. The decentralised strategy has used a key for energy share between buildings (taken from the last horizon) in order to predict distribution of solar electricity and to split the problem into several sub problems.

Table ***10*** shows an example of decentralised control strategies that have been compared to classical, close loop control. 4 variants have been defined with two different levels of detail of model inputs called "detailed" and "sobre" (e.g., solar gains) as well as for a perfect (taken from weather and occupancy files) prediction of boundary conditions ("parfait") and a naive prediction ("naif") in which boundary conditions are those from the past prediction horizon.

Table 10: Comparison different optimisation strategies

	Contrôle Réactif	Parfait Détaillé	Parfait Sobre	Naif Détaillé	Naif Sobre
Indicateurs de performances économiques et énergétiques					
Production solaire	43,426 kWh	43,426 kWh	43,426 kWh	43,426 kWh	43,426 kWh
Consommation du quartier	166,948 kWh	163,266 kWh	162,282 kWh	163,023 kWh	162,312 kWh
Coût de l'énergie consommée	3 576,43 €	3 339,03 €	3 398,27 €	3 432,94 €	3 420,03 €
Ecart relatif avec le contrôle réactif		6,64%	4,98%	4,01%	4,37%
Indicateurs de performances de l'autoconsommation					
Taux d'autoconsommation	20,6%	38,53%	30,30%	29,52%	28,32%
Taux d'autosuffissance	5,4%	10,25%	8,11%	7,86%	7,58%

All 4 decentralised strategies allowed to decrease the energy consumption in the district by 4% (naive) to more than 6% (perfect prediction). In terms of self-consumption, all methods allowed to increase the ratio from 20% (reactive control) to almost 30% and 30-40% for the perfect predictions.

The centralised algorithm would certainly have given better results, but calculation time for the optimal solution had been too high. It has nevertheless been compared in terms of calculation time (*Figure* ***147***) with the decentral solution. It has to be highlighted that a threshold of a maximum of 45 seconds by optimisation horizon had been used for stopping optimisation. This led to the fact that the centralised version did not reach the result of optimisation for 14 of 37 horizons and the time could not be directly compared. This again underlines the necessity of reduced order models or black box models for these usages.

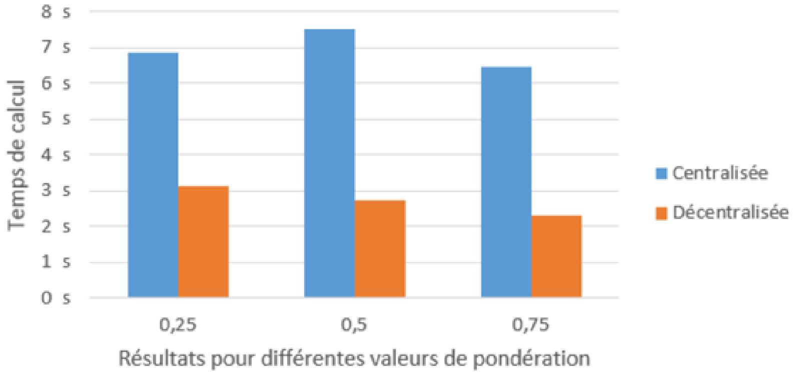

Figure 147 : Average calculation time per optimisation horizon for centralised and decentralised algorithm

CONCLUSION

The research presented in this report deals with the objective of the improvement of energy management and the rational use of fossil energy (and thus the increase of REN&R sources) in buildings and districts.

The results presented in the report have been exclusively generated or post-treated in research in which the author of this report has been advisor, or directly by the author. Input from external sources has been highlighted.

This research has been presented in four main chapters:

- energy systems in new and existing buildings and statements on the improvement potential of their energy management and control:

    - A typology of energy systems in buildings and districts is presented

    - The typology of the French building stock

    - In a last part, some statements on the potential of improvement of performances of energy systems in the French building stock

- tools and methods that have been developed for the conception as well as for the test and optimisation of control and energy management of systems. These tools are a) numerical simulation, b) in-situ or lab evaluation and c) hardware in the loop approaches.

- modelling/simulation approaches and suggested modelling choices depending on the simulation objectives.

    - A summary of choices of the level of detail for energy systems modelling and the potential impact on results. It shows the sensitivity of modelling approaches on simulation results.

    - A detailed chapter on the modelling of room or zone models based on different approaches. Results are presented for the use case of controller studies.

- specific adaptations of these tools for testing control systems and some examples of innovative optimisation algorithms.

  These examples are almost exclusively PhD projects in which the author has been one of the advisors. They show various applications of numerical simulation, with a broad scope in the usage of the models (conception, control, predictive control). For each case, information is given on modelling choices and how validation of these models has been considered.

The application of numerical simulation represents a huge field of potential, but also of uncertainty on the appropriate choice of modelling approach. This choice is until now mainly driven by former experiences on similar use cases. In recent work, simulation is more and more completed by methods based on sensitivity analysis. This is very helpful if the accuracy of simulation results shall be proven.

The next paragraph on perspectives shall detail approaches that could be undertaken in the future to ensure better accuracy of numerical simulation.

PERSPECTIVES

The work presented in this document has shown the complexity of all issues related to guarantee the quality of numerical simulation for a given purpose.

In order to suggest a methodology or steps to be undertaken in the future to progress in the quality of the results, ***4 main aspects are suggested as key perspectives***:

- Types of tools in the future

In the recent past, with the fast increase of calculation power, the trend goes to more and more complexity of modelling approaches. The problem is thus not anymore to be able to run simulations with a high-resolution model (e.g., CFD) which have conducted in the past to lumped parameter models for a thermal zone for example.

Besides the question if we always dispose of the necessary data to correctly parameter these models (which is definitively wrong in most cases, especially when the simulation scene exceeds a single building), a second question arises, if all necessary phenomena can and should be modelled in a single tool. From my point the answer is no. The necessary knowledge and also the effort of ensuring the validity of the models as well as maintaining these models would be too high, with only 1 significant, potential gain: simulation speed.

The recent past has shown that in most cases, the key points in the time to answer a question related to system behaviour or performance by simulation is by far not the simulation time (except for example CFD modelling) but mainly the time for describing the problem in a model assembly. Then, since model validity related to the available data is still an issue, sensitivity analysis is usually carried out. One could say then that there is still an issue with simulation time. But contrarily to a single simulation where many models are connected and must be solved by iteration, sensitivity analysis mainly consists in launching the same model assembly several times, with more or less intelligence behind the choice of parameter sets. And at this point, the calculation power of today will be useful to launch many simulations on parallel kernels to gain in speed.

From my point of view the best approach for the future is thus:

- Develop simulation modules for single phenomenon problems
- Validate these modules for one or different use cases and make them available
- Develop module communication interfaces (variables, protocols) that are standardised as much as possible
- Software platforms can then use these modules and plug them together to simulate a given problem

An example for this is the past and ongoing development in Matlab/Simulink or Modelica language. Validated model assemblies are and have been developed with standardised inputs and outputs. They can easily be plugged together and be used by other users, without the user to be specialist in modelling all necessary phenomena. This approach is probably the best choice when quality of results is searched.

On the other hand, as already experienced in the development of Simulink modelling toolboxes[143] in the past, it is very difficult to impose to the whole community a single modelling environment, especially if these environments must be purchased. This is one of the reasons why these toolboxes have no big market share anymore. A similar approach is ongoing with all Modellica developments (IBPSA project n°1, several toolboxes). But almost all users are working in DYMOLA environment, which is even more expensive as Matlab licences.

[143] SIMBAD HVAC and building toolbox ; CARNOT toolbox

A new potential can be seen in the recent and huge increase of development of packages in Python environment. Since these packages are completely open source, a new dynamic is being built around these packages. Perhaps this will allow this environment a breakthrough on the field of buildings and HVAC system modelling and simulation.

To reach this step of interfacing of modules, the key question is to be able to define a systemic picture of energy systems, buildings and districts. An example of this has been suggested in Chapter I of this report. The division into sub-parts allows to define data exchange interfaces between these modules and the interfaces can be standardised. Once available and accepted, all software packages (in a single or different environments) can then be plugged together.

Even in cases of different simulation environments, this approach will work if all interfaces are standardised. Once this done, the only difficulty left (in case of different programming environments) is to ensure convergence between the different modules if these include their own simulation kernel ensuring convergence. This is already done in co-simulation environments with a central convergence management (e.g., Daccosim[144]). Convergence can also be realised in a decentral way as shown in the work of Kaplan[145] for the example between DIMOSIM (python environment) and TRNSYS. This development has allowed to show how to easily connect two independent simulation tools with or without iterating between both simulation environments.

Once this achieved, the only question is, until which size, a singular software module should be developed? There are two possibilities:

- Bottom-up approach: each HVAC "component" is a single package. But what about the components below? It is difficult to find a correct border and to know up to which detail macro-components should go into detail.

- Global problem approach. It might be better to keep the existing tool variants with each tool allowing to simulate a problem (e.g., TRNSYS, Energy plus etc.). If new phenomena or modules are needed, they can be plugged to the existing tool via co-simulation. If this is well structured in all tools, each tool can easily and quickly be plugged to another one (or calling an external package) without constructing all from scratch. A simple example is the coupling of DIMOSIM and Envibate where buildings and systems are modelled in one tool and microclimate in the other one.

The answer from my point of view in terms of research tools is thus clearly the co-simulation approach. This allows good cooperation and flexibility for each tool developer while keeping the door open to collaborations and tool coupling. ***To allow this, standardised communication methods (e.g. FMU/FMI, socket protocols etc.) should be available in all platforms. This would open many collaborations and powerful tool combinations.***

For commercial tools, the answer might be different since from aspects of maintenance and simulation speed the constraints are completely different. Couplings to other tools that are maintained and updated separately can represent a huge amount of work and thus risk.

- <u>Tool validation</u>

As already stated in this report, tool validation represents a huge effort of work if done properly. The question is thus how to ensure the quality of results for a given problem or use case without exploding efforts. To date this is done by validating individual modules and specific couplings and, more and more, sensitivity analysis to simulate rather ranges of possible results than one

[144] Evora-Gomez J., Hernández Cabrera J. J., Tavella J. P., Vialle S., Kremers E., EIFER, European Institute for Energy Research Daccosim NG: co-simulation made simpler and faster, February 2019, DOI:10.3384/ecp19157785, Conference: Proceedings of the 13th International Modelica Conference, Regensburg, Germany, March 4–6, 2019

[145] J. Kaplan, Couplage de deux logiciels de simulation ; Internship report CSTB / Telecom Paris ; 2021

single result and/or to validate the sensitivity of a tool to specific parameters. This can include stochastic approaches and thus give a better idea of the quality of results.

Three topics will need an effort in the future:

- Generalise sensitivity analysis and provide ready to use modules for that. Each tool allowing to carry out building and system simulation should provide a possible range of results. ***Specific but generic sensitivity analysis software modules that can be plugged to various simulation tools would be very interesting and important.***

- More validation cases should be publicly available. ***Typical use cases with validation data sets are necessary***. Use cases as for example studies on energy consumption (without control aspects for load calculation), peak load analysis, controller studies can be listed and clustered in terms of model prerequisites. For each use case, data sets with parameters (and, if available results time series) should be publicly available in order to enlarge Bestest standard tests to a broader scope, including HVAC system tests.

- ***On the district scale***, validation is even more tricky. Contrarily to the zone or building scale there is a huge lack of input data needed for modelling the use cases. Often, the lack of data is so important that the use of models of any level of detail does not make a big difference (work to be published within the PhD thesis of L. Lefort[146]). Ideally, ***data bases with results on districts and for the key use cases would be a big step***. The necessary data are building and system parameters (as complete as possible), electricity, gas or fuel consumptions, and, if possible, measured occupant behaviour and actions. With the big boom of “smart metering” (or better metering), more and more data are cheaply available and could allow such test cases. The validation could thus be carried out as discussed in Chapter III.

- Perspectives of emulation

As presented in Chapter II and III, emulation of HVAC and control equipment is based on numerical simulation. In the recent past, more and more products include innovative control algorithms. The classic evaluation on steady state test rigs as carried out in a business-as-usual manner does thus not allow anymore to ensure the correct estimation of real performances or these products. If a nominal performance is available but does not happen in practice, the evaluation does not make sense, except if the extrapolation to the real case is possible. Products with lower nominal performance but much better control will be blocked by certification schemes, even if real performances (those that the user will pay with money) can be better.

Evaluation and certification based on emulation will thus play a bigger role as today. To ensure this properly, the used models must again be able to represent correctly all necessary phenomena. This part is again ensured by the corresponding use cases in the validation work.

New research work should be initiated on defining new test scenarios that allow, in tests that are as short as and realistic as possible, the correct evaluation of future products in a manner that allow extrapolation. A particular attention has to be paid on the type of tests that the errors committed in the car industry (consumption tests) are avoided.

- Real performances of systems

Finally, a last part where numerical simulation can and should pay a role, is the evaluation of performances in real life. The massification of performance evaluation should be a big issue. ***If all products that are installed in real buildings include, in the future, a module that properly (validated by certification) evaluates performances (instantaneous, daily,***

[146] Lefort L, Development of a reference method for urban-scale building energy simulation tools, Mines ParisTech, Efficacity, defense planned in september 2022, France

weekly, monthly, seasonal or yearly), real performances of all systems installed would be available. Energy statistics, REN&R statistics, average performances etc. would allow managing energy performance on a national or European level. Also, by analysing performances by system type, tax credits and divers funding could be better planned and thus increase the wished impact (depending on the wished indicators). If this is decided, the installed software and hardware module must be certified to guarantee objectivity.

Again, also in this case, numerical models would play a key role in allowing the construction of these software modules.

Finally, a summary of suggested actions:

- Standardise system component model borders with standardised inputs and outputs;
- Create more data bases for model and tool validation;
- Produce generic software modules that can be plugged to any model or tool for a standardised sensitivity analysis;
- Among researchers, develop a consensus on future product testing that fully profits from the potential of emulation. This will help to convince key actors to implement future standards for testing of innovative products and controls;
- Generalise online performance evaluation implemented in the controllers of energy systems. Certified evaluation modules that use measured on site would allow, in combination with simplified modelling approaches, the generalised evaluation of all energy systems in terms of consumptions and performance.

CHAPTER V

PRESENTATION OF RESEARCH ACTIVITY

1. PUBLICATIONS

1.1 PUBLICATIONS IN INTERNATIONAL JOURNALS

1. E. Garreau, Y. Abdelouadoud, M. Brugeron, E. Herrera, G. E. Kyriakodis, V. Partenay, P. Riederer, (2020). DIstrict MOdeller and SIMulator (DIMOSIM): a dynamic simulation platform with bottom-up approach for district and territory energetic assessment, to be published
2. G.-E. Kyriakodis, E. Bozonnet, and P. Riederer, (2020). Development of an Integrated Urban Model of Microclimate and HVAC Systems to Assess Energy Performance and Environmental Interactions, Energy & Buildings, to be published
3. N. Perez, C. Inard, P. Riederer, (2018). Development of a multi-objective optimization procedure dedicated to the design of district energy concept, Energy & Buildings 178 (2018) 11–25
4. T. Salque, D. Marchio, P. Riederer, (2014). Neural predictive control for single-speed ground source heat pumps connected to a floor heating system for typical French dwelling. Mar 2014, Building Services Engineering research and technology, Volume: 35 issue: 2, page(s): 182-197
5. T. Salque, D. Marchio, P. Riederer, (2013). Comparison of Single-Speed GSHP Controllers with a Calibrated Semi-Virtual Test Bench. International Journal on Advances in Systems and Measurements, vol 6 no 1 & 2, year 2013
6. Eun Chul Kang, P. Riederer, Seong Yeon Yoo, Euy Joon Lee (2012). New approach to evaluate the seasonal performance of building integrated geothermal heat pump system, Renewable Energy, 54, June 2013, p. 51-54
7. V. Partenay, P. Riederer, T. Salque, E. Wurtz, (2011). The influence of the borehole short-time response on ground source heat pump system efficiency, In Energy and Buildings, Volume 43, Issue 6, 2011, Pages 1280-1287, ISSN 0378-7788
8. F. Chlela, A. Husaunndee, C. Inard, P. Riederer (2009). A new methodology for the design of low energy buildings, Energy and Buildings, Volume 41, Issue 9, September 2009, Pages 982-990
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12. P. Riederer, D. Marchio, J.C. Visier, A. Husaunndee, R. Lahrech, (2002). Room thermal modelling adapted to the test of HVAC control systems, Building and Environment, Volume 37, Issues 8–9, August–September 2002, Pages 777-790
13. P. Riederer, D. Marchio, J.C. Visier, (2002). Influence of sensor position in building thermal control: criteria for zone models, Energy and Buildings, Volume 34, Issue 8, September 2002, Pages 785-798
14. R. Lahrech, P. Gruber, P. Riederer, P. Tessier and J. C. Visier, (2002). Development of a testing method for control HVAC systems by emulation, Energy and Buildings, Volume 34, Issue 9, October 2002, Pages 909-916.

1.2 PUBLICATION PROFESSIONAL JOURNALS

1. P. Riederer, D. Marchio, J.C. Visier, (2003). Modèle de zone adapté aux essais de régulateurs des systèmes de chauffage et de climatisation, Cahiers du CSTB, n° 437, mars 2003, cahier 3446.
2. A. Husaunndee, F. Bruyat, M. Jandon, R. Lahrech, P. Riederer, H. Vaezi-Néjad, J.C. Visier, (2002). Les laboratoires virtuels pour le développement, l'évaluation et le test de systèmes de régulation et de GTB, Revue CVC n° 11, Novembre 2002, pp. 27-31.

1.3 PUBLICATIONS IN CONFERENCES WITH REVIEW

2021

1. Kyriakodis, G-E; Bozonnet, Emmanuel; Riederer, Peter. An integrated approach to quantify the potential local climate mitigation of a district energy network compared to individual air conditioning systems. Proceedings of the Building simulation 2021 conference, Bruges, Belgium 2021

2020

2. Lucie Lefort, Romain Bonabe de Rougé, Pascal Schetelat, Thomas Berthou, Bruno Duplessis, Peter Riederer, Eric Peirano. Development of a methodology of validation for urban building energy models and application to French residential consumption. uSIM2020, Building to buildings: urban and community energy modelling, Online conference, November 12, 2020
3. Lucie Lefort, Romain Bonabe de Rougé, Pascal Schetelat, Thomas Berthou, Bruno Duplessis, Peter Riederer, Eric Peirano. Méthodologie de validation d'outils de simulation énergétique urbaine avec un cas d'application sur la Seine-et-Marne. Conférence IBPSA France, Reims, 2020
4. M. Brugeron, F. Wurtz, Y. Marechal, P. Riederer. Presentation of a generic architecture for predictive controller conception through an application on a residential building. Conférence IBPSA France, Reims, 2020

2019

5. G. Kyriakodis, E. Bozonnet, P. Riederer. Minimizing the inconsistencies of urban building energy simulations through strong microclimate coupling, Proceedings of the 5th International conference on countermeasures to urban heat islands conference, Hyderabad, India, 2019
6. G. Kyriakodis, E. Bozonnet, P. Riederer. Quantifying the Impact of Urban Microclimate in Detailed Urban Building Energy Simulations, Proceedings of the Building simulation 2019 conference, Rome, Italy 2019
7. M. Brugeron, F. Wurtz, Y. Marechal, P. Riederer. The presentation of a model-based predictive controller architecture through the interfacing of a dynamic simulation platform Dimosim and an optimization modeller OMEGAlpes. Proceedings of the Building simulation 2019 conference, Rome, Italy 2019

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8. Georgios-Evrystheas Kyriakodis, Emmanuel Bozonnet, Peter Riederer (2018). Towards the development of a coupled model for district simulation: buildings, energy systems and microclimate co-simulation. IBPSA France 2018, Bordeaux

2017

9. Georgios-Evrystheas Kyriakodis, Maxime Doya, Emmanuel Bozonnet, Peter Riederer (2017). Ecodistrict design and decision process through building energy and local microclimate assessment, Passive Low Energy Architecture design to thrive (PLEA); 2017, Edinburgh, Vol II, p. 1781-1788
10. Perez, N., Inard, C., Riederer, P., Partenay, V. (2017). A study on the multi-objective optimisation of district energy system performances, Fifteenth International IBPSA Conference, p.122-131

2016

11. Perez, N., Mailhac, A., Inard, C., Riederer, P. (2016). Outil d'aide à la décision multicritère pour la conception de systèmes énergétiques à l'échelle du quartier, Conférence IBPSA France 2016

2015

12. Partenay, V., Caccavelli, D., Riederer, P., Perez, N. (2015). Energy refurbishment of a scientific park using district simulation platform: case study of Sophia-Antipolis, Climamed eighth Mediterranean Congress of HVAC
13. Riederer, P., Partenay, V., Perez, N., Nocito, C., Trigance, R., Guiot, T. (2015), Development of a simulation platform for the evaluation of district energy system performances, Fourteenth International IBPSA Conference, p.2499-2506
14. Perez, N., Riederer, P., Inard, C., Partenay, V. (2006), 2015. Thermal building modelling adapted to district energy simulation, Fourteenth International IBPSA Conference, p.270-277

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18. S. Pincemin, V. Partenay, P. Riederer (2011). Optimisation des performances d'un champ de sonde par injection de coulis à haute performance thermique. Congrès Français de Thermique 2001, Société Française de Thermique SFT, 2011.

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19. V. Partenay, P. Riederer, S. Pincemin (2010). A New Model for BTES Systems – Model Development, Comparison and Application to an Office Building, Clima 2010 conference, Anthalia, Turkey, 2010
20. P. Riederer, V. Partenay (2010). Dynamic Test Method for the Determination of the Global Seasonal Performance Factor of Heat Pumps Used for Heating, Cooling and Domestic Hot Water Preparation, World geothermal congress WGC2010, Bali, Indonesia

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21. W. Keilholz, V. Ducreux, P. Riederer (2009). Solving differential equations in TRNSYS without programming, Building Simulation Conference – BS2009, Glasgow, Scotland
22. P. Riederer, W. Keilholz, V. Ducreux (2009). Coupling of TRNSYS with Simulink – a method to automatically export and use TRNSYS models within Simulink and vice versa, Building Simulation Conference – BS2009, Glasgow, Scotland
23. P. Riederer, V. Partenay, O. Raguideau (2009). Dynamic Test Method for the Determination of the Global Seasonal Performance Factor of Heat Pumps Used for Heating, Cooling and Domestic Hot Water Preparation, Building Simulation Conference – BS2009, Glasgow, Scotland
24. V. Partenay, P. Riederer (2009). A Global Approach for the Optimisation and Evaluation of Performances of BTES, EFFSTOCK conference 2009, Stockholm, Sweden
25. M. Philippe, S. Hagspiel, D. Marchio, V. Partenay, P. Riederer (2009), Analysis of 30 underground thermal energy storage systems for building heating and cooling and district heating, EFFSTOCK conference 2009, Stockholm, Sweden

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26. V. Partenay, P. Riederer, S. Pincemin (2008). Simulation de l'efficacité énergétique d'un bâtiment sur fondations géothermiques, IBPSA France 2008, Lyon, France

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36. N. Couillaud, P. Riederer, M. Jandon, Y. Diab (2005). Balancing Operation for the Optimization of Hydronic Networks, ICEBO - Proceedings of the Fifth International Conference for Enhanced Building Operations, Pittsburgh, Pennsylvania, October 11-13, 2005

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37. N. Couillaud, E. Bernadou, B. Georges, P. Riederer (2004), A virtual bench to test the performance and balancing of hydronic networks, 6th International Conference, Energy for Buildings, Vilnius, Lithuania, October 2004.
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40. P. Riederer (2003), From sizing and hydraulic balancing to control using the SIMBAD Toolbox, Building Simulation Conference - BS 2003, Eindhoven, Netherlands, August 2003.
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1.4 CONFERENCES AND WORKSHOPS WITHOUT REVIEW

1. Daniel Grivon Peter Riederer, Yves Stauffer, Andreas Hutter (2019). Smart control strategy for the reduction of energy consumption of central heating systems in large buildings. Building simulation 2019, Rome, Italy 2019
2. Y. Abdelouadoud, M. Brugeron, E. Garreau, E. Herrera, G. Kyriakodis, V. Partenay, P. Riederer (2019). A simulation tool for the analysis of energy concepts based on renewables and heat recovery for buildings and districts. Sustainable places 2019 conference, Cagliari, Italy
3. P. Riederer (2013). Conférence Inpac 2013. Amélioration des performances réelles de pompes à chaleur géothermiques
4. P. Riederer (2012), Conférence Inpac 2012: Résultats de suivi in-situ de pompes à chaleur géothermiques
5. P. Riederer, V. Partenay, T. Salque (2011). Conférence Inpac 2011. Evaluation et optimisation des performances réelles de systèmes de PAC géothermiques

1. P. Riederer (2009), Performances réelles des pompes à chaleur géothermiques, Revue technique du bâtiment. Septembre 2009.
2. P. Riederer (2009), Modelling and simulation of geothermal heat pumps, Journées Eco-constuction, CEP, Paris, 2009
3. P. Riederer (2004), Overview new features in Simbad 4, 2nd workshop Matlab/Simulink for Building simulation, CSTB, Paris, 14/15 October 2004.
4. Z. El Khoury, P. Riederer (2004), A new building multizone model for Simbad, 2nd workshop Matlab/Simulink for Building simulation, CSTB, Paris, 14/15 October 2004.
5. W. Keilholz, A. Bolher, N. Bus, F. Chlela, P. Corrales, P. Riederer (2004), Coupling Matlab and TRNSYS - Building data models for the use in TRNSYS and SIMBAD, 2nd workshop Matlab/Simulink for Building simulation, CSTB, Paris, 14/15 October 2004.
6. N. Couillaud, F. Bellenger, P. Riederer (2004), Analysis and optimisation of hydronic networks in buildings, 2nd workshop Matlab/Simulink for Building simulation, CSTB, Paris, 14/15 October 2004.
7. N. Couillaud, E. Bernadou, B. Georges, P. Riederer (2004), Un banc virtuel pour l'évaluation des performances des réseaux hydrauliques, XXIIèmes Rencontres AUGC – Ville & Génie Civil, Université de Marne-la-Vallée, juin 2004.
8. P. Riederer, W. Keilholz, M. Kummert (2004), Type 155 – un nouveau type TRNSYS pour coupler TRNSYS et Matlab, TRNSYS Userdays, CSTB, Sophia Antipolis, 9/10 mars 2004.
9. P. Riederer (2004) - Les laboratoires virtuels pour le développement, l'évaluation et le test de systèmes de régulation et de GTB, CNRS - Séminaire GAT modélisation, Université La Rochelle, 28/29 janvier 2004.
10. P. Riederer, N. Couillaud, A. Husaunndee, D. Jreijiry (2003) - Simbad Building and HVAC toolbox - new features for the future version 4.0, 1st workshop Matlab/Simulink for Building simulation, CSTB, Paris, 23/24 October 2003.
11. D. Jreijiry, N. Couillaud, A. Husaunndee, C. Inard, P. Riederer (2003) - A multizone building model in the Simbad toolbox coupling thermal, airflow and water flow phenomena, 1st workshop Matlab/Simulink for Building simulation, CSTB, Paris, 23/24 October 2003.
12. H. Vaezi-Nejad, F. Bruyat, N. Couillaud, M. Jandon, L. Nennig, P. Riederer (2003) - Development of Commissioning tools and test using the SIMBAD Building and HVAC toolbox, 1st workshop Matlab/Simulink for Building simulation, CSTB, Paris, 23/24 October 2003.
13. W. Keilholz, M. Kummert, P. Riederer (2003) - Type 155 - a new TRNSYS type for coupling TRNSYS and Matlab - example of using Matlab controllers with TRNSYS components, 1st workshop Matlab/Simulink for Building simulation, CSTB, Paris, 23/24 October 2003.

1.5 INTERVIEWS

L'avenir de la PAC est-il prometteur ? P. Riederer, Le magazine du confort thermique 5, mai 2008, p31-33

2. SUPERVISION OF INTERNSHIPS, PHD'S AND POSTDOCS AND MEMBER OF EVALUATION COMMITTEES

2.1 CODIRECTION AND ADVICE OF PHD CANDIDATES

1. Ali Chouman: Plateforme d'évaluation de modules de gestion innovante de systèmes, Université de Grenoble, PhD started in september 2021 (codirection 50%)
2. Alexandre Bryk: Modélisation et adaptation environnementale d'un quartier dans un contexte de climat futur et de canicule urbaine, Université de La Rochelle, PhD started in november 2021 (codirection 30%)
3. Lucie Lefort: Développement d'une méthode de référence pour la validation des outils de simulation énergétique des bâtiments à l'échelle urbaine, MINES ParisTech, defense planned in September 2022 (external advisor)
4. Mathieu Brugeron, Méthodologie d'évaluation de produits ou algorithmes de gestion avancée au niveau du quartier, CSTB/Université de Grenoble, June 2021 (codirection 40%)
5. Georgios Kyriakodis, Development of a coupled simulation tool for urban building energy demand, district energy systems and microclimate modelling, CSTB / Université de la Rochelle, August 2020 (codirection 50%)
6. Nicolas Perez, Contribution à la conception énergétique de quartiers : simulation, optimisation et aide à la décision, CSTB/Université de la Rochelle, October 2017 (codirection 50%)
7. Tristan Salque, Amélioration des performances de PAC géothermiques par couplage de mesures in-situ et de méthodes numériques inverses, CSTB/Mines Paristech, October 2013 (advisor)
8. Vincent Partenay, Thèse de doctorat, "Développement d'une méthodologie d'évaluation des performances de systèmes de pompes à chaleurs", CSTB / Ecole doctorale de l'Université de Savoie, October 2010 (codirection 50%)
9. Fadi Chlela, Développement d'une méthodologie de conception de bâtiments à basse consommation d'énergie, CSTB / Université de la Rochelle, février 2008 (advisor)
10. Nicolas Couillaud. Amélioration de l'efficacité énergétique des réseaux hydrauliques : optimisation de la conception, CSTB/Université de Marle-la Vallée, December 2006 (advisor)

2.2 TECHNICAL SUPERVISION OF DOCTORAL AND POSTDOCTORAL RESEARCHERS

1. Georgios Kyriakodis, Development of a tool for the coupled simulation of urban heat island, microclimate and energy systems, 12 months, PostDoc in collaboration with Lasie, University of La Rochelle.
2. Zaki El Khoury (2004), Développement d'un modèle de bâtiment multizone pour la bibliothèque SIMBAD (Matlab/Simulink), 12 months, PostDoc in collaboration with the laboratory Crigen, GDF
3. Liliana Corvino (2012). Contribution au développement d'un outil d'analyse des performances de pompes à chaleur. Master dei Talenti Neolaureati 2012, 12 months

2.3 MEMBER OF EVALUATION COMMITTEE OF PHD'S

1. Fatima HARKOUSS, Optimal design of net zero energy buildings under different climates. Université Nice Sophia Antipolis and Université Libanaise, June 2018
2. Mathieu Brugeron, Méthodologie d'évaluation de produits ou algorithmes de gestion avancée au niveau du quartier, CSTB/Université de Grenoble, June 2021
3. Georgios Kyriakodis, Development of a coupled simulation tool for urban building energy demand, district energy systems and microclimate modelling, CSTB/Université de la Rochelle, August 2020
4. Nicolas Perez, Contribution à la conception énergétique de quartiers : simulation, optimisation et aide à la décision, CSTB/Université de la Rochelle, October 2017
5. Alberta Tejada de la Cruz. Développement d'une méthode d'auto-paramétrage auto-adaptatif pour une pompe à chaleur en vue d'un fonctionnement optimisé, Mines Paristech, September 2016
6. Tristan Salque, Amélioration des performances de PAC géothermiques par couplage de mesures in-situ et de méthodes numériques inverses, CSTB/Mines Paristech, October 2013
7. Vincent Partenay, Thèse de doctorat, "Développement d'une méthodologie d'évaluation des performances de systèmes de pompes à chaleurs", CSTB / Ecole doctorale de l'Université de Savoie, October 2010
8. Mikael Philippe, Développement et validation expérimentale de modèles d'échangeurs géothermiques horizontaux et verticaux pour le chauffage de bâtiments résidentiels, CSTB / Mines Paristech , October 2010
9. Pierre Tittelein. Environnements de simulation adaptés à l'étude du, comportement énergétique des bâtiments basse consommation. Université de Savoie, December 2008
10. Fadi Chlela, Développement d'une méthodologie de conception de bâtiments à basse consommation d'énergie, CSTB / Université de la Rochelle, February 2008
11. Nicolas Coullaud. Amélioration de l'efficacité énergétique des réseaux hydrauliques : optimisation de la conception, CSTB/Université de Marle-la Vallée, December 2006
12. Stéphane GINESTET. Simulation dynamique des systèmes de climatisation. Application aux régulations innovantes de CTA. Ecole des Mines de Paris, November 2005
13. Kátia Cordeiro Mendoça. Modélisation thermo-hydro-aéraulique des locaux climatisés selon l'approche zonale (prise en compte des phénomènes de sorption d'humidité), Université de la Rochelle, March 2004

2.4 SUPERVISION OF LAST YEAR PROJECTS (3 - 6 MONTHS)

1. Ingrid Pech (2002). *Elaboration d'un guide pour l'implémentation de modèles dans la bibliothèque SIMBAD - Application aux capteurs solaires*, ISUPFERE, 6 months
2. Nicolas Couillaud (2003). *Implémentation de systèmes de production d'eau chaude pour la bibliothèque SIMBAD*, Université de la Rochelle, 6 months
3. Fadi Chlela (2004). *Développement d'une interface graphique pour la description du bâtiment*, Université Paris 10, 6 months
4. Gérald Masteau (2005). *Analyse des Performances des pompes à chaleur à absorption-diffusion*, Université de Savoie, 6 months
5. Cédric Gallois (2006). *Développement d'une méthode d'essais des performances thermiques des systèmes solaires combinés*, Université Franche-Comté, 6 months
6. Benoit Nguyen (2006). *Analyse technico-commerciale de bâtiments équipes de fondations géothermiques*, ENSMA, 6 months
7. Emmanuel Lebeau (2007). *Amélioration du laboratoire semi-virtuel du CSTB pour le test de systèmes solaires combinés*, Université de Perpignan, 6 months
8. Vincent Partenay (2007). *Analyse des performances de pompes à chaleur*, EPF, 6 months
9. Yoann ROUE et Benoît JULIEN (2007). *Les pieux énergétiques*, Polytech Savoie, 3 months
10. Olivier Raguideau (2008). *Géothermie très basse température : Etat de l'art et application numérique pour la détermination du coefficient de performance annuel d'une pompe à chaleur*, Université Paris-Sud 11, 6 months
11. Vanessa Ducreux (2008). *Géothermie très basse température : état de l'art, modélisation et couplage entre TRNSYS et Matlab Simulink*, Université Paris-Sud 11, 6 months
12. Simeon Hagspiel (2009). GEOBAT – Stockage géothermique pour l'optimisation des consommations énergétiques des bâtiments, Mines ParisTech, 3 months (external advisor)
13. Claire KAZGANDJIAN (2009). *Simulation numérique de systèmes de stockage inter-saisonnier par champ de sondes géothermiques*, Polytech Savoie, 5 months
14. Eddy Trouillas (2009). *Etude d'une plateforme et mise en place d'un banc d'essai de caractérisation des transferts pour le stockage d'énergie par géothermie*, Université de Perpignan, 3 months
15. Tristan Salque (2010). *Mise au point d'une nouvelle méthode dynamique d'essai de pompes a chaleur géothermiques*, INSA Strasbourg, 6 months
16. Clément Reysz (2011). *Identification d'un système de pompe à chaleur géothermique*, Polytech Montpellier, 4 months
17. Laura Barbier (2012). *Analyse des méthodes de stockage de l'énergie développées dans le projet MESSIB d'un point de vue normalisation et simulation d'un projet PAC eau-eau avec sondes horizontales*. Polytech Montpellier, 4 months
18. Soumia El Garrab (2012). *Suivi Energétique de la Cité du Design à Saint Etienne – Performances du système PAC Géothermique*, 6 months
19. Nicolas Perez (2012). B*anc d'essais semi-virtuel aéraulique*, ENS Cachan, 3 months
20. Luc Bonfiglio (2013), *Conception d'un banc d'essais semi-virtuel aéraulique*, Polytech Montpellier, 4 months
21. Robin Bessadier (2013). *Développement d'un banc d'essais semi-virtuel multi énergie pour le test de systèmes de chauffage et de climatisation des habitations de type résidentiel, École nationale supérieure de l'énergie, l'eau et l'environnement*, Grenoble, 5 months
22. Romain Trigance (2014). *Elaboration d'un outil de gestion énergétique à l'échelle des parcs scientifiques et techniques Smart Med Park*, Polytech Sophia, 6 months
23. André Mvé (2014). *Suivi sur site des systèmes hybrides*, Université de Pau et des Pays de l'Adour, 6 months
24. Saber Gharsally (2016). *Mise au point d'un nouveau laboratoire semi-virtuel*, Université de Picardie, 6 months
25. Jéremy Kaplan (2021), Couplage de deux logiciels de simulation. Internship CSTB / Telecom Paris, 6 mois

3. PROJETS AND RESEARCH ACTIVITY

3.1 NATIONAL RESEARCH PROJECTS

1. *Elaboration de tests de régulateurs pour systèmes de chauffage électriques selon la procédure adoptée par le CEN TC247 (SIMTEST-Elec-I)*, client: EDF, 2002, 6 months, role coordinator tasks CSTB
2. *Typologie de la régulation des systèmes de chauffage, ventilation et climatisation et comparaison des automates*, client: confidentiel, 2002, 12 months, role coordinator tasks CSTB
3. *Elaboration d'une méthode pour le test de régulateurs de systèmes de chauffage électrique avec correction de la sonde selon la procédure adoptée par le CEN TC247 (SIMTEST-Elec-II)*, client: EDF, 2003, 9 months, role coordinator tasks CSTB
4. *Optimisation d'une micro-pompe à chaleur à absorption-diffusion avec capteur géothermique vertical*, client: Ademe, coordinateur, 2004, 36 months, role coordinator tasks CSTB
5. *Capitalisation & Valorisation des pompes à chaleur géothermiques (VALPAC)*, client: Ademe, 2005, 24 months, role : Project Coordinator
6. *Développement d'un prototype de régulateur applique aux systèmes solaires combines (RSSC)*, client: Ademe, coordinateur CSTB, 2005, 24 months, role : Project participant
7. *Outils de conception de fondations géothermiques (COFOGE)*, client: Ademe (Prebat), coordinateur, 2006, 24 months, role : Project Coordinator
8. *Développement d'une plate-forme commune de simulation (Dynasimul)*, client: ANR (Prebat), coordinateur LOCIE, 2006, 36 months, role : WP coordinator and coordinator CSTB
9. *Développement d'une méthode d'essai globale des SSC (Eval-SSC)*, client: Ademe, coordinateur CSTB, 2007, 26 months, role : Technical Coordinator CSTB
10. *Stockage géothermique pour l'optimisation des consommations énergétiques des bâtiments (GEOBAT)*, client: Ademe (Prebat), coordinateur, 2008, 24 months, role: Project Coordinator
11. *Comparaison internationale bâtiment et énergie, tâche A3: Synthèse Composants et équipements innovants: Réseaux de chaleur (Expert CSTB: Peter Riederer, expert externe: Robin Wiltshire (BRE). https://www.prebat.net/IMG/pdf/a-total-2008.pdf , role : Project participant*
12. *Comparaison internationale bâtiment et énergie, tâche A3: Synthèse Composants et équipements innovants: Stockage de chaleur (expert CSTB: Peter Riederer; expert externe: J.C. Hadorn (Base Consultant).* https://www.prebat.net/IMG/pdf/a-total-2008.pdf, role : Project participant
13. *Echangeur géothermique Compact pour Logement Individuel et Performance du Système Energétique associé (Eclipse)*, client: ANR, coordinateur CEA-INES, 2008, 36 months, role coordinator tasks CSTB
14. *Développement d'une plateforme de test de pompes à chaleur géothermiques et Mission d'assistance pour le développement multi-site de la plateforme avec le BRGM*, client: Ademe, coordinateur, 2008, 24 months, role : Project coordinator
15. *Etat de l'art sur la géothermie très basse énergie afin de planifier des actions futures à engager*, client: Ademe, 2008, 12 months, parties sous-traitées (Alphéeis)., role : Project coordinator
16. *Suivi Énergétique du bâtiment platine de la cité du design à St. Etienne*, client: Ademe, 2010, 24 months, role : Project coordinateur
17. *Suivi sur site de Bâtiments équipés de pompes à chaleur géothermiques (VALPAC-ONLINE)*, client: Ademe, 2010, 36 months, role : Project coordinator

18. *Etude de l'impact du dimensionnement du champ de sondes d'un nouveau bâtiment de l'Hôpital de Rochefort*, client: Hôpital de Rochefort, 2010, 6 months, role : Project coordinator
19. *Définition d'une campagne de suivis des pompes à chaleur,* client: *Association Française des Professionnels des pompes à chaleur*, 2011, 3 months, role : Project coordinator
20. *Contrat d'assistance pour la conception et la mise en place d'un laboratoire semi-virtuel*, client: IREC – Catalogne, 2011, 6 months, role coordinator tasks CSTB
21. *BBC PACS Lot n°4.4.2 : Essais d'une pompe à chaleur géothermique pour la production d'eau chaude sanitaire*, client: Ademe, coordinateur EDF, partenaire, 2011, 36 months, role : Project participant
22. *Préconisations pour une meilleure modélisation des performances des bâtiments BBC et BEPOS (MODEBAT)*, client: EDF, partenaire, 2012, 36 months, role : Project participant
23. *Règles d'Expert pour L'Amélioration en LIgne des performances de PAC (REALIPAC),* client: Ademe, 2012, 24 months, role : Project coordinator
24. *Etude d'un système de puits canadien hydraulique pour le climat de l'ile de la Réunion (NaturalClim), client: Technopole de l'Ile de la Réunion, 2012, 12* months, role : Project coordinator
25. *Suivi des performances énergétiques de la Marpa Saint Paul en Pareds (85)*, client: Ademe, 2013, 3 years, role : Project coordinator
26. *Suivi des performances énergétiques de la résidence Mallève (Nantes)*, client: Ademe, 2013, 3 years, role : Project coordinator
27. *Etude sur les besoins en R&D pour le développement de pompes à chaleur*, client: Ademe, coordinateur CETIAT, 2013, 13.5 months, role coordinator tasks CSTB
28. *Projet Smart-Electrique-Lyon: Evaluation des stratégies de tarif électrique en laboratoire et in-situ*, client: AMI - Ademe, coordinateur EDF, 2013, 36 months, role : Project participant
29. *Conception/Fabrication d'un banc semi-virtuel sur mesure pour un industriel*, client: confidentiel, 2013, 12 months, role : Project coordinator
30. *"Mission d'étude Smart Grid – Technopole urbaine Nice Méridia " Partie Modélisation énergétique fine*, client: MNCA, coordinateur Embix, partenaire, 2013, 8 months, role Project participant
31. *Efficacity – Projet 2.1 – Récupération des énergies fatales, coordination du développement d'un outil de simulation de quartier*, ITE Efficacity, 2014, 3 years, Efficacity, role : Project co-direction
32. Suivi métrologique de 6 sites équipés de systèmes hybrides pour le chauffage et l'eau chaude sanitaire en maison individuelle, client: Ademe/GrdF, 2014, 48 months, *role: coordinator tasks CSTB*
33. *Efficacity – Projet WP2 : Construction des outils de simulation, ITE Efficacity, 2017, 5 years, role: Project participant*
34. *Econopac, Développement d'un outil d'aide à la conception et au dimensionnement d'un système de PAC innovante, 2018, 2 years, role: Project coordinator*
35. *EPA Paris-Saclay, Convention de partenariat R&D, D2Grid, 2020, 12 months,* role coordinator tasks CSTB
36. *EPA Paris-Saclay, Convention de partenariat R&D, D2Grid, seconde phase, 2020, 12 months,* role coordinator tasks CSTB
37. *Ville de Montpellier, Accord Cadre Recherche, Résilience des Réseaux, 2021, 12 months,* role coordinator tasks CSTB

38. *EUBAC, Numerical study of the impact of valve and actuator characteristics on performance evaluation results in the frame of the EUBAC certification, Eubac, 2021, 6 months,* role coordinator tasks CSTB
39. *Client confidentiel, étude de la faisabilité et du potentiel d'effacement de PAC, 2021, 3 months, role: coordinator CSTB*
40. *Développement d'un nouveau concept d'évaluation de PAC air/air par émulation, internal research project CSTB, 2021, 6 months, role: coordinator CSTB*
41. *Feuille de Route Recherche CSTB - Microclimat et Ilot de Chaleur Urbain, internal project, CSTB, 2021, role: codirection of writing*
42. *P. Jamet, O. Cauret, M. Andres, N. Monneyron, J.J. Graff, B. Raignaud, C. Boissavy, P. Delagelstom, F. Marcuccilli, T. Rouilly, C. Marvillet, P. Riederer, R. Vernier, J. Schmittbuhl, G. Brassard, Geothermal energy-Strategic road-map. Road-map for geothermal energy, 2011, role: Project participant*

3.2 INTERNATIONAL AND EUROPEAN PROJETS

1. *SIMulation models for TESTing control systems for heating ventilating and air conditioning application (SIMTEST)*, Europe (CEC DGXII C-O), agreement N°SMT4-CT, coordinateur Siemens, 1998, 36 months, role: project participant

2. *Development of the ETT software for application N° 1 - Individual zone control for heating and cooling applications*, European Building Automation controls association (EUBAC), 2005, 12 months, role: CSTB work coordinator during the first year before change of position

3. *THermal EneRgy from RenewAbles (Therra)*, commanditaire: Ademe (CSTB soustraitant pour l'Ademe), agreement : EIE/05/129/SI2.420023, coordinator : SenterNovem, 2006, 36 months, role: CSTB tasks coordinator

4. *Policy REinforcement concerning HEAT storage technologies (PREHEAT)*, client: Europe, agreement EIE/05/036/SI2.420010, coordinator : ECN, 2004, 30 months, role: project participant

5. *Multi-source Energy Storage System Integrated in Buildings (MESSIB)*, NMP2-LA-2008-211624, Grant Agreement Number 211624, coordinator: ACCIONA, task leader, 2008, 48 months, role: WP leader
6. International Energy Agency Building Energy Simulation Test and Diagnostic Method (IEA BESTEST), NREL/TP-550-43827 (participation in the starting phase only, first results), Sept. 2008, role: Project participant
7. *SEasonal PErformance factor and MOnitoring for heat pump systems in the building sector (SEPEMO)*, CIP-IEE-2008 - IEE/08/776/S12.529222, 2008, 36 months, role: CSTB work coordinator

8. *Building and district thermal retrofit and management solutions (Thermoss)*, Horizon 2020 research and innovation programme, Grant Agreement 723562, coordinator: Exergy, 2016, 42 months, role: CSTB work coordinator and WP leader

9. *Coupling renewable, storage and ICTs, for low carbon Intelligent energy management at district level (Resilient)*, Europe (EeB.NMP.2012-1), Grant Agreement No.: 314671, coordinator: Dappolonia, 2012, 48 months, role: CSTB work coordinator and WP leader

10. *Energy Efficient Optimised District Heating and Cooling (E2District), Europe (H2020-EE-2015-2-RIA), grant agreement n°: 696009, coordinator: Cork Institute of Technology, 2016, 36 months, role: Project participant*

11. *Recovery of Urban Excess Heat (ReUseHeat), Europe (H2020-EE-2016-2017), grant agreement n° 767429, coordinator: IVL Svenska Miljoeinstitutet AB, 2017, 48 months ,* role: CSTB work coordinator

12. *Collective Intelligence for Energy Flexibility (COLLECTIEF), Europe (H2020-EE-2021-2025), grant agreement n° 101033683, coordinator: NORGES TEKNISK-NATURVITENSKAPELIGE UNIVERSITET NTNU, 2021, 48 months ,* role: CSTB work coordinator and task leader

3.3 PUBLIC REPORTS RELEVANT FOR THIS WORK

1. *S Bonk, A Loose, C Schmidt, P Riederer, R Haberl…, Report on testing procedures for SHP systems; Technical Report 5.1.4; European QUAIST project, Project IEE/08/593/SI2.529236, 2012*