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TRNSYS INTEGRATED MODELING SUPPORT TOOL FOR A FAST BUILDING-PLANT SYSTEM DESIGN

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Abstract

The present thesis stems from the benefits of the application of energy analysis in any stage of building-plant system design. The research highlights the barriers that prevent this integration and finally proposes the development of a dynamic modeling support tool able to simulate, with a reasonable workload, a very large number of integrated building-plant systems with different scales and resolutions, in order to have a guided design support for architects and HVAC designers/engineers, reducing their modeling effort and errors. The starting point is represented by a flexible and detailed model created with the calculation engine TRNSYS, which allow for the dynamic and integrated simulation of the building envelope, all the heating plant subsystems, and all the plant components related to the production of domestic hot water.

The research explores then strategies and simplifications that can considerably reduce the number of necessary inputs for the simulations, thus minimizing the modeling, implementation and simulation runtime of the model, while still maintaining an acceptable degree of accuracy with respect to the computational results and real energy consumptions. Those results are achieved by defining a methodology, which consists in developing a sizing protocol and a simplification protocol and applying them to real life, complex case studies, first modeling detailed models and progressively enhancing the level of simplification. At each progressive simplification step, the comparison with the detailed model results is given in terms of building energy needs, power curves, efficiencies, modeling and simulation workloads. In particular results show that the accuracy of the most simplified model is always below the 16% with respect to the most detailed model, with a 90% modeling and simulation workload reductions, able to make the tool easy to be adopted at every stage of building-plant system design.

"Fatti non foste a viver come bruti, ma per seguir virtute e canoscenza"

— Dante Alighieri

For a sustainable future, the result of our intellect, curiosity and thirst for knowledge.

Index

PART 1

Building Energy Simulations

Chapter 1

1 Introduction

1.1 Buildings energy consumption

Humans today live in a built environment: a global man-made system of cities, villages and infrastructure of which buildings are an essential part. Buildings connect us with the past and represent the greatest legacy for the future, they encourage productivity, embody our culture, provide shelter and supply living, working and storage space. They have a constantly changing role, representing either support systems or communication and data terminals, centres of education, justice, community, and so much more. They are incredibly expensive to build and maintain and must constantly be adjusted to function effectively over their life cycle. Buildings certainly play an important part in life on the planet and as the world population continues to grow, as old buildings need replacement and as requirements for buildings change, the activity of building is a never-ending and highly relevant effort.

In fact the making of buildings involves several activities, that can be summarized in building design and building construction. The first is the activity that results in detailed drawings and technical descriptions of a building, able to satisfy a task that indicates goals, requirements and evaluation criteria (for instance concerning building function, floor area, life span, architectural image and initial costs), while the second is the activity that actually produces buildings according to the plans and specifications that result from building design. The building industry, including both design and construction, is a major component of the world economy and provides jobs to many people.

Now the energy use of the built environment has become a major concern. On a global level humanity faces the depletion of fossil fuel supplies; moreover, the use of fossil fuels is an important factor in environmental pollution, and the extraction and transport of fossil fuels often cause harm to local ecosystems. Reduction or more rational use of fossil fuels and development of alternative energy sources (renewable energy) are the only solution to these problems. As already formulated in 1987 by the World Commission on Environment and Development in its well-known Brundtland-report: "Energy is necessary for daily survival. Future development crucially depends on its long-term availability in increasing quantities from sources that are dependable, safe, and environmentally sound" *(Brundtland et al., 1987)*.

Today the energy problem is still increasing and is not local or isolated, including all the civilized countries in different ways. In particular the amount of energy used in the built environment is substantial: buildings are omnipresent, and most of them use energy for heating, cooling and lighting.

According to reports from the U.S. Department of Energy, buildings are responsible for a relevant portion of total yearly energy consumptions and greenhouse gas emissions, ranging from 40% to 50% depending on the sources. Of those consumptions, nearly 40% is directly attributable to the heating, venting and air conditioning of the premises, as shown in Figure 1-1 *(Chen, 2009)*. Not only, of all electricity generated in U.S. approximately 75% is consumed by the building sector.

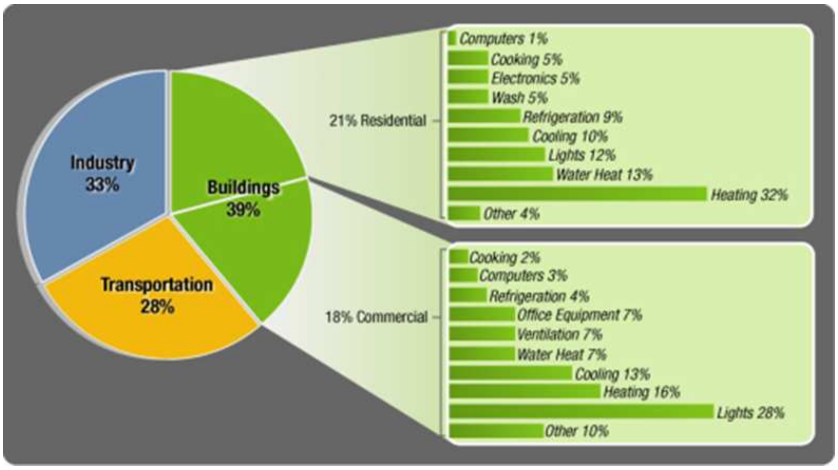

Figure 1-1: Energy consumption in U.S. divided by sector and final use (source: U.S. Department of Energy)

Those criticalities have prompted the U.S. Government to put into place Executive Orders and Mandates to respond to the challenges. The Energy Policy Act of 2005, also known as Public Law 109-58[1], in an attempt to counter the growing energy problem, defines High performance buildings as: "buildings that integrate and optimize all major high-performance building attributes, including energy efficiency, durability, life-cycle performance, and occupant productivity". It also provides a series of incentives designed to reduce the initial cost of investing in energy-efficient building systems and incentives for the use of innovative

[1] Public Law 109–58, 109th Congress, AUG. 8, 2005. Energy Policy Act of 2005

technologies to avoid greenhouse gases and new energy sources. This commitment is further stressed with the Energy Independence and Security Act of 2007, Public Law 110-140[2], pursuing a greater energy independence by increasing the production of clean renewable fuels and increasing the efficiency in various sectors. The act also aims to create a nationwide zero-net-energy initiative for commercial buildings built after 2025 and requires new and renovated federal buildings to reduce fossil fuel use by 55% (from 2003 levels) by 2010, and 80% by 2020. All new federal buildings must be carbon-neutral by 2030. It is interesting to note how the Act defines High efficiency buildings as "a building that integrates and optimizes on a life cycle basis all major high performance attributes, including energy conservation, environment, safety, security, durability, accessibility, cost-benefit, productivity, sustainability, functionality, and operational considerations" promoting the application of sustainable and integrated design and construction.

On the other hand, Europe shows similar results to U.S. in term of percentage division of energy consumption by the building sector although energy consumption per person tends to be lower. Nonetheless, energy security and increasingly relevant climate changes led the European Community to provide a dramatic improvement in energy efficiency, directly affecting the building sector, deemed as one of the most energy intensive and at the same time the one with the largest energy saving potential, requiring significant improvement in the energy performance of buildings.

Following the ratification and subsequent entry into force of the Kyoto protocol and the Copenhagen Agreement[3], European Community and all its Member States adopted the Energy & Climate Package in 2009, also

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[2] Public Law 110–140, 110th Congress, DEC. 19, 2007. Energy Independence and Security Act of 2007

[3] Outcome of the 2009 United Nations Climate Change Conference (COP15)

known as the 20-20-20 initiative, envisioning a 20% emissions reduction, 20% increase of renewable energy and 20% increase in energy efficiency by 2020. The EU also committed to a reduction of 80-95% of the Green House Gas emissions by 2050 as part of the roadmap for moving to a competitive low-carbon economy by 2050.

The greatest energy saving potential is found in buildings, as stated by the European Commission in the "Energy Efficiency Plan 2011"[4]. A minimum energy savings in buildings could potentially generate a reduction of 60-80 Mtoe/year in final energy consumption, as stated by BPIE *(Buildings Performance Institute Europe, 2011)*, making a considerable contribution to the reduction of GHG emission and to the achievement of prefixed goals. However only if buildings are transformed through a comprehensive, rigorous and sustainable approach this could be achieved.

The European Community developed a policy framework for buildings well before the introductions of those goals, going back to the early 1990s and constantly evolving since then. Individual state members adopted various measures to actively promote the improvement of energy performance in buildings. In 2002 the issue gained awareness with the adoption from European Community of the Energy Performance Building Directive, or EPBD[5]. The EPBD was also recast in 2010[6] to make the goals more ambitious and to reinforce its implementation. In the communication proposing this revision, the commission stated: "The sector has significant untapped potential for cost effective energy savings" realising this potential will depend crucially on the commitment

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[4] Communication "Energy Efficiency Plan 2011" [COM/2011/0109]

[5] DIRECTIVE 2002/91/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 16 December 2002 on the energy performance of buildings

[6] DIRECTIVE 2010/31/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 19 May 2010 on the energy performance of buildings (recast)

of Member States, and the involvement of stakeholders from government, industry and civil society.

In an important step toward energy independence the EPBD recast introduces the concept of nearly zero energy buildings forcing all new buildings to adopt this standard by the end of 2020. To serve as an example all new public buildings are required to be nearly zero energy starting from 2018. The recast also defines nearly zero energy buildings as "a building that has a very high energy performance, where 'the nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including clean energy produced on-site or nearby". To the EU member states is also required to prepare national plans in order to increase the number of nearly zero energy buildings also considering possible differentiations according to building categories. Each member state is also requested to introduce a national definition of the "nearly Zero Energy Buildings" according to EU guidelines, introduce intermediate goals to improve the energy efficiency and performances of new buildings from 2015. By this date each state is also asked to detail information on policies, incentives and other measures adopted for the promotion of nearly Zero Energy Buildings, including details on the use of renewable sources in new buildings and existing buildings undergoing major renovation.

Aside from national or supranational initiatives and regulations such as the ones discussed above, various other programs are flourishing in the private sector, such as the USGBC LEED or the CASBEE rating systems, defining standards and parameters to evaluate the level of sustainability of buildings *(Fowler et al., 2006).*

Concluding we can say that he policy framework around the building energy issue with regulations, incentives and initiatives to achieve high levels of energy efficiency in buildings and strongly reduce energy consumptions, ensuring at the same time high levels of health and comfort, is actually available and can make a positive impact but they need to be properly implemented from design to construction and operation of buildings.

1.2 Design of energy-efficient buildings

As previously discussed, the energy problem has had a profound impact on the developments in building during the last four decades. In particular the starting point was the energy crisis of the 1970s which prompted a general use of thermal insulation materials, double glazing and tighter building shells, all of which are now considered standard measures. Since then, researchers and architects have developed an extensive set of specific measures and features that help to make buildings more energy-efficient. Many of those, for instance high-efficiency heating systems or heat exchange systems for ventilation air, has long been in common use *(Althof et al., 2001)*. In many countries requirements regarding energy efficiency have been included in the building regulations, ensuring that designers and builders address this issue. In order to persuade the industry to go beyond these requirements a range of other incentives is being used, including financial aid, contests for designing energy-efficient buildings, and the assignment of special status to specific buildings.

The increased attention to energy efficiency of buildings has also resulted in a need to understand the principles of heat and mass transfer in buildings, and to apply these principles to the building design process. The key discipline that studies building energy issues is building physics. Building physics covers all physical aspects of buildings: thermal, hygrometric, ventilation, lighting and acoustical; it provides computational and measurement methods to describe and quantify the related physical phenomena. Regarding building energy issues, the discipline provides computational methods that allow to assess energy use, temperature distribution, and thermal comfort based on human response models. It studies parts of buildings (e.g. thermal bridges, the building envelope or individual rooms), whole buildings and even urban environments. In doing so, building physics provides the knowledge basis for other disciplines including mechanical engineering (the discipline that deals with heating, ventilation and air-conditioning systems), architecture (the discipline that designs buildings) and others.

However, in spite of all efforts achieved so far in developing energy-efficient buildings, energy conservation measures and methods to support the design of energy-efficient buildings, there are both opportunities and needs for further improvements.

In fact, the set of measures and features that make buildings more energy-efficient ranges from general principles (for instance compact building form or zoning) to specific, off-the-shelve systems (for instance heat pumps and solar collectors) and apart from a few exceptions (like zoning) these principles materialize in the form of distinct energy conservation measures or components that are integrated in these buildings. But is important to note that in general the contribution to the overall energy efficiency of the building provided by these components strongly depends on the thermal interaction between the component and the rest of the building (e.g. the interaction between a sunspace and the adjacent building). Also it must be noted that many of them not only have an impact on energy efficiency, but on other performance aspects like thermal comfort, daylighting, ventilation and moisture balance and last but not the least, they play an important role in architecture as they are tangible additions to buildings that demonstrate the ambition of the architect to achieve an environmentally friendly building design *(Snow and Prasad, 2002)*.

Yet in many projects the actual contribution of energy conservation measures or components to the energy efficiency of the buildings in which they are integrated remains unclear; the lack of literature on monitoring and evaluation of building projects applies here, too. For most components the impact of integration with occupant behaviour, building control settings, climate conditions and urban context is unknown, not took into account or rapidly evaluate in the final stages of design.

So, an opportunity of improvement is related to the design decisions concerning the integration of energy conservation measures in buildings that need careful consideration during the building design process as the objective of making a building energy-efficient needs to be balanced with other, often conflicting requirements.

A first possible solution to this problem is the implementation of the "Integrated Building Design" approach, also known as "Whole Building Design" or more in general Integrated Design Process (IDP).

The concept of an integrated approach to the solution of a problem is not new. Its modern definition takes its roots from the concept of holism, a term coined in 1926 by Jan Christian Smuts, a South African Prime Minister and philosopher, indicating the idea that natural systems and their properties should be viewed as wholes, not as collections of parts. This often includes the view that systems function as wholes and that their functioning cannot be fully understood only in terms of their component parts.

Integrated building design draws upon those concepts of synergies and interconnectedness and is based on two major concepts: an integrated design approach and an integrated team process. The integrated design approach asks all the members involved in the design, construction and operation of the building to look at the project objectives and components from various different perspectives. This approach is a deviation from traditional design process, which tends to isolates the various specialties from each other leaving the single specialists to find a solution to the single problems based on their own expertise.

At the same time, to make this integrated approach possible, the introduction of an integrated team process is needed. In this process, outlined in Figure 1-2, a design team composed by all specialists involved in the design process and all affected stakeholders work together during various project phases to evaluate the design and all possible options in term of its objectives: cost, quality of life, future flexibility, efficiency, overall environmental impact, productivity, creativity, and how the occupants will be enlivened.

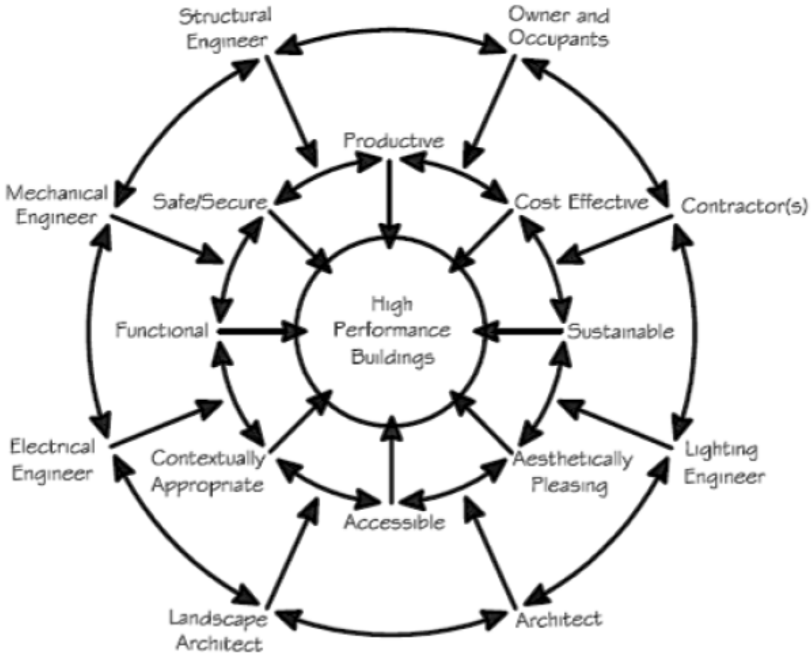


Figure 1-2: Integrated Building design and its objectives

During the design of a building, various objectives are set, and each of them can be equally important, it is essential for a successful design to identify those goals early during the design process and evaluate their interdependencies to proper balance them. A crucial element of the IPD approach is therefore shifting design decisions upstream in the project's process *(AIA, 2007).* The "MacLeamy Curve", as shown in Figure 1-3, illustrates the idea of making design decisions earlier in the project when the occasion to influence positive outcomes is maximised and the cost of changes minimised *(Aziz, 2011).*

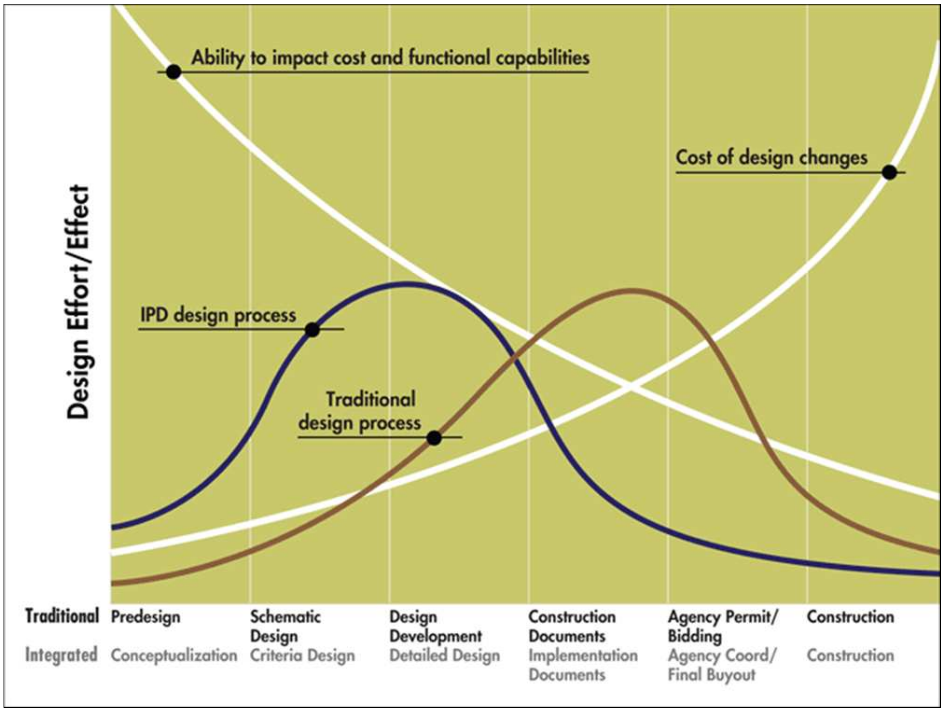


Figure 1-3: The "MacLeamy Curve" IPD impact on the design process

By involving the various figures of the building design process from its beginning, integrated building design enables the design team to adopt an interactive approach. This enables to promptly elaborate interdependencies and develop different strategies during early stages of building design maximizing the ability to impact costs and functional capabilities of the buildings while limiting costs of changes in the design to achieve them.

Interactivity constitutes one of the major differences compared to traditional design, where experts in specific fields of building design (like systems, structural or energy) are typically drawn into the design process too late to positively influence it, when major decisions are already taken and the costs of design changes hinder the implementation of different strategies *(Graham, 2006)*.

1.3 Design computational support

In the "Integrated Building Design" approach described above, in order to make well-considered decisions, all the decision-makers need to have information on the actual or expected behaviour of the building. This information can either be obtained from measurements, from computations and in a small part from the experience.

Measurements can be taken from a real building or from an experimental set-up, while the use of experience as source of information for making design decisions actually bases itself on observation from previous buildings, through the same principles of measurements and/or computation. But the use of experience is limited to similar buildings under similar conditions, and is only of limited use when developing new, innovative building concepts.

On the other hand, computer modelling and simulation is a powerful technology for addressing interacting architectural, mechanical, and civil engineering issues in buildings.

The different computational tools that are used during the building design process can be positioned in a general framework as presented by Hendricx *(Hendricx, 2000)*, who discerns three categories of tools: modeling tools, design tools and analysis tools. The first category of modeling tools relates to the use of computers to represent the evolving ideas of a building as an artifact during the design process. These tools allow to graphically capture the (intermediate) design and to capture relevant information like dimensions, shape, materialization etc. The category of design tools uses the computer to generate design alternatives; here the computer helps to modify and improve on existing building designs. This category contains both automated design (where the computer itself generates design alternatives) as well as assisted design (where man and machine collaborate to generate design alternatives), so case-based reasoning systems are tools that belong in this category. Finally, the category of analysis tools uses the computer to evaluate buildings or building designs. Here the computer helps to assess properties and performances. A subset of the set of analysis tools is building performance simulation tools. Building performance simulation deals with different kinds of building performance aspects (in contrast to analysis tools that deal with building properties). The most important performance aspects are energy transfer, structural stability, acoustics, (day)lighting, indoor air quality and air flow. Of these, building energy simulation and structural stability are the most prominent fields.

In particular Research and Development in the field of building energy simulation have produced a large number of energy-related computer programs. These tools range from simple to sophisticated computer programs, and range from tools that consider one performance aspect only to tools that take a more integral view. Also, they might be intended to be used by designers, consultants, or might be developed for use by experts working in a research context.

In any case, the most important aspect is that, respect on measurements and experience, building energy simulations can be used to study existing or future buildings and can really help, during every stage of integrated design, in reducing emission of greenhouse gasses and in providing substantial improvements in fuel consumption and comfort levels, by treating buildings and their thermal systems as complete optimized entities and not as the sum of a number of separately designed and optimized sub-systems or components *(Hensen, 2004)*.

In fact, with a similar concept to the one of the integrated approach, the efficiency of energy conservation measures cannot be studied in isolation, because the interaction between components can have a substantial effect on the efficiency of each individual component, and considering also the impact of climate conditions and occupant behaviour, it become clear that it’s almost impossible to predict building performances without use of computational tools *(de Wilde and*

Augenbroe, 2009). Nonetheless, recently, there has been a strong push toward zero/nearly zero energy buildings and the nature of the aggressive goals of NZEBs is another example that requires the creation of energy models during any design phase in order to predict the real behaviour of the building *(Utzinger, 2009).* So, even if with conventional buildings and installations there is often no need for simulation because standard methods and data provide enough information for design, in less simple situations, where complex building physics or complex installations are involved, a proper (integrated) design cannot be achieved without the help of simulations, that must be an essential part of the building design process *(Clark, 2015; Augenbroe, 2011)*. After all experiences with real buildings have shown that low-energy design is not intuitive and that simulation should therefore be an integral part of the design process *(Hayter et al., 2001; Torcellini et al., 1999).*

Now, despite the importance during the design process and although in the last ten years the building performance simulation discipline has reached a high level of maturation, offering a range of tools for building performance evaluation, there are concerns about the actual role and use of building performance simulations. In fact, for a long time the researchers has discussed about the barriers that prevent the integration of analysis tools and the building design process *(Hensen, 1993, Degelman et al, 1993; Radford, 1993; Aho, 1995; Mac Randal, 1995; Robinson, 1996; Hand, 1998; Augenbroe, 2001; Donn et al., 2001)* with doubts whether existing computational tools are used at all during the design process, and if so, whether the capabilities of the tools are fully exploited.

The discussion is still open (Clark et al., 2015) and there are various schools of thought about what causes the lack of integration:

- Simulation tools may not play an important role in the selection of energy saving conservation measures since these tools requires too much time and expertise, and are considered not compatible with architect's working methods and needs. For this reason, they are mainly used in later phases than those relevant for the selection, most of the times also with different purposes like optimization and verification rather than to support choices *(Van Dijk et al., 2002; Gratia et al., 2002)*;

- Current tools are inadequate, user hostile and too incomplete to be used by architects during the design process and consequently the energy analyst is often included too late to influence the outcome of the design *(Graham, 2006)*, leaving little opportunity for engineers to collaborate with architects in the design of energy efficiency aspects of the building envelope and systems. In this context a gap still exists between architects as users and building performance simulation tools *(Warren, 2002)*, where some designers are still finding it difficult to use even basic tools *(Punjabi et al., 2005)* and most energy conservation components are selected based on analogy: use of similar components in previous buildings by the architect or consultant or the use of these components in demonstration projects;
- Building thermal simulation tools still have a low impact in the building design community, even with legislation, industrial and technological development requiring performance oriented and energy efficient buildings, because current outputs from simulation tools are sometimes considered unrelated to concepts that are meaningful to the building designers and incompatible with their constructivist/experimental/'learning by doing' way of approaching problem-solving, basing the problem of integration on aspects related to data interpretation and practice *(de Souza, 2012; de Souza, 2013)*;
- Even though techniques of building performance simulations are undergoing rapid change and improvements in computing power, algorithms, not feasible few years ago, the balance between

achieving sufficient accuracy and the ability to provide highly flexible and fast feedback to the designer is still today a topic of discussion, as simplified BPS tools are fast but only provide simplified feedback while more advanced BPS tools are difficult to use and are often slow in comparison to the simpler tools. Further-more, only a fraction of these BPS tools can be used in automated processes required to perform building energy optimization and simplified BPS tools may evidently increase risks of returning inaccurate results *(Negendahl et al, 2015)*;

In particular the major problem is that existing simulation tools are not practical for the design process due to their high level of expertise needed for full use of simulation tools, high costs (both time and money) connected to simulation efforts, and problems related to data exchange (mismatch between available information about an intermediate building design and information requirements by simulation tools).

Therefore, in spite of the great potential and availability of existing instruments, the suitability of current computational tools to support the building design process remains an issue of debate; the way forward might be the modification of existing tools or the development of new tools that fit better into the design process, in other words the development of easy-to-use computational tool able to respect the two most important general needs of the design process, time and accuracy of results.

1.4 Research problem and goal

The general problem addressed in this thesis is properly the latter, the integration of building performance analysis tools and the building design process. As previously mentioned, although building performance analysis can be expected to be an essential part of the building design process, actual application of analysis tools to provide information to support building design decisions does not live up to this expectation.

During the design process, the energy analyst is often included too late to influence the outcome of the design, leaving little opportunity for engineers to collaborate with architects in the design of energy efficiency aspects of the building envelope and systems that affect heating, cooling and ventilation loads.

As well, simulation tools do not play an important role in the selection of energy conservation measures, since these tools requires too much time and expertise and consequently it appears that decision-making on energy saving building components is based on simple, heuristic decision rules.

However, there are compelling reasons to strive for a better integration of the building analysis tools and further integration into the building design process, from its first to its last phase:

- During the design process a great number of decisions need to be taken. Typical design assessment criteria are costs, flexibility, energy efficiency, environmental impact as well as comfort of occupants. It is self-evident that a more efficient use of building performance simulations would be very beneficial for the end result *(Hensen, 2004)*;
- Building energy analysis tools can provide essential and detailed information about the thermal performance of buildings that have not yet been built. This permits objective comparison of different design options allowing design teams to make better informed design decisions, and contributes to preventing over-engineering of buildings from an energy-saving point of view *(de Wilde, 2004)*;
- In an era where international consensus seems to be settling on a goal of Net Zero Energy Buildings, there is a great need for building performance analysis and simulation tools that model building performance in all its real-world messiness and compare design strategies, test control strategies and estimate energy use patterns;

- The building performance objectives have raised the bar of building performance and this means that evaluating different design options is becoming more arduous than ever before. The building geometry, envelope and many building systems interact, thus requiring optimizing the combination of the building and systems rather than merely the systems on an individual level. One promising solution is to use building performance simulation as a means to evaluating many different design options and obtain the optimal or near optimal *(Attia et al., 2013)*;
- BPS with hourly or sub-hourly data provides the possibility of constructing detailed building consumption profiles and can provide an added value to the regular monitoring process: where there is no historical data available, no data can be subjected to any of the mathematical analysis methods. In such a case, virtual data can be created in a couple of days or weeks depending on the complexity of the building and experience of the modeler, providing an edge over an empirical approach, where normally several weeks or even months of actual data need to be collected before there is sufficient data to train one of the mathematical analysis methods *(de Wilde et al., 2013)*;
- Sustainable building design requires considering the geometric and visual properties of the design as well as the physical, technical, and economic engineering interdependencies that determine the building's performance. To achieve significant improvement, one key is using the appropriate building modeling methods, considering the relevant engineering interdependencies to support the design process and the involved design experts *(Geyer, 2012)*;
- Current systems are becoming very complex. To support their design and to facilitate testing, simulation is becoming an essential method for improving the design of plants as well as to

optimize their behavior. Simulation is considered as a basic tool for a virtual commissioning of plants, which is intended to optimize the structure of plants during engineering processes as well as to test and to fine-tune control algorithms. These kinds of tasks require many experiments. Making them on the real plant directly would be time-consuming and costly, therefore, the preferred approach is to shift the experiments into the simulation world. Furthermore, experiments on real systems can be unsafe, unrepeatable under the same conditions and costly *(Novak et al., 2015)*;

Now, all these reasons have to meet with the needs related to the design process and the needs related to the composition of the integrated design team.

Needs related to the design process itself, as can be imaged from the previous Section 1.3, can be easily identified in time and accuracy, since they are both unconnected to the composition of the design team but linked to the correct progress of the design process itself *(Picco et al., 2015)*. Accuracy is an essential prerequisite to every analysis used to inform decisions in every field, since if the analysis is not accurate the results could be misleading and the decisions based on those results could be non optimal or even wrong.

The problem becomes significantly more relevant during the design process of buildings, where the decisions taken can concern a relevant amount of energy and money, affecting the building for a large number of years. To worsen this issue is the difficulty to change wrong decision made during previous design in subsequent design phases or even during management phase.

Accuracy is therefore an imperative of energy analysis and cannot be overlooked; the problem is that an accurate energy analysis of a building is not an easy task and requires long times and heavy workloads for the creation of a detailed model, which consequently requires a level of details not always available at each phase, an adequate time to perform various simulations and finally, extrapolation and elaboration of the results.

So accuracy is in contrast with the necessity to minimize the time needed for the analysis, but to minimize times simplifications of the building model and simulation tools are needed, with the drawback of a loss in accuracy. Using a common saying we can state that accuracy and time are two sides of the same coin, the more an analysis must be accurate the more time is needed to execute it, the less time is available to execute it the less accurate the results will be.

It is also interesting to note how the more the design process is in its advanced stages, the more details are available and longer is the time available to develop complex and accurate energy analysis. On the other hand the more the design is in its initial phases the less time is available for the analysis, but at the same time the less and more undefined are the details available on the building itself, permitting less accurate analysis.

Summarizing:

- To be easily adopted, energy performance simulations must fit with the needs related to the design process, represented by time and accuracy;
- Time is required to perform accurate simulations, but design is a dynamic process, which evolves through time and can’t be easily stopped to perform too long detailed simulation, especially at the early stages;
- It is therefore extremely important to identify the adequate level of accuracy needed at each design phase and develop a corresponding model of the building simplified enough to not require data not yet available, to be executed and evaluated compatibly with the corresponding design times and at the same

time complex and complete enough to guarantee an adequate level of accuracy so that the results obtained can still be relevant;

the research question answered has been:

Is it possible to obtain a sufficiently simplified (easy to use and flexible) modeling support tool such as to be compatible with time requirements and available information at all stages of integrated design but still able to generate sufficiently accurate results to identify the correct behaviour of the building-plant system and draw conclusions on the various design choices?

In order to answer the last question, the research goal has been the development of a new modeling support tool (created using the dynamic calculation engine TRNSYS) able to simulate a very large number of integrated building-plant systems at any stage of the building process, thanks to its flexible structure and the possibility to apply a sizing protocol and a simplification protocol that can permit, depending on the design phase, to considerably reduce the number of necessary inputs for the simulations, thus minimizing the modeling, implementation and simulation runtime of the model, while still maintaining an acceptable degree of accuracy with respect to the computational results and real energy consumptions.

About the needs related to the composition of the design team, various researches have been made trying to identify the real information needs of designers in the various design phases.

Of particular interest on this subject is a research carried out by Michael Donn, Steve Selkowitz and Bill Bordass *(Donn et al., 2009)*. Quoting their work, there is a general agreement within the community of building performance analysts that design decisions made from the first hours and days of the design process are critical to the successful operation of a building. This has led many researchers to the development of environmental design decision support tools for use in all the design process, especially in the early phase. The stereotypical approach to these tools is to run many, even hundreds of thousands simulations and to summarize their results in charts, tables and even simple digital interfaces. These summaries are presented as design advice or rules of thumb. But this pre-processed information often represents a limited subset of the infinite variety of potential designs.

In fact these summary guidance projects serve an educational purpose and rarely assist the development of a design strategy, not fitting comfortably into a world that needs quantifiable answers to design questions about the specific site and program that are posed very early during concept design.

The conclusion is that design teams need rigorous tools that analyse the specific ideas and issues, tools that can be used during the whole process of the building design answering the following key questions:

- likely costs of operation; these costs should be energy demand, CO_2, productivity, maintenance, and should be presented in hourly, daily, weekly and seasonal plots.
- likely variation of comfort variables in space and time: thermal, lighting, glare, provided just by the building with no energy consuming services, so that the inherent building performance is revealed; and with services in place to reveal the likely interaction of building, people and services.
- likely risks to comfort and cost of poor equipment reliability, poor/normal installation practice, poor control performance;
- likely interaction between equipment and user-operable controls (lights, open-able windows, shades);
- likely impact of climate change in a manner that helps the client to budget properly.

All these criteria require answers that are sufficiently based on models of the building physics and are specific to the building site, climate, likely or better real-world data on user-behaviour, maintenance and building operation.

So the goal is to put in the design team's hands tools that help them to model normally observed human behaviour and real buildings with design performance analysis that, like architectural sketches on tracing paper, are gradually changed during the entire design process.

In this way, we can also add the conclusions presented by Attia *(Attia et al., 2011; Attia et al., 2012)* on the characteristics needed by a simulation tool usable especially during the early design phases. The tools must be characterized by intelligence, usability and interoperability, in other words they have to be:

- Very easy to use;
- Easy to Learn;
- Sufficiently accurate;
- Informs design decisions;
- Use minimum amount of input;
- Allows alternative comparison;
- Match the cyclic design iterations;
- Adaptable to the users expertise;
- Flexible and fast enough to facilitate changing representations of innovative design concepts thus being able to dynamically scale the model resolution to fit the different information levels *(Struck,2012)*;

Another interesting point of view is finally presented by Laure Itard, who presents *(Itard, 2003)* the needs of design Engineers in relation to energy analysis and simulation tools. From these studies it follows that a tool should have the following properties:

- The effect of building physics parameters on installation capacities and energy use should be visible;
- Integral effects should be visible;
- The result should be in a form that allows for clear communication with other figures involved in the design process;
- It should be possible, without too much difficulty, to change to other simulation environments or to use more detailed software;
- The simultaneous cooling and heating demand should be made visible;
- The required input should match the data known in the current design phase;
- The accuracy of the input data and of the results should be in agreement with the accuracy needed in the related design phase;
- It should be possible to enter more accurate data and to produce more accurate results as the design process progress;
- It should be possible to test the effect of control strategies on the energy use in an early stage.

In the belief that a good simulation tool to be applied in every design phase must meet as many of those needs as possible prioritizing the duality between time and accuracy, but without neglecting the importance of a correct definition of input and output to maximize its effectiveness, the development of the new modelling support tool has tried even to satisfy all the features mentioned here related to the needs of the design team.

1.5 Thesis outline

The research presented in this thesis, based on the question problem and goal just described, has the following outline:

- Analysis of the context and starting point for the research, with an in-depth review of the existing design support theories and tools, with assessments describing their strengths, weaknesses and possibility of improvement in the integration of design process and building performance simulations;
- Development of a new modelling support tool able to overcome the current limits of integration;
- Application to a suitable number of case studies, in order to validate the tool and its whole methodological structure;

In particular Chapter 2 discuss the state of art of the existing theories and tools, also in order to understand the best approach and procedural aspects for the development of the new modelling support tool, that must be characterized by great usability during all the stages of the building-plant system design.

All the features of the new tool are described in the Chapter 3, including the starting detailed TRNSYS model, its multiple flexibility and the applicability of a sizing and simplification protocols able to reduce both the simulation and modelling workloads, in order to match all the design times and requirements but still maintaining an acceptable degree of accuracy.

Chapter 4 shows the application of the tool to three different case studies, in particular starting from the detailed model and progressively enhancing the level of simplification to demonstrate the feasibility of the overlying ideas and to validate them, especially in terms of time-accuracy ratio, with respect to both computational results and real energy consumptions.

Finally, Chapter 5 completes thesis by providing a summary of the work and conclusions of the research.

Chapter 2

2 Design support theories and tools: state of art

Chapter 1 revealed that many researchers continue to observe a lack of integration of analysis tools in the building design process with doubts whether existing computational tools can be considered applicable to the design process due to their high level of expertise and time needed for their full use. Accordingly, it also stated that yet in many projects the selection of energy conservation measures or components mainly takes place in an intuitive manner, based on earlier use of the same components in previous buildings and in analogy with demonstration projects, leaving unclear or unknown the actual contribution of these components to the energy efficiency of the buildings in which they are integrated.

The mainly conclusion is that both the existing selection procedure of energy saving components, as well as the existing tools that support that procedure need to be improved.

In this context, this chapter deals with theories and tools already created to support energy-efficient design process. The main goal, for theories, is to illustrate the many ways set up in helping the integration of energy simulations and to find basis for the strategy to adopt in the development of the new tool. For the existing tools, the aim is to report the various assessments about their adequacy in providing support for the building design, therefore to identify possibilities to improve them and future tools.

In fact, some of the ideas from theories and improvement of tools described in this chapter have been exploited for the development of new simulation tool shown in the following Chapter 3.

2.1 Existing theories

As just stated, many ways have been taken trying to incorporate energy simulation advices during building design, like the creation of protocols guidelines and decision making processes.

Discussing some of the many researches carried out on this subject, we can start mentioning the creation of modelling protocols for the energy design assistance, like the one proposed by Chris Baker, Prasad Vaidya, and Alan D.'Souza *(Baker et al., 2010),* helping designers and also the development of energy simulation tools.

In fact, modelling protocols illustrates methodology on how to execute efficacious energy analysis, obtaining correct and relevant results.

Modelling protocols can also help developing more efficient tools and codes increasing the reliability on simulation tools and avoiding wrong results or allowing more detailed and accurate evaluations adding information to the results and helping the user in their analysis. In the aforementioned instance various advice on how to provide more valuable baseline criteria are given, taking into account variables previously excluded and improving the methodology itself.

Another interesting and easy way for implementing energy simulation advices in building design process is the creation of guidelines to solve specific problems like proposed, as an example, by Robert Hendron *(Hendron R., 2006)* in its studies on whole-house energy analysis procedures for existing homes.

Those guidelines do not directly propose a simulation model or specific solution to the energy saving problem, but help the energy counsellor in the development of a correct methodology for the evaluation of energy consumption of the building, in the specific case illustrating how to produce an adequate pre-retrofit model and post-retrofit model of the building to be analysed. The guideline also proposes recommended values for characterizing the building parameters in case those are not available, like R-values, energy efficiency of existing plant equipment or how to correctly evaluate operating conditions of the building. Although not directly related to the simulation process, guidelines can help the user in avoiding errors and speeding up the simulation process, helping the accuracy and the integration of the energy analysis in the design process.

The third, but most important way for this research, to introduce energy simulations in the energy-efficient building design is the development of a performance-based decision making approach like the one proposed by Pieter de Wilde *(de Wilde et al., 2001, de Wilde et al., 2002, de Wilde, 2004)*. The approach defines the essential steps that should always be taken for well founded selection of energy saving building components, structuring the sequence and interrelations of these steps, with the additional aim to enable the maximal use of computational tools during the building design, especially in the early phases.

The steps are the following:

Development of an option space;

The first step in making performance-based design decisions is to identify which alternative design options are to be considered; in systems engineering the set containing all options is named the option space. Options can be generated by definition of different system configurations (combinations of sub-systems, for instance combinations of a building design with different energy saving building components) and by changing the parameters of these system configurations. For specific design situations it is possible to identify specific parameters which can be varied over a permissible range; this is named parameterization of the option space. It is recommended to include the initial building design, without extra energy saving component, as zero-option. Note that it is imperative that the option space contains a manageable, finite set of options. Evaluation of all possible combinations of a building design with all available energy saving building components (complete enumeration and subsequent selection of the optimal solution) is not within reach: it is easy to develop a host of different system configurations, which are all subjected to variable parameters, and thereby to explode the option space to unmanageable dimensions. For this reason expert knowledge and expertise regarding the design under development remain essential to success, since only experts in the field will be able to develop an option space that contains the relevant and most promising design options.

Identification of the relevant functions of the design options;

In parallel to the development of the option space, thought must be given to the functions that these design options must fulfill. Identification of the relevant functions (performance aspects) is essential for finding the relevant criteria for making the pending design decision. Obviously, the main function of the use of energy saving building components is to make buildings more energy-efficient. Yet energy efficiency is only one of many objectives that must be considered in the building design process; the notion of "energy efficient building design" as a mono-discipline is clearly fictitious. For instance an important function relevant to many energy saving components is the building function of maintaining thermal comfort. A rational selection of energy saving building components is only possible if different functions are identified and considered. Those functions are related to the aspect-systems to which the components belong. It is imperative that the set of relevant intended functions (criteria) remains manageable, too. Again, expertise is essential. In cases where the expert evaluating the options is not the building designer, negotiation and discussion should lead to a finite set of functions/criteria that will be evaluated.

<u>Specification of performance indicators, objectives, requirements and constraints;</u>

Once the relevant functions of the alternative design options have been identified, (technical) performance indicators must be selected that describe how well these options perform their functions; performance indicator values will represent the performance of all alternative options. It is important that the list of performance indicators is complete (adequately covers all relevant functions), operational (meaningful), and non-redundant (preventing double counting of the same achievement). Additionally, the set of performance indicators should help to decompose the relevant functions into manageable, measurable performance aspects, while at the same time being of minimal size. Note that performance depends on the interaction of a system with its environment. Therefore the explicit definition of the (virtual) experiment that will be carried out needs to be included in the definition of the performance indicator. For instance, the main function to "make the building energy-efficient" can be measured using the energy consumption per year, or using peak heat demand. However, an energy consumption value for a given design option is meaningless when it does not come with a specification of the types of energy use that are studied (heating, cooling, lighting), the location for which the energy consumption is predicted (for instance Atlanta or Amsterdam), the occupant behavior and HVAC control that is assumed (operated all year, only in weekends).

<u>Prediction of performance;</u>

As the performance of a design option (building plus energy saving component) is a function over the properties of these options when subjected to specific conditions, an experiment is needed to measure or predict this performance. Since the building does not yet exists, the easiest option is to conduct a virtual experiment using building performance analysis tools running on computers. The resulting set of performance indicator values is named outcome space. Note that within the procedure to select energy saving components the use of analysis tools is straightforward, consisting of selection of a tool that is able to return performance indicator values for the design options as specified in the previous steps, and of carrying out the experiment as required.

<u>Evaluation of predicted performance and selection of the most desirable option;</u>

In this step all options must be checked for meeting the requirements; options that not meet those are ruled out. The remaining options must be ordered based on the extent to which they meet the objectives. This implies that (subjective) values must be assigned to the data in the output space, resulting in the utility of each option for each performance aspect (function). In order to make a tradeoff between the different utilities for the different performance aspects (functions), an additive utility function can be used.

The five steps described above have been very important for this research because they have constituted the methodological basis for the development of new simulation tool. In this regard, more details will be shown in the Chapter 3.

2.2 Existing tools

In this section, is reported the analysis of the different main categories of existing tools, their role in supporting the energy-efficient building design and the creations, assessments and possibilities for improvement that many researchers have proposed toward the most important tool category for this research, the analysis tools.

2.2.1 Categories

Starting from the first point, as previously stated, Hendricx discerns three main categories of tools: modeling tools, design tools and analysis tools. Modeling tools help to represent (draw, render, view) a design, design tools help to generate new design alternatives, options or variants, and analysis tools analyze specific aspects of a given design.

However, the three categories do not cover a number of other tools: process/planning tools, communication tools and tools used during building construction for instance are not covered by the framework. Secondly, it is important to note that tools can be embedded in support environments, able to provide functionalities that support the use of other tools, such as easy access through (standardized) interfaces to embedded tools, coupling of tools, use of shared information storages.

The framework that results is summarized in the figure 2-1.

Now, within the different categories a huge number of individual tools is available and all can be used in building design projects. The largest number of tools can be found in the category of analysis tools, while in the category of modeling tools there is a smaller number of tools, even if they all enjoy a broad uptake in architectural practice. In fact, almost every building design project now uses these tools to describe the building design and in particular some well-known tools in this category include AutoCAD, Archicad , Microstation and SoftCAD.

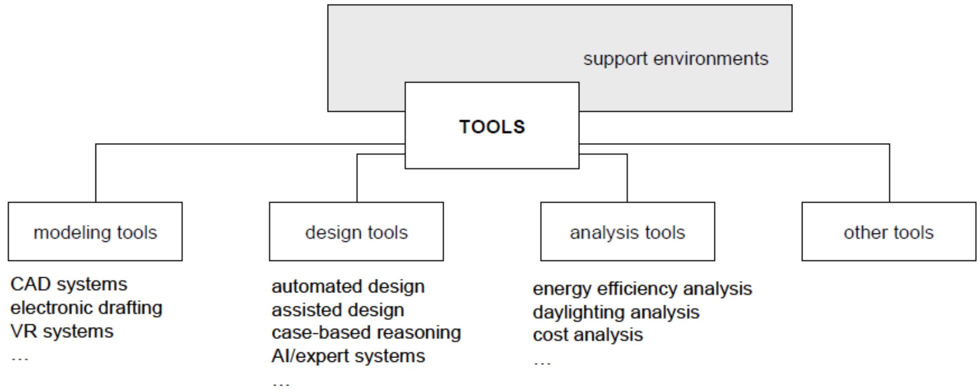


Figure 2-1: General overview of different categories of tools

About the category of design tools, they appears to be less developed, even if it is hard to give a conclusive overview of all existing tools in this field because of the large number of design options and aspects. On the one hand work in the field of case-based reasoning, artificial intelligence and expert systems target this category, but the resulting tools do not seem to have reached building design practice yet. On the other hand electronic product catalogues can very well be used as design tool. It is also interesting to note that when focusing on energy design tools, a close examination reveals that most tools that are described as energy design tools actually are energy analysis tools in the sense of the categories described above.

Going then to the support environments, defined as tools that provide functionalities that support the use of other tools, it can be stated they are still in a development phase.

In fact, they can have different forms with common elements that are modules to communicate with the user, control embedded tools, and manage information exchange. Their development, especially for support the energy-efficient building design, must meet multiple requirements: provide access to suitable tools for relevant steps of the design process, manage information exchange between user and embedded tools, and provide additional functions to the user when compared to the functions of the embedded tools. Key issues that miss from ongoing development efforts and which should be targeted in future development of support environments are the embedding of different analysis tools in one performance domain (e.g. energy analysis), allowing to use the best tool for one specific analysis task, and the absence of efforts to develop a mechanism that determines which tool is most suitable to perform a specific task.

Surely, together with the analysis tools, support environments will represent the most important tools in the integrated energy-efficient building design.

2.2.2 Analysis tools

The category of analysis tools can be subdivided, since there are different types of analysis. First of all there is difference between tools that analyze building design properties and tools that analyze building design performances. Properties are characteristics of the building or building design that are set down with the building design itself, like for instance the floor area, internal volume. Instead performances are related to the building functions and result from the interaction of building properties and building usage, like for instance energy efficiency depending on interaction of thermal properties of building and HVAC-system with the climate, internal gains and schedules.

The category of performance analysis tools can then be subdivided in a set of tools that analyze dynamic performance aspects and a set of tools that analyze static performance aspects. Building simulation tools, the most important sub-category for this research due to their central role in the energy efficient design process, are tools for analyzing building behaviour, and hence are synonymous with tools for analyzing dynamic performance aspects.

The Figure 2-2 shows all the sub categories of the analysis tools.

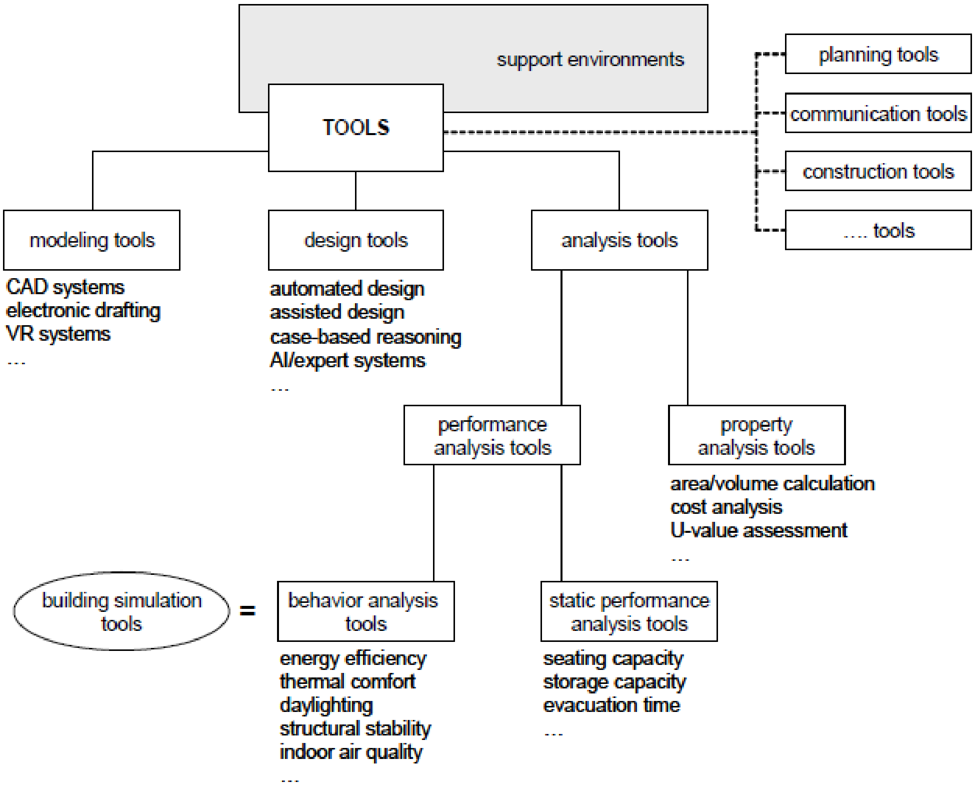


Figure 2-2: Sub-categories of analysis tools

Now, what are the main requirements of the analysis tools that support the steps of building performance prediction (building simulation tools)?

And what are the most widely used existing tools belonging to this subcategory, essential to analyze energy efficiency of whole buildings? Are they all able to be easily used during all the stages of the building-plant system design?

To answer the first question, analysis tools must:

- be able to accommodate the specific building design alternatives;
- be able to carry out the virtual experiments that have been defined, returning either building properties and requested performance indicator values, or generating data from which these performance indicator values can be easily derived;
- be able to provide the requested information rapidly, without halting the design process for extended periods;
- be able to provide accurate information, with regard to the project details available at each step;
- be applicable during all the design phases, starting from the conceptual to the final phase;

Going to the second and third question, following a list with authors and researchers *(de Wilde, 2004; Urban et al., 2006; Brown et al., 2010; Ellis et al., 2006; Itard, 2003; Attia et al., 2009)* assessment and descriptions of more than ten different most widely used tools is reported.

A complete overviews of tools currently available can be found in the building energy software tools directory provided by the US Department of Energy *(Us Department of Energy, 2015)*, directory that now lists more than 450 tools.

EnergyPlus

EnergyPlus is DOE's (US Department Of Energy) whole-building energy simulation engine based on two predecessors, BLAST and DOE-2. EnergyPlus includes advanced simulation features like sub-hourly time steps, simultaneous solution of zone conditions and HVAC system actions, a modular HVAC structure that accommodates a wide range of system configurations. Originally released in 2001, EnergyPlus is continually updated. It forms the analytical basis for energy-efficiency standards such as ASHRAE 90.1 and for both free and commercial energy analysis products. Regarding the capabilities of EnergyPlus to provide computational support in the energy-efficient building design, the following observations have been made:

- EnergyPlus supports an extensive set of options regarding both architectural and HVAC-components. Components that are not yet available can be expected to be developed in the near future.
- EnergyPlus has a large set of user-definable output formats, not only including energy use and thermal comfort, but also reporting daylighting, electrical power production/use etc.
- Application of EnergyPlus is not rapid; modeling design options in this tool is quite an effort.
- The applicability of EnergyPlus to early design phases depends entirely on the capabilities of the users to develop corresponding building models in this tool. The feeling is that is more geared towards evaluation of later design stages.

ESP-r

ESP-r is a dynamic thermal simulation program which supports an in-depth evaluation of the factors that influence the energy and environmental performance of buildings. The ESP-r system has been the subject of sustained developments since 1974. ESP-r is used extensively in both building research and in energy/HVAC consultancy.

Regarding its capabilities, the following observations have been made:

- ESP-r already accommodates a large combination of buildings and energy saving components. Where no pre-defined components are available, there are many users and developers that are able to add components to this tool.
- ESP-r allows many user-defined performance predictions; in fact, the tool is probably one of the most versatile options regarding energy, daylighting, CFD, and complex control system simulation. However, this comes at a price: making ESP-r generate exactly the

required performance prediction requires a high programming literacy.

- Deployment of ESP-r in general is not rapid. A special ESP-r application, the Project Manager has been developed to make ESP-r usable as a support instrument in the building design process. The Project Manager is an application which controls the process of simulation from the initial planning, through the phases of description, simulation, assessment and reporting. The principal aim is to hide complexity by arranging for a single point of problem definition and evolution and a single simulator which can recognize partial problems and act accordingly.
- Depending on the capabilities of the users to develop corresponding building models in this tool, ESP-r can be used in all design phases. Overall however, the feeling is that ESP-r is more geared towards evaluation of later design stages.

Building Design Advisor (BDA)

BDA is a software environment that supports the integration of multiple building models and databases used by analysis and visualization tools, through a single, object-based representation of building components and systems. BDA (Building Design Advisor) acts as a data manager and process controller, allowing building designers to benefit from the capabilities of multiple analysis and visualization tools throughout the building design process. BDA is implemented as a Windows-based application.

Regarding the capabilities of the BDA to provide computational support for the procedure for selection of energy conservation measures, the following observations have been made:

1. BDA can accommodate option spaces that can be handled by the analysis modules (the current version includes links to a simplified Daylighting Computation Module (DCM), a simplified

Electric lighting Computation Module (ECM), and the DOE-2.1E). The description of these designs can be supported by using the BDA databases/libraries.

2. Although operational conditions can be modified by the user, the building analysis in the BDA appears predefined, allowing all building design variants described to the BDA to be evaluated and represented in the decision desktop in the same manner. In other words: there probably is only limited room to make the BDA predict building performance in the metrics of the specific performance indicators.
3. Because of the default selector in the BDA, the BDA can be employed rapidly.
4. However, the speed of the computations performed with the BDA depends on the speed of its components; for thermal simulation, the BDA is therefore just as fast as traditional DOE-2 simulations.
5. The same default selector makes the BDA suitable for use in early design stages, when not all details of a building are available.

Capsol (Physibel)

Capsol is a thermal building simulation program to calculate multi-zone dynamic heat transfer, which takes into account heat capacity (Cap-) and solar radiation (-sol).

About its adequacy to provide computational support for the energy design procedure, the following observations have been made:

- Capsol can perfectly accommodate option spaces that are based on architectural variation. It is not intended to analyze HVAC-systems, so HVAC-related energy saving building components are more difficult to simulate.
- Capsol has an extensive set of options to generate thermal performance data according to user preferences.

- Capsol does not require programming efforts to do simulations, describing a simulation is straightforward. Calculation times are state of the art, allowing the simulation of a multizone building for a full reference year with hourly climate data in a timeframe of minutes.
- It's intended to be applicable in all phases of the building design process. It is applicable during early phases, provided that the user can model the building and enter appropriate (default) values that are needed for the simulation.

IDA Indoor Climate and Energy

IDA Indoor Climate and Energy (IDA ICE) is a whole year detailed and dynamic multizone simulation application for the study of indoor climate as well as energy. IDA ICE is mainly designed for HVAC designers and sustainable design engineers and allows simulation experts to build their own air handling units, plants and control systems. Advanced users may also add new equation based models.

For this software, the main observations have been:

- IDA-ICE is geared towards architectural (e.g. atria) and specifically HVAC-related energy conservation measures.
- Because of its embedding in a general simulation environment, IDA-ICE allows to obtain specific, tailor-made performance predictions; however, this requires expertise to work with the general IDA-tool.
- IDA-ICE seems to be more suitable for use during later phases of the design process, where much information on component-level is available.

Matlab/Simulink

Matlab is a general computing and analysis environment used by engineers worldwide, in all kinds of domains. Simulink allows modeling, simulation and analysis of dynamic systems. Some research institutes and universities have used these tools to do building performance simulation. Recently it has also been developed a first HVAC toolbox for the MATLAB/Simulink environment called SIMBAD Building and HVAC Toolbox, able to perform transient simulations of HVAC plants with short time steps. The toolbox provides a large number of ready to use HVAC models and related utilities to perform dynamic simulation of HVAC plants. This toolbox, in connection with other existing toolboxes (Neural network, fuzzy logic, optimization...), offers a powerful and efficient tool for design and test of controllers. The tool is primarily intended to those involved in control of HVAC systems and is dedicated to the development and test of control algorithms or of prototypes of controllers linked to the PC via a data acquisition system (real time simulation).

Regarding the capabilities of Matlab/Simulink to provide computational support for the energy design procedure, the following observations have been made:

- Basically any system can be analyzed using Matlab/Simulink; however, a complete modeling effort (from problem description to development of mathematical equations) will be required, since other models are not easily obtained.
- Matlab/Simulink will allow all kinds of performance predictions, but again at the cost of a complete modeling effort.
- Because of the need to do all modeling, Matlab/Simulink is not rapidly applicable to building analysis problems, even if the new tool SIMBAD try to reduce the efforts in this field. However the latter seems to be more suitable for use during later phases of the design process, where much information on component-level is available, especially regarding the control sub-system.

TRNSYS

TRNSYS (TRaNsient SYstem Simulation Program) is an energy simulation program whose modular system approach makes it one of the most flexible tools available. With more than 35 years of commercial availability, TRNSYS is still a component-based software package that allows to validate new energy concepts, from simple domestic hot water systems to the design and simulation of buildings and their equipment, including control strategies, occupant behaviour, alternative energy systems (wind, solar, photovoltaic, hydrogen systems).

It includes a graphical interface, a simulation engine, a large suite of tools and a library of components (called Types) that range from various building models to standard HVAC equipment to renewable energy and emerging technologies. It also includes a method for creating new components that do not exist in the standard package and it provides also the possibility to interface with various other simulation packages such as COMIS, CONTAM, EES, Excel, FLUENT, GenOpt and MATLAB.

The general interface is called Simulation Studio, the environment that serves as a robust, intuitive, graphical front end of the simulation, making the user's job of assembling a detailed system, with all its single components, a simple effort - similar in nature to hooking up the pipes and wires in a real system.

In fact the dynamic simulation of every system is performed in TRNSYS connecting each system Type/component, in the graphical interface Simulation Studio, according to an input – output logic (the outputs of one component are graphically connected to the inputs of another).

Each Type/single component of the system can be considered as a “black box”, that processes input data as a function of defined algorithms, starting from user-defined parameters, and produces output data. The task of each Type is to solve simple problems, and their interconnection allows the user to solve the complex problem that he is analyzing.

About its adequacy to provide computational support to the integrated design process, the following observations have been made:

- The main strength of TRNSYS is that, due to its modular approach, it is extremely flexible for modeling a variety of energy systems in differing levels of complexity.
- Flexibility is also enhanced thank to the supplied source code and documentation that provide an easy method for users to modify or add components not in the standard library. The extensive documentation on component routines, including explanation, background, typical uses and governing equations of all the components, permits also to better govern the simulation without hiding the user any aspect;
- On the other hand, as seen for Energy plus and ESP-r, the standard application of the software requires expertise and time;
- The applicability of TRNSYS to early design phases is possible, but it depends entirely on the capabilities of the users to develop corresponding building models in this tool.

Energy-10

Energy-10 is a design tool for architects and engineers, that analyzes energy consumption of buildings consisting of either one or two zones. Development of building models can be highly automated, and evaluation is very fast. Results are ranked based on energy performance and compared to a base-case.

Regarding the capabilities of Energy-10 to provide computational support for energy-efficient design, the following observations have been made:

- Energy-10 only accommodates building that can be modeled as one or two zones. Various energy-efficient strategies can then be applied to the building that provide energy conservation measures with default properties and settings. However, describing specific design options is much harder; this requires defaults to be manually changed. The set of energy-efficient strategies does not yet include all energy saving components.

- Energy-10 only provides feedback on energy consumption (for heating, cooling and lighting). Thermal comfort is not evaluated, nor is there any chance to make Energy-10 adhere to specific experimental conditions other than those governed by modifiable parameters. The ranking mechanism does not seem to add real important information especially since Energy-10 produces a one-criteria evaluation only.
- Energy-10 is extremely fast in doing hourly simulations.
- Because of the easy building model development, Energy-10 is very well suited to be used during early phases of the building design process.

MIT design advisor

MIT design advisor is a simplified software tool for architects to assist with early-stage design of energy efficient buildings. It is designed to not require extensive technical background or lengthy amounts of training, so to be useful to non-expert users and is characterized by a short setup time. This is achieved by restricting the input space to the most critical design parameters to rapidly predict a design's performance.

About its adequacy to provide computational support for the selection of energy conservation measures, the following observations have been made:

- Primary objective of the tool is not an exact performance prediction of the final building design. What is important is that the user is able to identify which design factors have the highest impact on energy use and thermal comfort relative to the others.

- The tool is presented by a schematic interface for data input, divided in nine sections from one to six data point each, defining climate, geometry, occupancy, ventilation, mass, insulation, windows and overhangs. Setup information for up to four building scenarios can be saved simultaneously for fast and easy design revision and iteration. As soon as the simulation is completed, graphical results are available indicating energy consumption, lifecycle costs, thermal comfort, daylighting illustrations, and building code compliance.
- Despite the poor details in the inputs, the computational model is still quite sophisticated. Climate data for a typical meteorological year are used and for each hour of the year, a thermal balance with the room is computed taking into account internal and external loads, ventilation, air conditioning and thermal mass. Heat transfer through the window units is computed by solving a 1-D network of thermal resistors. A heat balance is solved for each node to determine the nodal temperatures and the total heat flowing into or out of the room.
- Some of the mayor upside of this tool are: the simplified user interface and limited number of data required which make this tool particularly interesting for early design phases allowing simulations to be run in only few minutes, the possibility of comparing up to four different scenarios and the web-based design which makes the tool accessible everywhere over the internet.
- The downsides are represented by some strong model assumptions like the neglected ground heat flows, the limited and close structure of the input data, the poor/non-existent interoperability with other tools and building modelling, poor information on the validation of the model, total absence of plant

characterization and the absence of a standalone version of the tool (only the web-based version is available).

- An optimization tool recently proposed also grants an interesting addition to the capabilities of this platform, allowing comparing distributed generation alternatives with energy efficiency measures in term of annual energy uses and costs.

Opt-E Plus

Opt-E Plus is a tool for automated multivariate optimization for energy analysis, based on EnergyPlus and developed by The Advanced Commercial Buildings Research group at the National Renewable Energy Laboratory (NREL).

It's a tool that automatically runs thousands of simulations and identifies design options that provide the most economical energy savings, only usable by NREL personnel and not yet available for the public.

The philosophy of the tool is the following: building design problems are inherently multivariate and multi-criteria. Multivariate optimization is much more difficult than the simpler problem of minimizing a single variable. Because the optimization process is computationally intensive and demands hundreds or even thousands of individual simulation runs, it is essential to identify ways to decrease the run time of EnergyPlus simulations to expedite the overall process so the model created by the tool for the optimization is sufficiently simple to be simulated in little time but enough complex to be considered sufficiently accurate for the optimization process itself.

The optimization tool employs multiple modules, including: a graphical user interface (GUI) for selecting options and viewing results, a database for storing component performance data and costs, a pre-processor to convert high-level input parameters into a detailed building model, the EnergyPlus whole building simulation engine to analyze the model, an optimization engine to select design options, and a simulation run manager to handle simulation runs on different computing resources. The GUI features a building creation wizard, an options browser, and a results browser. The building creation wizard presents a series of tabs with high-level parameters that define the overall type and location of the building, while the options browser allows the user to select from 40 major design options that are grouped into categories of program, form, fabric, and equipment. Cost data are also associated with each option and GUI provides a results browser that renders all the simulations on a chart of percent energy savings versus percent cost savings.

Regarding the capabilities of Opt-E Plus to provide computational support for energy-efficient design, the following observations have been made:

- Using the tool particular attention must be given to adjusting factors such as minimum system time step, minimum temperature convergence, maximum number of warm-up days and zone multipliers.
- The optimization engine module is the heart of the optimization tool. It determines which design options are to be simulated and then analyses the results in the context of the performance objective that is to be minimized. The optimization engine then decides which options to keep and which to change before it launches a new set of simulations.
- The tool is surely interesting, combining the EnergyPlus engine, the strong optimization potential and short simulation time. Unfortunately the number of simulation needed requires considerable computing resources and is not yet suitable for end-use. The tool and its validation are also more oriented in the optimization direction rather than simulation and lastly it is not available to end-users making the information on the tool itself in an indirect and fragmented way.

<u>H.e.n.k.</u>

H.e.n.k. is a software tool developed by Deerns Consulting Engineers, with the support of the Dutch Agency of Energy and Environment (Novem) and the association of Automation in Building and Installation Technologies (Vabi). It tries to respond to the need of good tuning between building and installations to achieve energy saving and high quality of indoor climate by developing a tool that can be used from the very beginning of the building design to support decision making and enhance the communication within the design team.

With H.e.n.k. an attempt has been made to build a software that fits the usual reasoning of engineers and that produces the results they need for the further design.

The way data must be entered in H.e.n.k. is inspired by the method used by engineers at the very beginning of a project. Walls are defined by their total heat transfer coefficients avoiding the specification of the wall parts, not yet defined until later design phases, believing wall composition does not strongly influence energy use and capacities.

Inside spaces are defined by gross floor area and main function of the building taking into account that there is always a certain mix of function and that internal room distribution is a fluctuating parameter; thus the model is not divided in zones. Indoor air temperature is given as input data to calculate to capacity of the equipment to be installed.

Two input levels are defined inside the software, the first level must always be filled by the user and contains information with a non-negligible influence on the calculation, the second level contains data that is less relevant to the specific design like properties of sunshades. Those data are not needed in early design phase, however, they may be needed while studying the effect of equipment or control strategies on energy use.

The calculation method, expressly developed, is based on hourly energy balance taking into account all relevant processes; the model is not completely dynamic because the indoor temperature is fixed by the user. Heat accumulation is taken into account by response factors for step changes of the part of the heat that can be accumulated and for step changes of the indoor temperature. When neither heating nor cooling are required, inside temperature is fixed to be the average of maximum and minimum indoor temperature. When the building closes and the temperature can freely fluctuate a temperature profile for the cooling down temperature is drawn up by the tool.

The obtained results are then represented through an output interface based on the typical needs of an engineer during the early design phase like duration curves, hourly data, maximum loads, expected environmental performance; all the output are available in formats that allows to easily produce graphics and comparisons.

The most important observations have been made for this software are the following:

- The principal limitation of the method used is that the longer the building is not heated or cooled, the more uncertain the calculated energy use and capacities become, turning even unusable if the building is unheated or uncooled for more than two days a week.
- The calculation method is in general simplified and not freely available to end users. Furthermore, there is no link of the input interface with other software and the input of the geometry is manual and time consuming.
- The tool itself is not designed to run detailed simulations and is not integrated with any other software to execute more detailed simulation at future design phases, requiring the creation of a new model from the ground up.

ZEBO

ZEBO is a decision support tool for the study and design of net zero energy buildings (NZEBs) in hot climates during early design phases based on EnergyPlus and specifically oriented to the Egyptian market. Architects and architecture students with no experience on building energy efficiency make the initial target audience. The tool is partially educational but can also be used by architects with limited budget to lower the barrier to achieve NZEBs during early design phases.

The tool is based on a one page interface that communicates with EnergyPlus. The ZEBO creates an IDF file than the simulation runs the EnergyPlus engine. The simulation results are then generated and ZEBO extracts the required output and represent them graphically.

Designed to be easy to learn, use and with the minimum amount of input the user interface is condensed in a single page with a limited number of data entry points similar to MIT design advisor, which describe the building in its main characteristics. All fields feature a standard value compatible with the recommendations of the Egyptian legislation and are linked to a library of typical values.

The model passed to EnergyPlus as a simple multi-dimensional rectangular zone, has been created to represent mechanically cooled housing unit. The model is coupled with the climatic and urban context and allows maximum design flexibility for a range of architectural early design parameters including the site urban density and climatic conditions.

Once the output is displayed the user can pass to the photovoltaic program module to optimize the electrical yield.

As for the MIT design advisor, the most important observations made for this software have been:

- The tool is strongly oriented on its user-friendly approach and even if more focused on Net Zero Energy Buildings and on

Egyptian territory, it can enable simple, fast, accurate simulation and brief continuity with the design process.

- The simplified user interface and limited number of data required which make this tool particularly interesting for early design phases allowing simulations to be run in only few minutes and the possibility of comparing different scenarios with little efforts.
- The strong model assumptions and poor information on the validation of the model represent the weaknesses of the tool.

2.2.3 Remarks and possible improvements

From the assessment of existing analysis tools made in the previous section, it is clear that all the tools presented can play an important role in the selection of energy conservation measures and, broader, in the energy-efficient building design.

But there is also room for improvement, especially regarding modeling-related aspects.

In fact, on one hand, the six first thermal building analysis tools that seems to be more suitable for use during the later phases of the design process (Energy Plus, ESP-r, Capsol, IDA-ICE, Simulink and TRNSYS) are all capable of supporting the selection of energy conservation measures but on condition that enough time is available to do the required (and mostly very specific) modeling and simulation work.

Hands-on application also shows that these tools need expert intervention in order to allow analysis of specific building option spaces and even if they can return information on building performance that can be used to calculate performance indicator values, yet many of them do not seem to be very tailored towards directly outputting performance indicator values.

To summarize, these tools are applicable in all design phases but they need expert intervention to model building designs and their deployment is time expensive;

On the other hand, the tools that seems to be more suitable for use during the early phases of the design process (Energy-10, Plus, MIT design advisor, Opt E-plus, H.e.n.k., Zebo) has sometimes strong assumptions and poor validation, with the possibility to simulate only simple building geometries (most tools assume box-like internal spaces that are all situated on floors of the building, making it difficult to simulate more expressive floor plans and spaces like staircases or atria with stack effects or stratification).

So, what is the best way of improvement?

As suggested by the research of P. de Wilde *(de Wilde, 2004)* improvement can be achieved by reverse-engineering of the first kind of tools, which consists of unravel the amalgamated design alternatives and information types that a tool can capture as well as the different ways that the tool can act on this input. If this can be achieved it will become easier to select the type of analysis model that is relevant in a design context, provide the analysis tool (model) with all relevant data, and do a specific virtual experiment without having to worry about the modeling task. It would be helpful if analysis tools then would return performance indicator values as specified through these virtual experiments, instead of current raw performance data.

The most important strength of this new approach is that reverse-engineering of tools is able to impact the speed of building simulation efforts maintaining their capability to do accurate simulations. In particular acceleration of performance prediction by tools currently no longer depends on the speed of the actual computational procedure (run-time) only. Although full simulations of a complex building for a full hourly reference year can still claim some hours, the main barrier regarding speed now is the need to develop and test a building model and the climate conditions, HVAC-settings, occupant behaviour etc assumed in that model.

In other words, the better alternative to extreme simplification, hiding or automation of tool functionalities can be found in the option of subdividing tool functionalities in small but relevant modules that meet specific design analysis needs.

This new approach, together with the requirements discussed in the Chapter 1 about the energy simulation tools have guided, as shown later, the development of a new modelling support tool, final goal of this research.

PART 2

New modeling support tool

Chapter 3

3 Development of a new modeling support tool

3.1 Requirements and software used

In the previous chapters it has been discussed about the strategies, options and requirements needed for the development of new building modeling support tools, able to destroy the actual barriers to their integration into the building design process, or, in other words, able to fit with the needs related to the design process itself and the needs related to the composition of the integrated design team.

The process that have guided the creation of the new modeling support tool presented in this chapter has started and has been developed precisely on the basis of these strategies and requirements, which are summarized below with the aim to briefly introduce the characteristics of the new tool and to make evident its ability to meet themselves.

First of all, it has to be specified that the new tool comes from a work of reverse engineering applied to one of the most flexible and detailed analysis tools presented in the Chapter 2, TRNSYS (TRaNsient SYstem Simulation Program, TRNSYS version used: 17.00.0019).

In fact, with its modular approach, TRNSYS allows the modeling of any type or variety of energy systems in differing levels of complexity and boundary conditions and permits also to govern the simulation without hiding the user any information. It is be able to carry out every virtual energy experiments that can really be defined.

Toward the definition of a specific functionality and design analysis, in this specific case the reverse engineering work has resulted in the creation of a flexible building-plant system simulation model, (in the main general TRNSYS interface "Simulation Studio") able to do the dynamic and integrated simulation of a very large number of integrated building-plant systems, including the simulation of the building envelope, all the heating plant subsystems, and all the plant components related to the production of domestic hot water.
The dynamic simulation model has been supported by the development of two different protocols, the sizing and the simplification protocol, able to properly create, together with the TRNSYS model, the complete modeling support tool mentioned, characterized by a guided, clear and univocal methodological structure (Figure 3-1).

In fact, the first protocol, composed of four different Excel spreadsheets, allows the complete sizing and characterization, in terms of inputs and parameters, of all TRNSYS components involved in the dynamic model and the energetic and economic analysis of the main simulation results, while the second permits to apply, depending even on the design phase, specific simplifications that can reduce the modeling implementation and simulation runtime, still maintaining an acceptable degree of accuracy of the results.

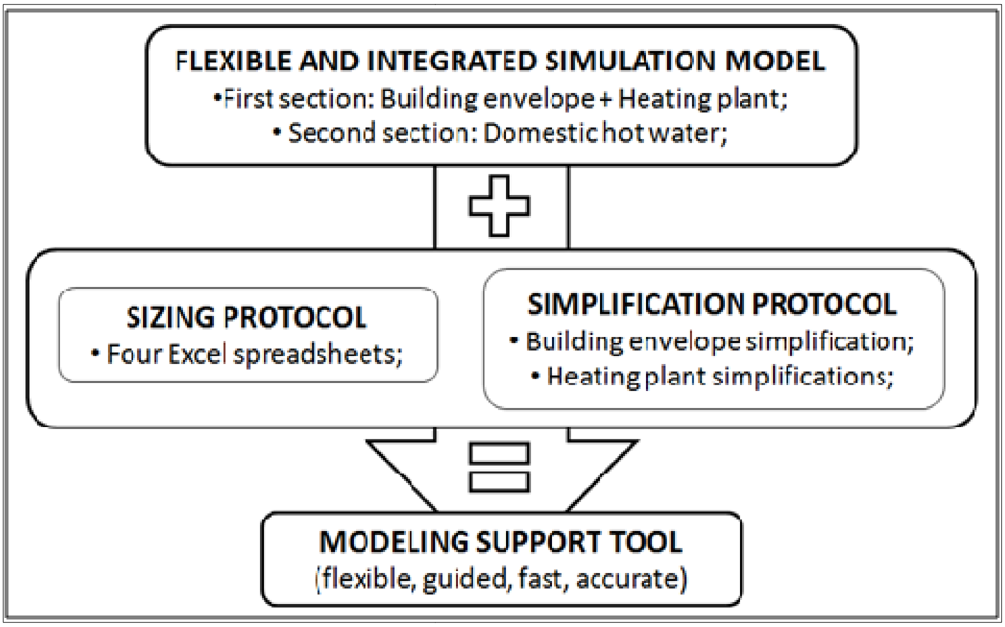


Figure 3-1: Modeling support tool development

The whole modeling support tool has been developed following the steps of the performance-based decision making approach showed in the Section 2.1:

Development of an option space: the tool is characterized by three different main kind of flexibility (hydraulic schemes, plant components, building scale flexibilities as shown in Section 3.1) creating a large but at the same time a defined option space;

Identification of the relevant functions of the design options: the final aim of the tool is the energy analysis and comparison of different building-plant system configurations, where each component contributes to achieve the maximum efficiency of the whole system. Therefore, the relevant functions of the design options are the energy use end the thermal comfort.

Specification of performance indicators, objectives, requirements and constraints: to perform how well the options perform their functions, both in the dynamic model and in the sizing protocol the tool immediately return, as main outputs, performance indicators and variables like building and plant subsystems internal temperatures, building energy needs and power curves, plant subsystems efficiencies;

Prediction of performance: the dynamic model through the TRNSYS simulation engine provides for this step;

Evaluation of predicted performance and selection of the most desirable option: the sizing protocol is used not only before the simulation, but even after, in order to do the energetic and economic analysis of the main simulation results and the choice of the best building-plant configuration;

The tool has been developed also in order to meet the following important requirements, mentioned in the previous chapters, for its easy integration in the building-plant design process:

- *To be easily adopted, energy performance simulations must fit with the needs related to the design process, represented by time and accuracy. In other words, they must be able to provide the requested and accurate information rapidly, without halting the design process for extended periods*: as already mentioned, one of the main focus of the research after the creation of the flexible but detailed dynamic simulation model has been the development of the sizing and simplification protocols, both able to considerably reduce the number of necessary inputs for the simulations, thus minimizing the modeling, implementation and simulation runtime of the model, while still maintaining (regarding in particular the simplification protocol) an acceptable degree of accuracy with respect on the computational results and real energy consumptions. The extremely positive results achieved in this way has been reached through the case studies shown in the Chapter 4, where starting from the most detailed model and progressively enhancing the level of simplification, the comparison between the detailed and simplified models has been analysed to find the best balance between the quality/accuracy of energy results and time requirements dictated by the design.

- *Design teams need rigorous tools that analyse the specific ideas and issues, answering key questions as likely costs of operation and likely variation of comfort variables in space and time*: the aim of the tool is not the extreme simplification or the hiding or automation of all its possible functionalities. It can be used in every specific design condition in order to evaluate, from an energetic and economic point of view (sizing protocol), different building-plant-system configurations.
- *Modeling support tools, especially in the early design phases, must be very easy to use, easy to learn, must allow alternative comparison , match the cyclic design iterations and be adaptable to the users expertise*: the flexibility of the tool together with its guided, clear and univocal structure meet this requirements;
- *The required input should match the data known in the current design phase and it should be possible to enter more accurate data and to produce more accurate results as the design process progress. The tool must be applicable during all the design phases, starting from the conceptual to the final phase*: the tool can surely be adopted during all the design phases. It can be adopted in a full or in a partial way, depending on the specific objectives or on the design phase and available information, with all or only one of the proposed simplifications.
- *The result should be in a form that allows for clear communication with other figures involved in the design process*: the number of

possible outputs of the tool is very high, from the operating temperatures in all the components involved in the simulation to the unsteady heat balance regulating each component. However in order to describe the main relevant functions of the design options the simple and clear performance indicators mentioned above are immediately returned by the tool, then allowing the user to further investigate the results if necessary.

3.2 Detailed model

In this section an in-depth description of all the features of the starting detailed and integrated dynamic TRNSYS model of the new modeling support tool is reported. In fact, the detailed dynamic model can be considered the first step of the tool creation, the basis on which the sizing and simplification protocol has been applied in order to further improve its applicability in all the integrated design phases.

As previously specified, it consists in a flexible building-plant system simulation model created in the main general TRNSYS interface "Simulation Studio", able to carry out dynamic simulations of a very large number of integrated building-plant systems, including the simulation, for a maximum number of 15 heated thermal zones, of the:

- Building envelope,
- Heating plant, with all its subsystems (HS);
- Domestic hot water system (DHW);

3.2.1 First and second sections

In particular the whole model can be divided into two different sections, the first related to the building envelope and the heating plant, while the second related to the production of the domestic hot water.

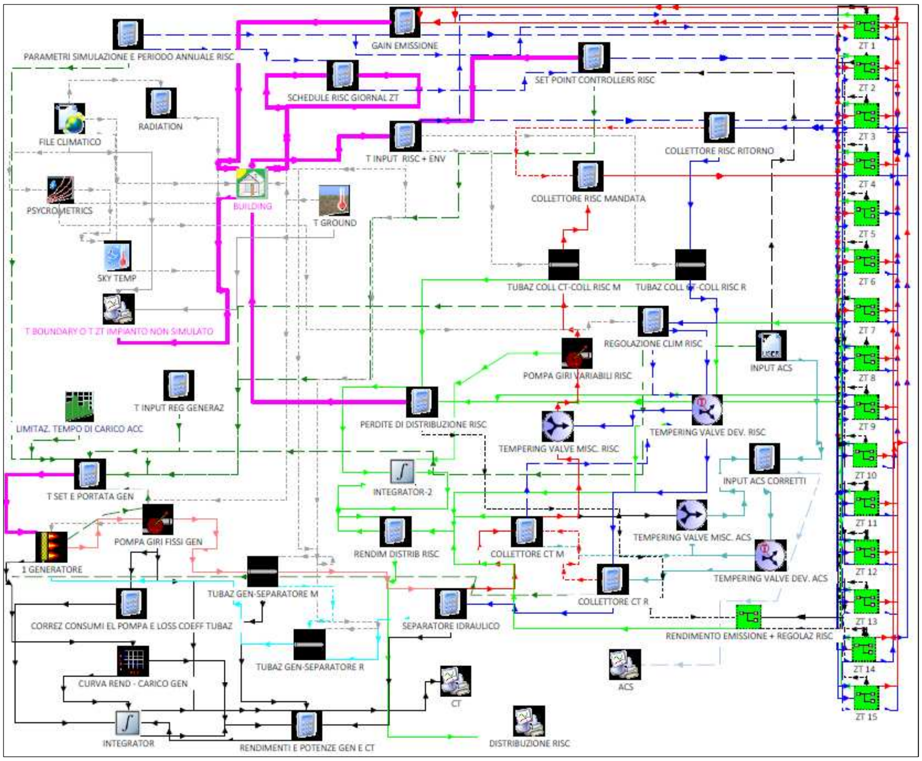


Figure 3-2: First section of the TRNSYS detailed model

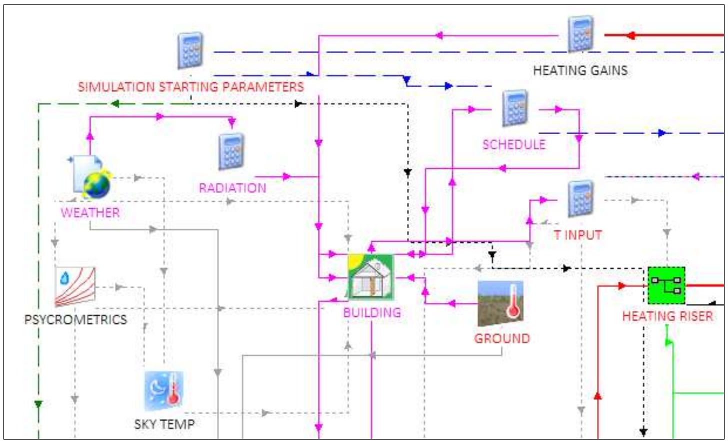


Figure 3-3: Extracted view of the TRNSYS detailed model (Building envelope and boundary conditions)

The Figure 3-2 and 3-3 show two different views of the first section, where the dynamic operation of the heating plant is modeled through the TRNSYS components called "Types", all connected according to an input – output logic and related to the following building /plant parts:

- Building envelope and boundary conditions;
- Generation subsystem (HS);
- Storage and distribution subsystems (HS);
- Emission and control subsystems (HS);

In fact, as specified in the Section 2.2.2, in TRNSYS each Type/single component of the simulated system can be considered as a "black box", that processes input data as a function of defined algorithms, starting from user-defined parameters and/or inputs, and produces output data. The task of each Type is to solve simple problems, and their interconnection allows the user to solve the complex problem that he is analyzing. In this case each Type corresponds to a single component of the whole building-plant system.

The figure 3-4, for example, shows the standard internal configuration of one of the TRNSYS Types used, with the required parameters and inputs (the latter usually constituted by the outputs of other Types) necessary for its operation in the whole simulation model.

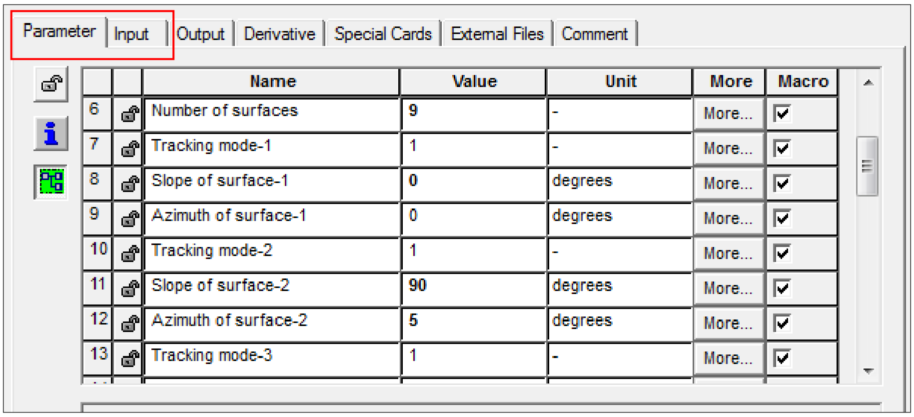


Figure 3-4: Internal configuration of the TRNSYS Types

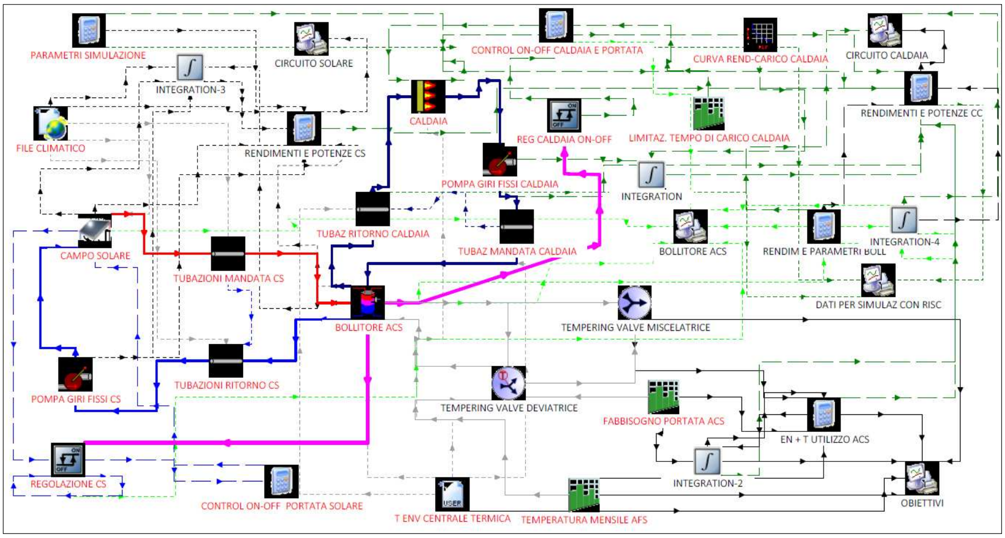


Figure3-5: Second section of the TRNSYS detailed model

The figure 3-5 shows the second section of the detailed model, the one related to the production of the domestic hot water. Even in this case the dynamic operation of DHW plant is modeled through the TRNSYS Types, now related to the following DHW plant parts:

- DHW loads;
- Storage and distribution subsystems (DHW);
- Solar integration (DHW);

Considering together the first and second section, the total number of TRNSYS Types used for the creation of the whole detailed model is 221.

About the building envelope, in the specific "Trnsys3d" tool, a three-dimensional representation of the entire building can be created, as well as all relevant shadowing objects comprising all the adjacent building structures and the specific solar obstructions (Figure 3-6).

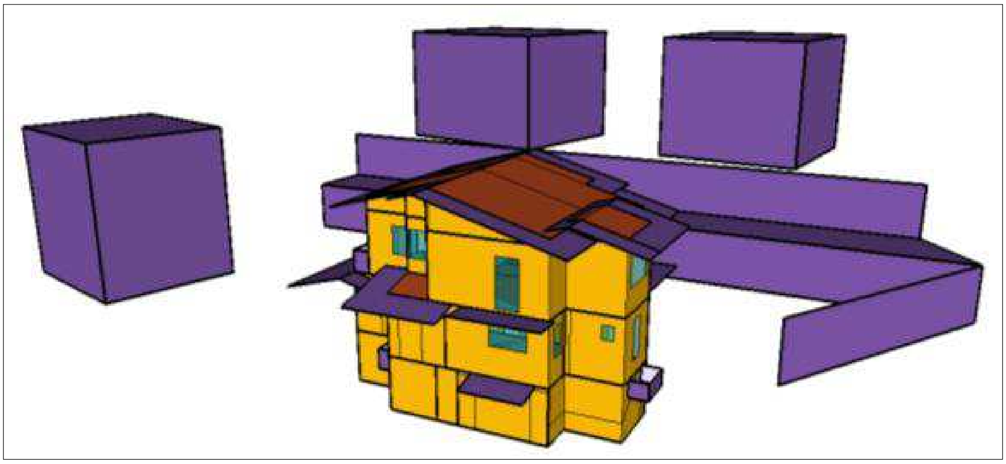


Figure 3-6: “Trnsys3d” building modeling

To characterize the various zones, each one is defined in terms of materials and layers of walls and windows, thermal bridges, internal gains, temperature set-points, heating and ventilation schedule, external and boundary conditions. To specify these items, the “TRNBuild” tool is used (Figure 3-7), which is the TRNSYS tool specifically dedicated to the characterization of the building envelope, connected both to the “Trnsys 3d” tool and to general TRNSYS interface “Simulation Studio” through a specific TRNSYS Type (Type56).

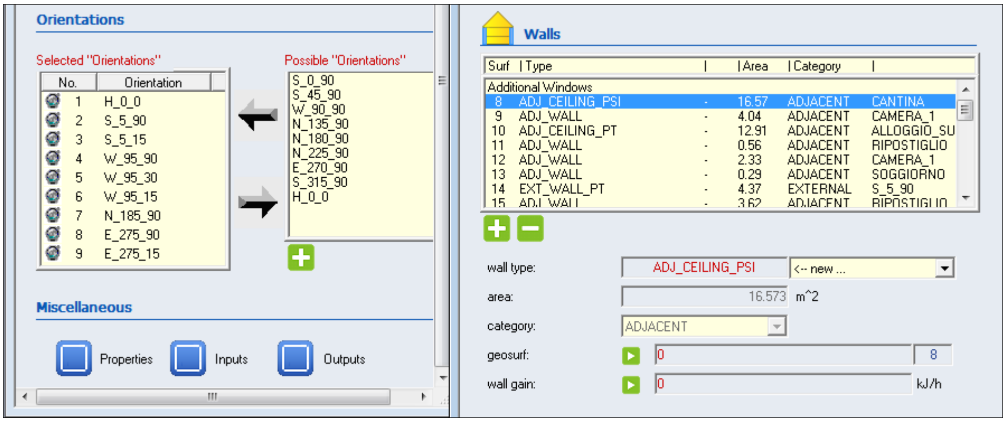


Figure 3-7: TRNBuild tool interface

3.2.2 Multiple flexibility

Now, what is the most important feature of the model?

As repeatedly highlighted before, its multiple flexibility.

In fact the energy model presents three kind of "flexibility":

- Hydraulic scheme flexibility, with 36 different plant scheme available;
- Plant components flexibility, with multiple options for all the subsystem's components;
- Building scale flexibility, with different scale and resolutions for the representation of the building;

About the hydraulic scheme flexibility and in order to describe all the hydraulic schemes that can be simulated by the integrated model, the following two different main configurations can be considered:

- Hydraulic schemes – A
- Hydraulic schemes – B

The first is shown in the Figure 3-8, and it represents the plant configurations composed of only one single generator with internal DHW heat exchanger, used for DHW and/or heating.

In the same scheme there can be, for the domestic hot water an:

- Instantaneous production, with priority;
- Storage production, with or without priority;
- Solar integration;

For the heating system, there can be an:

- Heating system without hydraulic separator or storage, so a direct circuit from the generation;
- Heating system with hydraulic separator or storage;

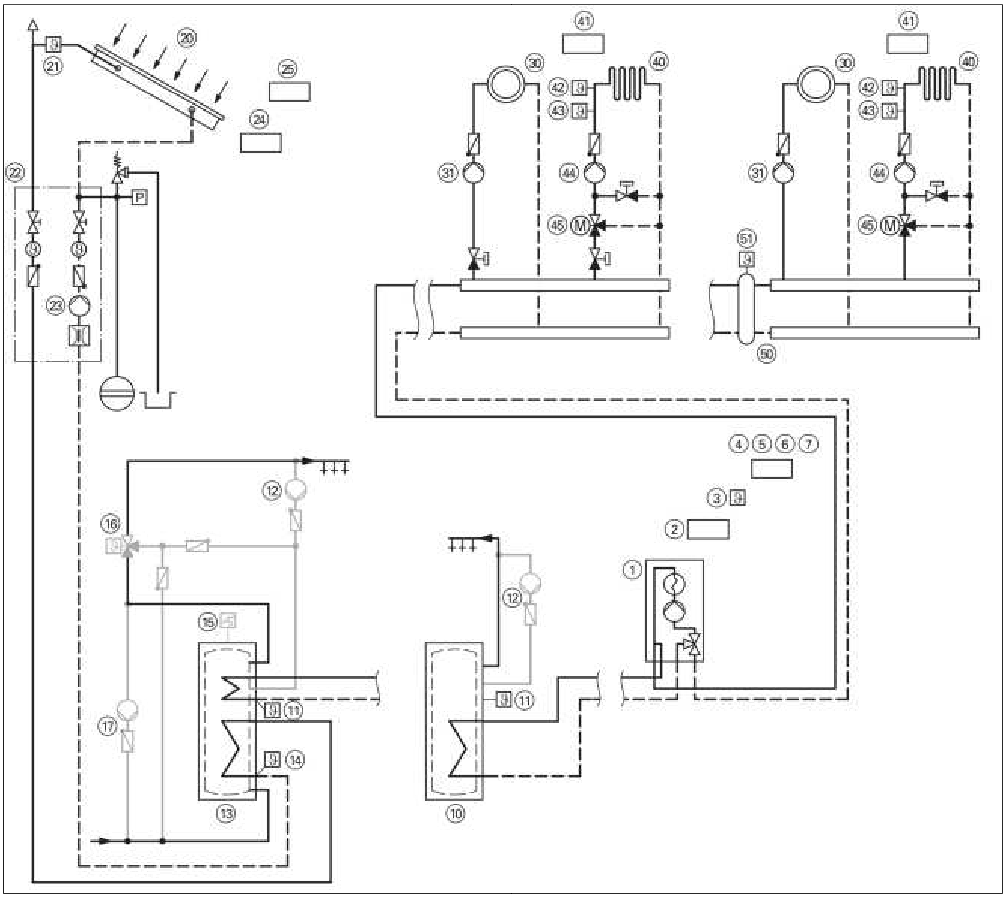


Figure 3-8: Hydraulic schemes - A

The second is shown in the Figure 3-9, and it represents plant configurations composed by one or multiple generators with external DHW heat exchanger, used for DHW and/or heating.

As well as the previous schemes, there can be, for the hot domestic water a:

- Storage production, with or without priority;
- Solar integration

while, for the heating system, an:

- Heating system without hydraulic separator or storage;
- Heating system with hydraulic separator or storage;

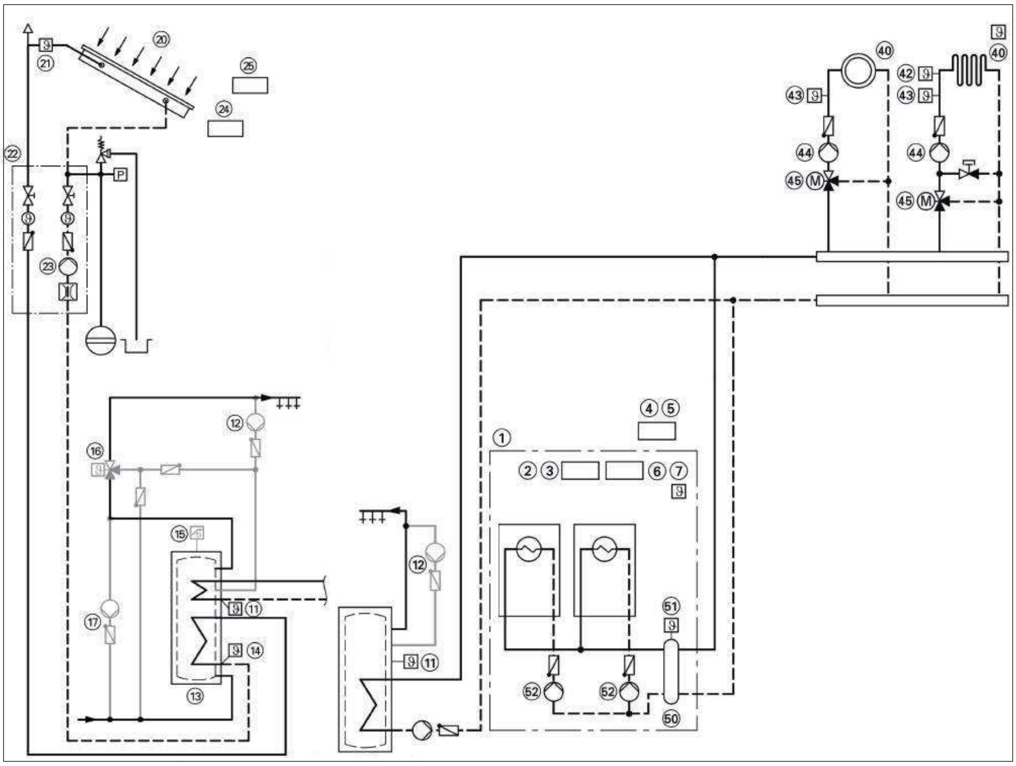


Figure 3-9: Hydraulic schemes - B

All the possible combinations can be summarized in the following table (Table 3-I), generating 36 different hydraulic schemes ready to be simulated by the only one TRNSYS dynamic and integrated simulation model described before.

The hydraulic scheme representation of each single combination is shown in Appendix A.

Table 3-I: Hydraulic scheme combinations

			DOMESTIC HOT WATER (DHW)					
		No DHW	Instantaneous production		Storage production			
			No solar	Solar	No solar		Solar	
			Prior.	Prior.	Prior.	No prior.	Prior.	No prior.
	No HS	/	A1	A2	A3	/	A4	/
HEATING SYSTEM (HS)	Direct HS	A5	A6	A7	A8	/	A9	/
	Hydraulic sep. HS	A10	A11	A12	A13	/	A14	/
	Storage HS	A15	A16	A17	A18	/	A19	/
	Direct HS & DHW	B1	/	/	B2	B3	B4	B5
	Hydraulic sep. HS & DHW	B6	/	/	B7	B8	B9	B10
	Storage HS & DHW	B11	B16	B17	B12	B13	B14	B15

Going to the second kind of flexibility, the plant components flexibility, it can be stated that, for each hydraulic combination, a lot of component variations are allowed.

In particular, for the Emission and internal Control subsystems it can be simulated, alternatively and always in the same detailed TRNSYS simulation model, the behaviour of:

- Radiators;
- Radiant panels;
- Fan coils;
- District heating heat exchangers;
- On-off, P, PI, PID control;

For the Distribution subsystem there can be different:

- Piping length, material and insulation;

- Pumps with fixed or variable speed, with control at constant or proportional pressure;

About the Storage subsystem it can be changed the:

- Volume;
- Number and internal heat exchanger properties;
- Stratification effects;

For the Generation subsystem there can be:

- One or multiple cascade/integrated generators;
- Different generator types, like boiler supplied with traditional or renewable fuels, heat pumps, cogeneration systems;

Concluding with the third and last kind of flexibility, the building scale flexibility, the integrated and dynamic model can be used in the following three different scales and resolutions for the representation of the building:

- Small scale & High resolution, for the simulation of an independent apartment, a commercial unit or an independent building floor, where one thermal zone is composed by only one room;
- Medium scale & medium resolution, for the simulation of an apartment building or a multi-floor building, where each thermal zone is respectively equal to one apartment or one floor;
- Large scale and small resolution, for the simulation of the district heating, where each thermal zone is equal to one building;

3.2.3 Strengths and Weaknesses

Once described the huge flexibility of the detailed and integrated simulation model, the questions are: What are its main strengths and weaknesses? Is it very easy and fast to use during all the design stages taking into account times and information required during the different phases?

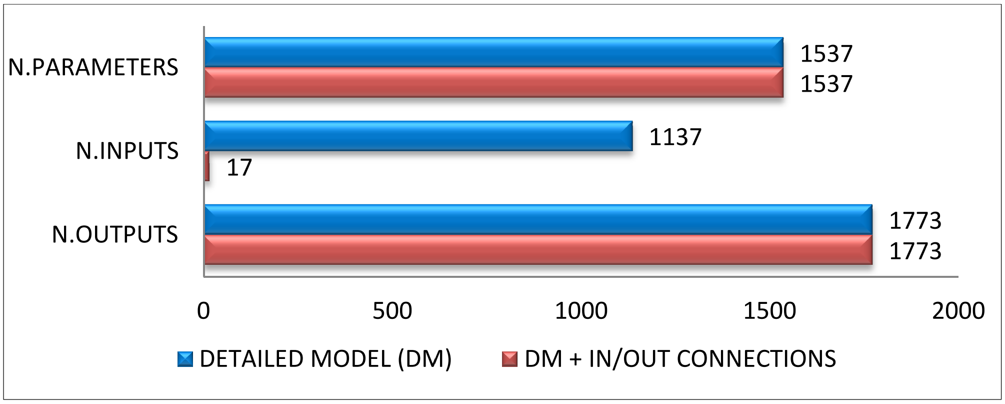
In order to answer these questions it can be stated first that its strength is surely the multiple flexibility with fixed input/output connections.

In fact, the whole detailed model is composed by 221 types that require a great number of parameters and inputs to be set and a modeling workload of weeks should have done, every time, without using a model with fixed input-output connections. The latter permits to extremely reduce the number of inputs to be set and the modeling workload associated (Graph 3-1 and Graph 3-2[7]), still maintaining a very high flexibility and a great number of outputs able to describe the actual operation of each component of the building-plant system.

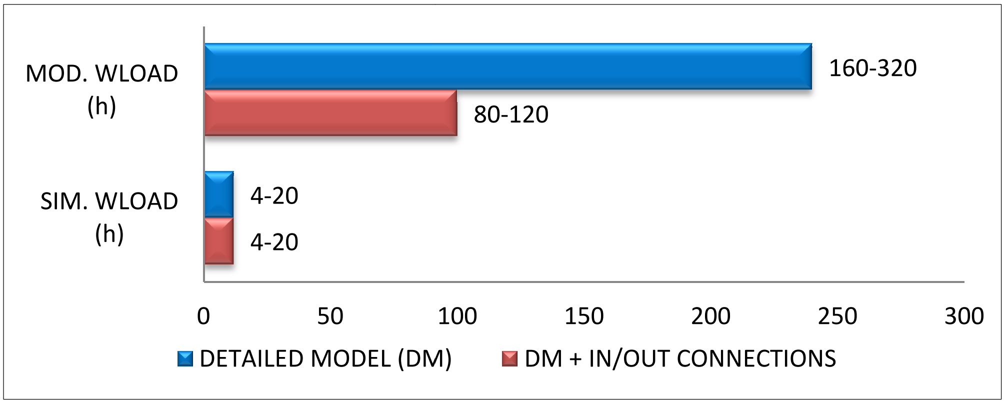
On the other side, the major weakness is that the modeling and simulation workloads, around 80-120h and 4-20h, are still too long for design support;

So, in order to improve this times the sizing and simplifications protocols described in the following sections has been created.

[7] Modeling workload and simulation workload has been estimated from repeated attempts through the case studies shown in the Chapter 4. In particular the modeling workload can be defined as the average time spent to prepare the simulations, considering already available all the data needed to characterize the various building thermal zones. Simulation workload consists in the average runtime of the simulations using TRNSYS.



Graph 3-1: Fixed input-output connections variable savings



Graph 3-2: Fixed input-output connections workload savings

3.3 Sizing protocol (SZp)

The sizing protocol is the first protocol created in order to have a further workload reduction related to the use of the detailed dynamic model previously described, allowing the latter to be more easily used during every stage of the integrated building-plant system design.

As introduced in the Section 3.1, it permits, first, to do the complete and automated sizing and characterization, in terms of inputs and parameters, of all the TRNSYS Types/components involved in the dynamic model, for all the 36 hydraulic schemes contemplated and second, after the performance of the simulation, to allow the energy and economic analysis of the main simulation results, in order to guide the choice of the best building-plant system configuration.

In particular the sizing protocol is divided into the following four different Excel spreadsheets:

- Sizing protocol 1 (SZp1): it permits the domestic hot water sizing (second section of the TRNSYS integrated model);
- Sizing protocol 2 (SZp2): it's related to the building ideal load and DHW simulation results analysis;
- Sizing protocol 3 (SZp3): it permits the complete heating system sizing (first section of the TRNSYS integrated model);
- Sizing protocol 4 (SZp4): used for the final energy and economic result processing;

Thanks to these four different spreadsheets, each one with its own task, the protocol define a precise modeling and simulation process to be followed, creating a design support tool with the clear and univocal methodological structure previously mentioned for several times.

In fact the whole process involves the following consecutive steps, typical of any building-plant system design process:

SZp1 - DHW sizing: sizing of each component related to the production of the domestic hot water (Types of the second section of the TRNSYS integrated model) using the SZp1;

Second section - DHW simulation: dynamic energy simulation of the DHW plant, using the second section of the TRNSYS integrated model (simulation time-step 1min), with the basis of the sized parameters and inputs coming from the SZp1 and with the goal of fixing the amount of thermal energy for DHW required to the common distribution and generation subsystems of the upstream central plant;

Building ideal load simulation: dynamic energy simulation of the building envelope, using the first section of the TRNSYS integrated model (simulation time-step 1h) without all the Types related to the simulation of all the subsystem of the real heating plant, with the aim of fixing the amount of ideal thermal energy demand of the building envelope during a full year heating service.

SZp2 - Building ideal load and DHW simulation results analysis: Analysis of the results of the simulations previously performed using the SZp2, in order to define the overall thermal energy demand of the building and the users, the latter necessary for the selection and sizing of the common plant able to satisfy the needs;

SZp3 - Heating plant sizing: choice of the hydraulic scheme between the 36 available and complete sizing of each component of the heating plant (Types of the first section of the TRNSYS integrated model related to the heating plant) using the SZp3;

First + Second section - DHW + HS simulation: dynamic and integrated energy simulation of the whole building-plant system using the first and second sections of the TRNSYS integrated model (simulation time-step 1min);

SZp4 - Integrated simulation results analysis**:** energy and economic analysis of the simulation results through the SZp4, to evaluate the technical and economic feasibility of the simulated solution;

In the next sections the detailed description of the characteristics of each spreadsheet constituting the sizing protocol.

3.3.1 SZp1- DHW sizing

The sizing protocol 1 is the one related to the DHW sizing.

The spreadsheet starts with the determination of the users DHW daily instantaneous demand (time step equal to one minute), in order to establish their consumption profile in terms of flow rates, energies and temperatures. The Figure shows, for example, the DHW flow rate profile sized in the protocol and entered (as parameters) into the appropriate TRNSYS Type in the simulation.

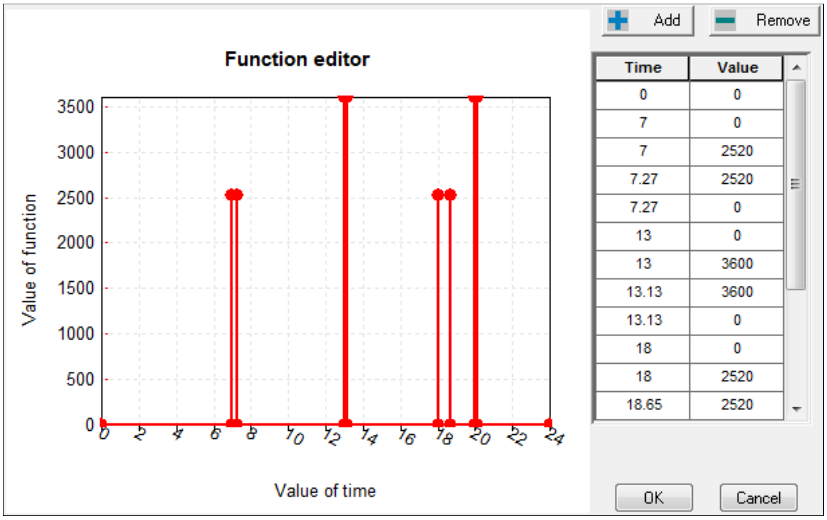


Figure 3-10: DHW daily flow rate demand

The protocol continues with the choice of the DHW plant type (instantaneous or storage production, the latter with or without priority and both with or without solar integration), then with the sizing of all the components involved in the second section of the TRNSYS dynamic model, starting from the solar collectors and the solar circuit (if provided) to finish with the DHW storage and/or the DHW generation circuit.

In particular, the spreadsheet is structured in such a manner that it performs, with the minimum number of possible inputs (inputs of the spreadsheet, not to be confused with those of the dynamic simulation model), not only an automatic, progressive and guided plant sizing, but also a sizing directly related to all the TRNSYS Types of which inputs and parameters (now the TRNSYS Types inputs and parameters, as shown in Figure 3-4) are required in the simulation model.

To clarify the concept we report the following example, taken from the protocol and reporting the sizing of the solar collectors, identified in the dynamic model with the specific TRNSYS Type 1a (Figure 3-11).

Solar collector sizing
Trnsys Type 1a "SOLAR COLLECTORS"

Description	Value	Parameter
Model and brand	Viessmann Vitosol 200-F	/
Gross area (m^2)	2.51	/
Absorber area (m^2)	2.32	/
Aperture area (m^2)	2.33	/
Maximum efficiency a_0 (%)	0.824	6 - Intercept efficiency
First-order coefficient a_1 (W/m^2K)	3.792	7 - Efficiency slope
Second-order coefficient a_2 (W/m^2K^2)	0.021	8 - Efficiency curvature
Total number of needed collectors	15	/
Total gross area (to check with the available gross area)(m^2)	37.65	/
Total absorber area (m^2)	34.80	2 - Collector area
Total aperture area (m^2)	34.95	/
Available-needed gross area check	OK	/
Maximum number of collectors for single subfield	3	/
Connection type between collectors of each subfield (series or parallel)	Series	/
Number of subfields to be connected in parallel	5.00	/
Maximum number of collectors connected in series for each subfield	1	1 - Number in series
Single collector test flow rate ($l/h/m^2$)	25	5 - Tested flow rate
Heat transfer fluid provided	H2O + propylene glycol 40%	/
Heat transfer fluid thermal capacity (kJ/(kgK))	3.803	3 - Fluid specific heat
Heat transfer fluid density (kg/m^3)	1004	/

Figure 3-11: Solar collectors sizing

KEY
Spreadsheet input
Automatic calculation
Note-information
Trnsys Types input/parameter

Figure 3-12: Spreadsheet cells key

In the Figure 3-12 there is the key of the cells shown in the Figure above (the same is used for the whole protocol) from which is possible to understand how, from simple inputs (Spreadsheet input) readily available from the component technical data sheets, the protocol allows for automatically fill in the dynamic TRNSYS model with inputs and parameters required for each Type (TRNSYS Types input/parameter). The latter are often values obtained through calculations (Automatic calculation) that, if not automated, would require every time excessive design efforts, providing therefore a significant reduction in the sizing workloads and in the setting workloads of the dynamic model. Moreover, the TRNSYS inputs and parameters not subjected to any change in the dynamic model, are not taken into account by the protocol in order not to confuse the novice users, whose only task is fill in the protocol with the component technical data sheets, then enter into the dynamic model only the TRNSYS input and parameters that the protocol itself provides, a number far lower than the one initially requested for each Type, as it can be seen from the comparison reported in the following Section 3.3.5, the latter related in particular not only to the SZp1, but also to the SZp3, structured in the same way.

3.3.2 SZp2 - Building ideal load and DHW results analysis

The sizing protocol 2 is the one needed for the building ideal load and DHW simulation results analysis or, in other words, the analysis of the results of the simulations previously performed in the tool (see the tool's design process listed in the Section 3.3), with the aim to fix the overall thermal energy demand of the building and the users, the latter essential for the selection and sizing of the common plant able to satisfy the building heating and the DHW production;

The protocol provides first to enter, for the part related to the heating service, the ideal loads of each thermal zone, from which it mainly define the:

- Values of maximum heating power required from each zone, necessary to the next emission subsystem sizing;
- Values of the maximum heating power required from the entire building and load profile of the day with maximum demand of thermal energy, for the next sizing of the possible storage

subsystem (storage of technical water only for the heating service);

- Thermal power curve of the heating service, the curve that describes, in addition to the annual amount of thermal energy required (equal to the area under the curve) the distribution of the power required during the entire year of the simulation, as shown in the example of Figure 3-13.

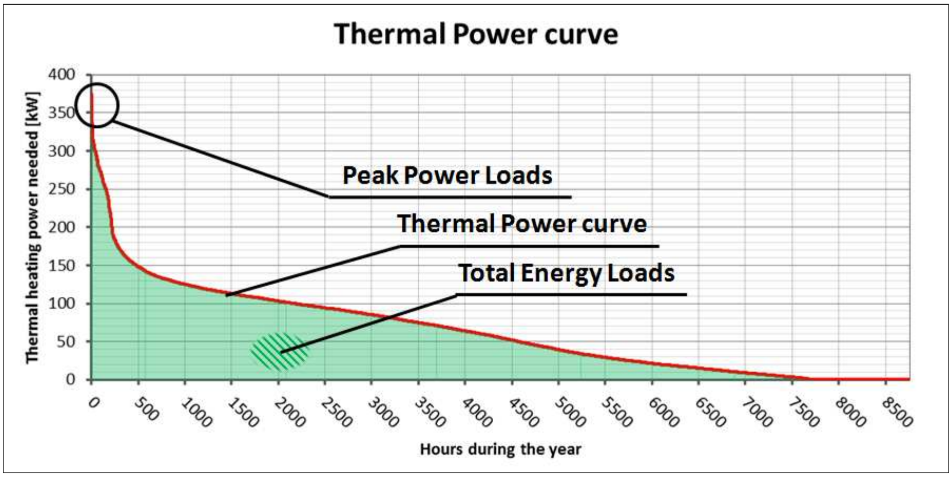


Figure 3-13: Thermal power curve

Subsequently it provides, for the part relating to the DHW production, to enter the loads required by the common distribution and/or generation subsystems, to define, also in this case the:

- Value of maximum DHW power required;
- Thermal power curve of the DHW service;

and finally, adding the two contributions, it comes to the determination of the:

- Value of maximum thermal power required for heating + DHW services;

- Load profile of the day with maximum demand of thermal energy for heating + DHW, for the following sizing of the possible storage subsystem (storage of technical water for heating + DHW services) as shown in the Figure 3-14;

MONTHLY LOAD PROFILES OF THE DAY WITH MAXIMUM THERMAL ENERGY DEMAND - HEATING + DHW SERVICES (kWh)																			
Month	Day	1.00	...	6.00	7.00	7.27	8.00	...	18.00	18.65	19.00	20.00	20.13	21.00	22.00	23.00	24.00	TOT
Jan	14	5.81	...	6.43	43.91	10.78	25.19	...	26.18	31.55	20.45	3.48	0.40	2.58	3.59	4.28	4.30	258.94
Febr	32	4.97	...	6.11	42.99	10.65	24.94	...	26.13	31.54	20.46	3.59	0.45	2.89	4.20	5.03	5.12	256.68
Mar	79	3.97	...	4.08	38.23	9.37	22.15	...	21.90	27.45	17.81	1.92	0.26	1.67	2.88	3.77	3.87	196.39
Apr	94	2.57	...	2.95	34.57	8.95	21.09	...	18.28	20.76	13.23	0.58	0.04	0.24	0.71	1.50	1.71	145.84
May	127	0.00	...	0.00	29.10	7.96	18.31	...	18.68	23.10	14.85	0.53	0.00	0.00	0.00	0.00	0.00	112.53
Jun	158	0.00	...	0.00	27.70	7.79	17.93	...	14.78	21.15	13.60	0.49	0.00	0.00	0.00	0.00	0.00	103.44
Jul	189	0.00	...	0.00	22.04	7.45	16.97	...	16.75	23.06	14.95	0.54	0.00	0.00	0.00	0.00	0.00	101.76
Aug	242	0.00	...	0.00	25.00	7.68	17.70	...	15.37	18.81	11.85	0.42	0.00	0.00	0.00	0.00	0.00	96.83
Sep	263	0.00	...	0.00	31.10	8.26	19.17	...	17.60	21.01	13.52	0.48	0.00	0.00	0.00	0.00	0.00	111.15
Oct	289	6.42	...	3.67	36.10	9.05	21.34	...	17.88	23.56	15.41	0.55	0.00	0.00	0.07	0.42	0.51	157.93
Nov	330	5.64	...	6.59	37.23	10.17	24.52	...	24.56	28.50	18.42	3.38	0.44	2.83	4.22	5.07	5.21	239.51
Dec	359	5.11	...	5.67	40.66	10.22	23.99	...	25.13	30.18	19.59	4.08	0.53	3.42	4.96	5.92	6.08	244.92
MAX	14	5.81	...	6.43	43.91	10.78	25.19	...	26.18	31.55	20.45	3.48	0.40	2.58	3.59	4.28	4.30	258.94

Figure 3-14: Load profiles of the day with maximum energy demand

- Thermal power curve of the heating + DHW services;

Every analysis performed by SZp2 is strictly functional first to the choice of the hydraulic scheme to be taken for the specific case study and then to the next sizing of the heating plant, the latter done through the SZp3, having precisely as a starting point the results of the protocol here discussed. In fact, the values of the powers required and thermal power curves extrapolated can give useful suggestions to the designer during the hydraulic scheme's choice, to be made within the large but defined option space created in the tool.

3.3.3 SZp3 - Heating plant sizing

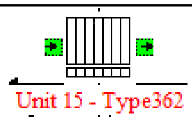
The SZp3 is the part of whole sizing protocol related to the heating plant sizing.

In particular the protocol, as mentioned above, starts with the choice of the hydraulic scheme between the 36 available and continues with the complete and guided sizing of each component of all the heating plant subsystems, from the emission to the generation subsystem, where the user is allowed to make all the different and alternative choices listed in the Section 3.22, in particular in the part related to the so called "Plant components flexibility".

The spreadsheet is structured in the same way of the SZp1and it permits, with the minimum number of input variables (inputs of the spreadsheet) to do an automatic, progressive and guided sizing of all the heating plants components/Types constituting the first section of the TRNSYS integrated model.

About this, another example is reported in the following Figures 3-15 and 3-16, concerning the automated sizing of one of the possible kind of emission subsystem: the radiators. With the same key of the cells shown in the Figure 3-12, even in this case is clear how, starting from the simplest technical data, the protocol allows the automatic determination of all and only the TRNSYS parameters needed by the specific Type for the dynamic simulation of the component.

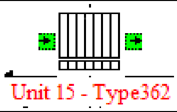
RADIATORS CHARACTERISTICS
Trnsys Type 362h "RADIATOR"



Description	Value	Parameter
Radiator material (cast iron, steel, aluminum)	Aluminum	/
Design supply temperature (°C)	75	/
Design temperature drop into the radiators (°C)	10	/
Thermal emission of the single element ΔT=50°C (W)	96.8	/
Exponent n	1.322	10-Radiator exponent
Water content of the single element (l)	1.53	/
Weight of the single element empty (kg)	1.89	/
Thermal capacitance of the radiator material (kJ/kgK)	**0.913**	/
Thermal capacitance of the radiator full of water (kJ/K)	**8.13**	/

Figure 3-15: Radiators characteristics

RADIATORS SIZING
Trnsys type 362h "RADIATORS"



Thermal Zone	ΔT TZ - Radiator (°C)	Emission of the single element (W)	Number of elements	7-Maximum mass flow rate (kg/h)	9-Nominal power of radiator DT=60°C (kJ/h)	11-Radiator thermal capacitance
TZ1	50	96.8	7	56.43	3104.23	56.92
TZ2	50	96.8	6	45.75	2660.77	48.79
TZ3	50	96.8	7	53.92	3104.23	56.92
TZ4	50	96.8	8	65.74	3547.69	65.05
TZ5	50	96.8	9	71.39	3991.15	73.18
TZ6	50	96.8	5	34.62	2217.31	40.66
TZ7	50	96.8	5	34.40	2217.31	40.66
TZ8	50	96.8	4	29.05	1773.84	32.53
TZ9	50	96.8	4	29.45	1773.84	32.53
TZ10	50	96.8	5	35.02	2217.31	40.66
TZ11	50	96.8	6	49.64	2660.77	48.79
TZ12	50	96.8	6	49.42	2660.77	48.79
TZ13	50	96.8	6	46.22	2660.77	48.79
TZ14	50	96.8	7	56.74	3104.23	56.92
TZ15	50	96.8	8	62.25	3547.69	65.05

Figure 3-16: Radiators sizing

3.3.4 SZp4 - Integrated simulation results analysis

The last sizing protocol is the one used for the energy and economic analysis of the results coming from the simulation regarding the whole building-plant system, composed by the first and second sections of the TRNSYS integrated model. The aim of the protocol is to assess the technical and economic feasibility of the simulated solution;

Now, what are the main results extracted from the nearly 1800 available outputs of the integrated model? As previously introduced, both in the dynamic model and in the sizing protocol the tool immediately return, as main outputs, the most important performance indicators and variables to understand the behavior of the building-plant system, like the:

- Building and plant subsystems internal temperatures;

- Building energy needs and power curves;
- Plant subsystems efficiencies;

About the first, the internal air and operative temperatures of each heated thermal zone of the building and the final outlet temperature of the DHW, allows to evaluate the technical feasibility of the assumed building-plant system, i.e. its ability to maintain the thermal comfort conditions initially fixed, essential for the future normal operation (Figures 3-17 and 3-18).

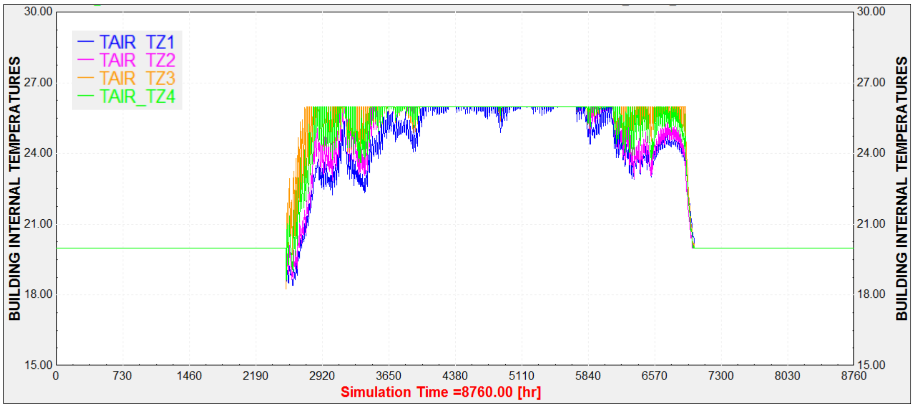


Figure 3-17: Example of building internal temperatures

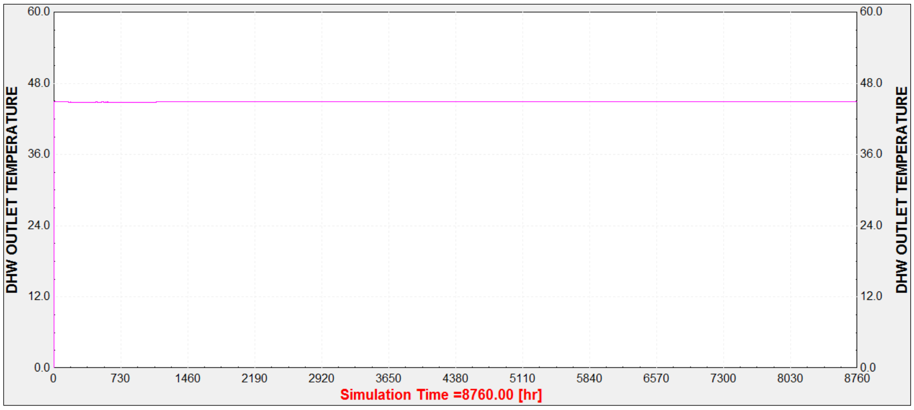


Figure 3-18: Example of DHW outlet temperature

If this first check is not satisfied the system must be changed or rejected.

The building energy needs with the resulting thermal power curves and all the plant subsystem efficiencies allows, on the other hand, assessing the economic feasibility. In fact, through all these results, together with the unitary costs of the primary energy, the protocol is able to perform a fast and automated economic evaluation of the investment compared to the “as is” situation or alternative simulated solutions, with the final determination of the three most important economic performance indicators:

- NPV - Net Present Value of the investment;
- IIR - Internal Rate of Return IIR of the investment;
- PB - pay-back time of the investment;

The Figures 3-19, 3-20, 3-21, 3-22, 3-23 show the energy needs and efficiencies directly returned by the tool, constituted by all the terms of the global energy balance of all the different hydraulic schemes available to be simulated, here summarized in the five largest schemes, able to include all the others. In particular, referring to the Table 3-I and all the 36 hydraulic schemes represented in the Appendix A:

The Figure 3-19, relative to the scheme A12, include the global energy balance of the schemes A1-A2-A5-A6-A7-A10-A11-A12;

In this case, for the part of the plant only related to the production of the DHW, the performance and energy parameters, with their relationships, are:

- Q_{dhw} (kWh)= annual DHW energy demand;
- Q_{gdhw} (kWh)= annual DHW energy demand covered by the generation;
- $Q_{sdhw\text{-}out}$ (kWh)= Q_{dhw}-Q_{gdhw}= annual solar energy removed from the DHW storage, i.e. annual DHW energy demand covered by the solar collectors;

- η_{sdhw}= annual DHW storage efficiency;
- $Q_{ssol-in}$ (kWh)= $Q_{sdhw-out}/\eta_{sdhw}$= annual solar energy introduced in the DHW storage;
- η_{dsol}= annual solar distribution efficiency;
- Q_{sol} (kWh)= $Q_{ssol-in}/\eta_{dsol}$= annual energy provided by the solar collectors;
- η_{gsol}= annual solar generation efficiency;
- Q_{rad} (kWh)= Q_{sol}/η_{gsol}= annual incident radiation on the solar collectors;

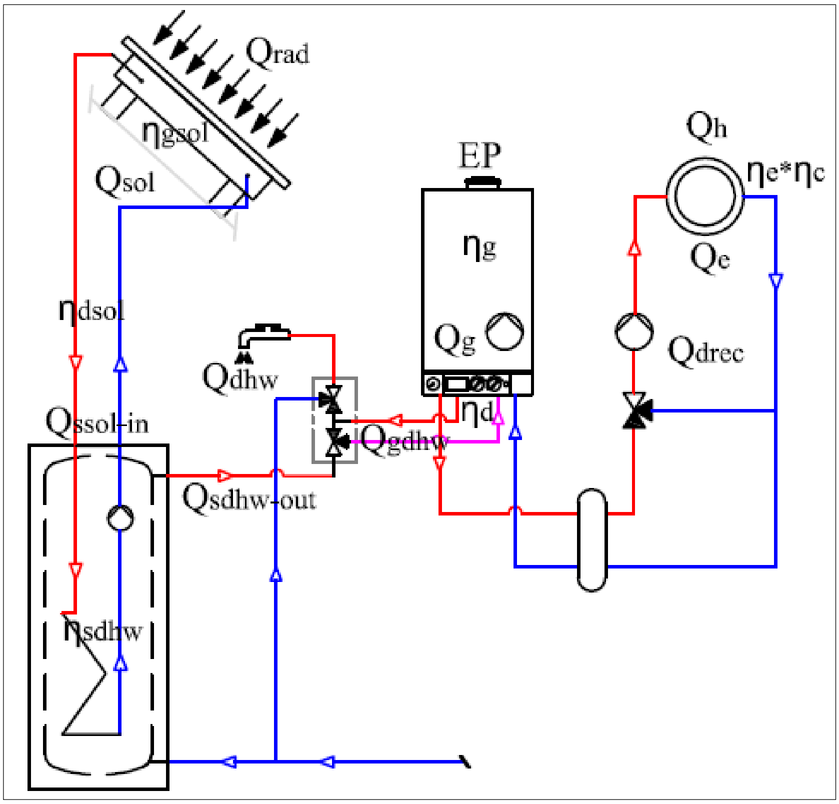


Figure 3-19: Performance indicators hydraulic schemes A1...A12

for the part of the plant only related to the heating service:

- Q_h (kWh)= annual heating energy demand;
- η_e*η_c = annual heating emission efficiency * annual heating control efficiency;
- Q_e (kWh)= $Q_h/(\eta_e*\eta_c)$= annual heating energy introduced in the building from the emission subsystem;
- Q_{drec} (kWh)= annual recovered distribution losses;

and for the common part of the plant:

- η_d= annual overall efficiency of the distribution subsystem;
- Q_g (kWh)= $(Q_e+Q_{drec}+Q_{gdhw})/\eta_d$= annual energy provided by the generation;
- η_g= annual overall efficiency of the generation subsystem;
- EP (kWh)= Q_g/η_g= annual primary energy introduced in the generation;

<u>The Figure 3-20, related to the hydraulic scheme A17, include the global energy balance of the schemes A15-A16-A17;</u>

In this case, for the part of the plant only related to the production of the DHW, the performance and energy parameters are exactly the same of the previous scheme (Figure 3-19), while for the part of the plant only related to the heating service:

- Q_h (kWh)= annual heating energy demand;
- η_e*η_c= annual heating emission efficiency * annual heating control efficiency;
- Q_e (kWh)= $Q_h/(\eta_e*\eta_c)$= annual heating energy introduced in the building from the emission subsystem;
- Q_{drec} (kWh)= annual recovered distribution losses;

- η_d= annual heating distribution efficiency;
- $Q_{s\text{-}out}$ (kWh)= $(Q_e+Q_{drec})/\eta_d$= annual heating energy provided by the storage;
- η_s= annual heating storage efficiency;
- $Q_{s\text{-}in}$ (kWh)= $(Q_{s\text{-}out})/\eta_d$= annual heating energy introduced in the storage;

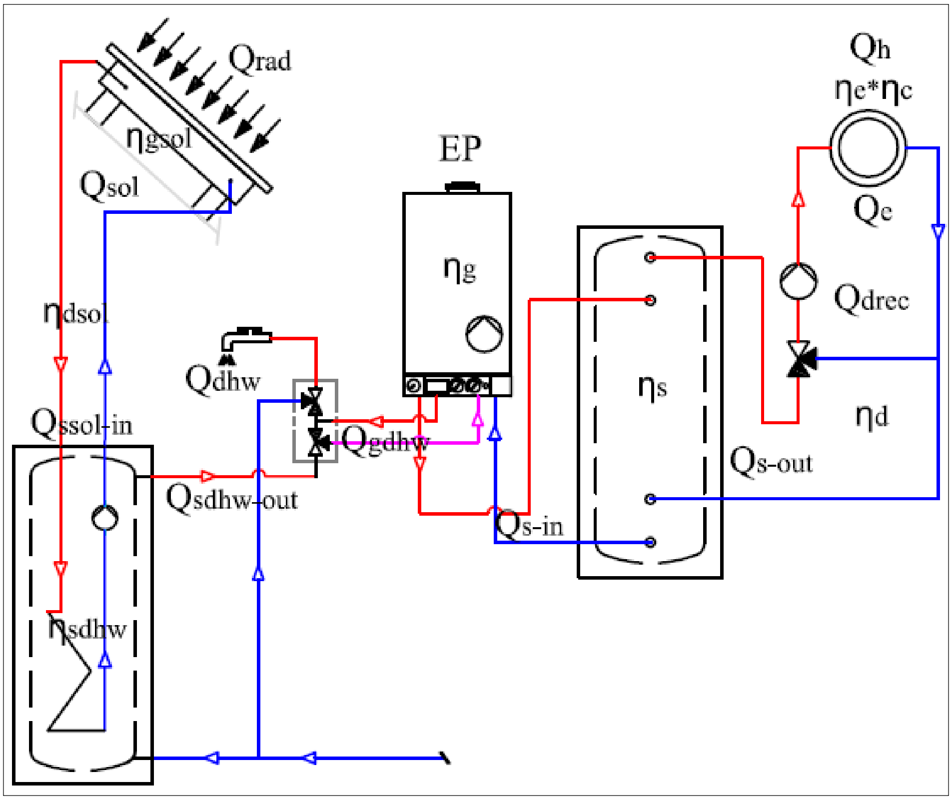


Figure 3-20: Performance indicators hydraulic schemes A15-A16-A17

and for the common part of the plant:

- η_g= annual overall efficiency of the generation subsystem;

- EP (kWh)= ($Q_{s\text{-}out}$+Q_{gdhw})/η_g= annual primary energy introduced in the generation;

The Figure 3-21, relative to the hydraulic scheme A19, include the global energy balance of the schemes A18-A19;

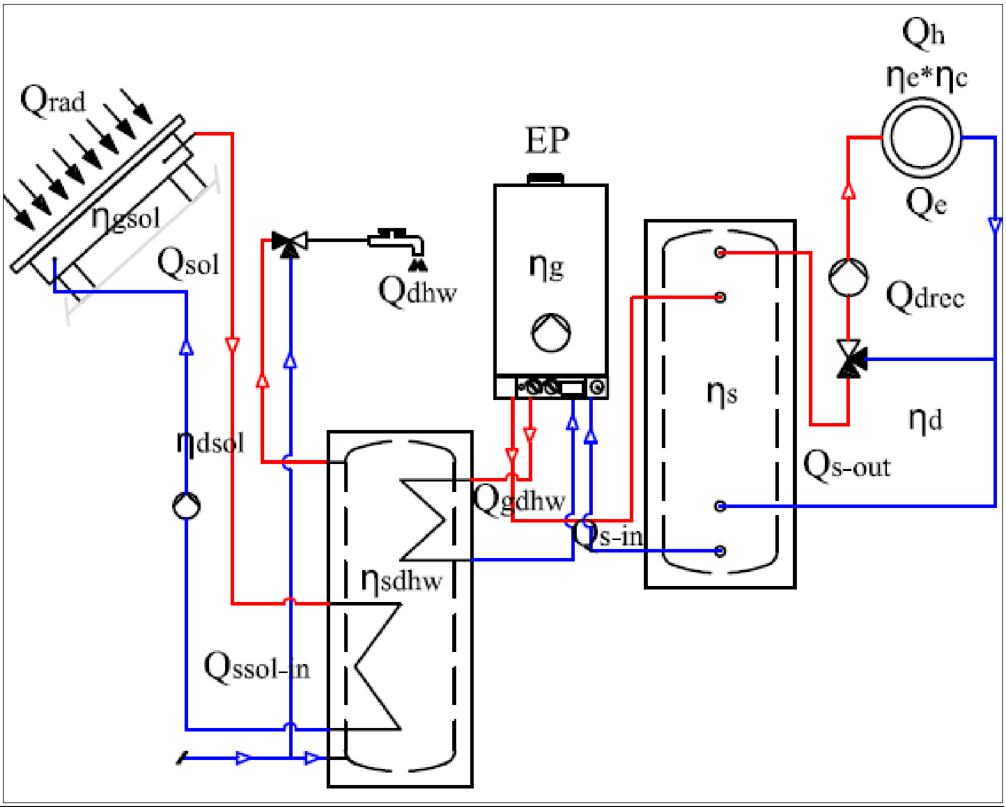


Figure 3-21: Performance indicators hydraulic schemes A18-A19

In this case, for the part of the plant only related to the production of the DHW, the performance and energy parameters are:

- Q_{dhw} (kWh)= annual DHW energy demand;
- η_{sdhw}= annual DHW storage efficiency;

- Q_{gdhw} (kWh)= annual energy introduced in the DHW storage from the generation, i.e. annual DHW energy demand covered by the generation (with η_{sdhw}=1);
- $Q_{ssol-in}$ (kWh)= Q_{dhw}/η_{sdhw}- Q_{gdhw}= annual solar energy introduced in the DHW storage, i.e. annual DHW energy demand covered by the solar collectors (with η_{sdhw} =1);
- η_{dsol}= annual solar distribution efficiency;
- Q_{sol} (kWh)= $Q_{ssol-in}/\eta_{dsol}$= annual energy provided by the solar collectors;
- η_{gsol}= annual solar generation efficiency;
- Q_{rad} (kWh)= Q_{sol}/η_{gsol}= annual incident radiation on the solar collectors;

while for the part of the plant only related to the heating service and for the common part, the indicators are exactly the same of the previous scheme (Figure 3-20).

The Figure 3-22, relative to the hydraulic scheme B15, include the global energy balance of the schemes A3-A4-A8-A9-A13-A14-B1-B2-B3-B4-B5-B6-B7-B8-B9-B10-B11-B12-B13-B14-B15;

In this case, for the part of the plant only related to the production of the DHW, the performance and energy parameters are exactly the same of the previous configuration (Figure 3-21), while for the part of the plant only related to the heating service:

- Q_h (kWh)= annual heating energy demand;
- η_e*η_c= annual heating emission efficiency * annual heating control efficiency;
- Q_e (kWh)= $Q_h/(\eta_e*\eta_c)$= annual heating energy introduced in the building from the emission subsystem;
- Q_{drec} (kWh)= annual recovered distribution losses;

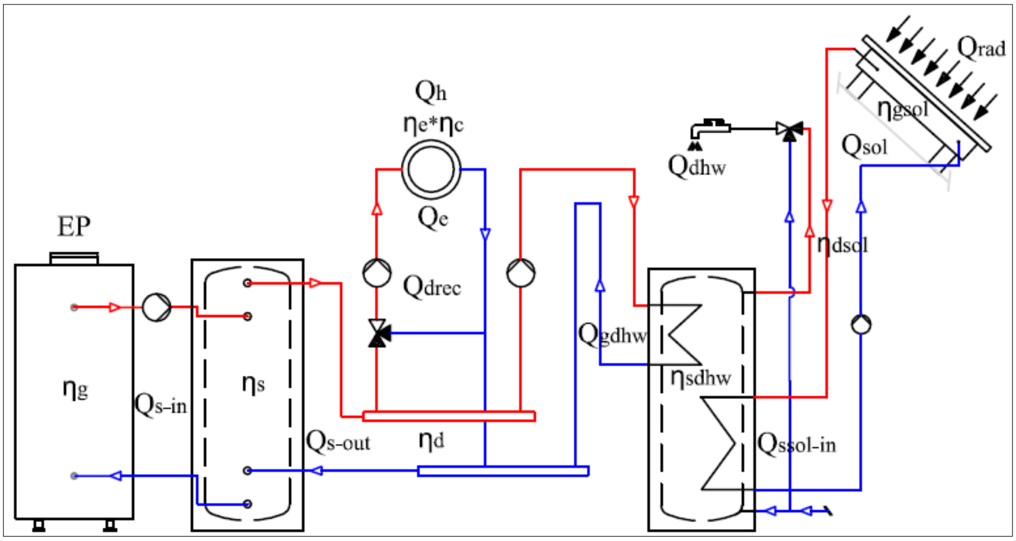


Figure 3-22: Performance indicators hydraulic schemes A3…B15

and for the common part of the plant:

- η_d= annual overall efficiency of the distribution subsystem;
- $Q_{s\text{-}out}$ (kWh)= $(Q_e+Q_{drec}+Q_{gdhw})/\eta_d$= annual energy provided by the storage;
- η_s= annual storage efficiency;
- $Q_{s\text{-}in}$ (kWh)= $(Q_{s\text{-}out})/\eta_d$= annual energy introduced in the storage;
- η_g= annual overall efficiency of the generation subsystem;
- EP (kWh)= Q_g/η_g= annual primary energy introduced in the generation;

The Figure 3-23, relative to the hydraulic scheme B17, include the global energy balance of the schemes B16-B17;

In this case, with a combined storage, for the part of the plant only related to the production of the DHW, the performance and energy parameter is the only:

- Q_{dhw} (kWh)= annual DHW energy demand;

while, for the part of the plant only related to the heating service:

- Q_h (kWh)= annual heating energy demand;
- η_e*η_c= annual heating emission efficiency * annual heating control efficiency;
- Q_e (kWh)= $Q_h/(\eta_e*\eta_c)$= annual heating energy introduced in the building from the emission subsystem;
- Q_{drec} (kWh)= annual recovered distribution losses;
- η_d= annual heating distribution efficiency;
- $Q_{s\text{-}out}$ (kWh)= $(Q_e+Q_{drec})/\eta_d$= annual heating energy provided by the storage;

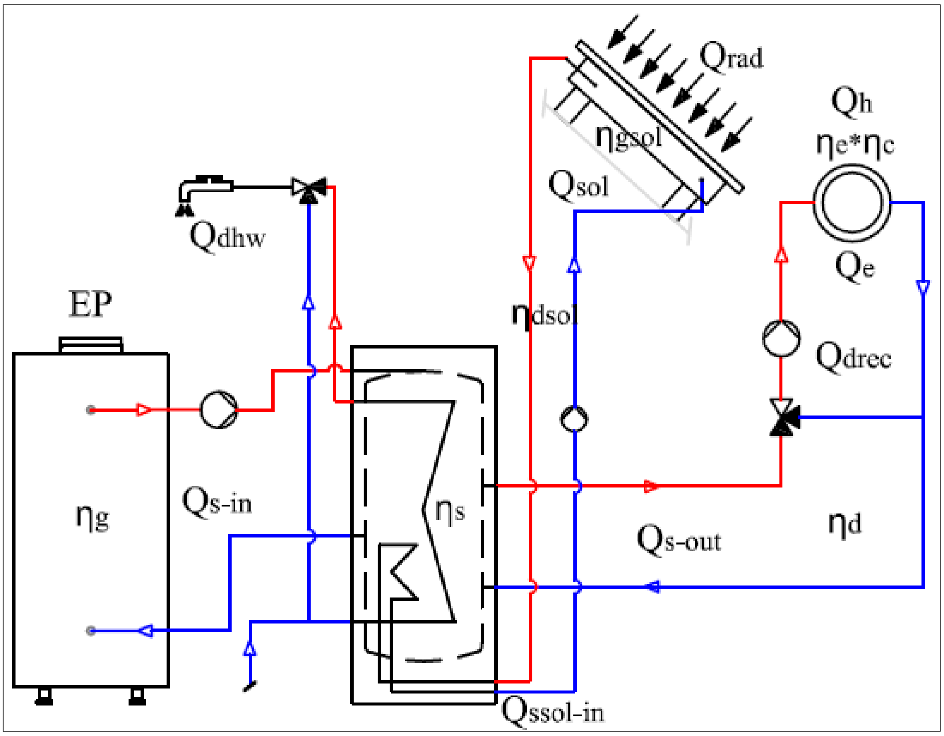


Figure 3-23: Performance indicators hydraulic schemes B16-B17

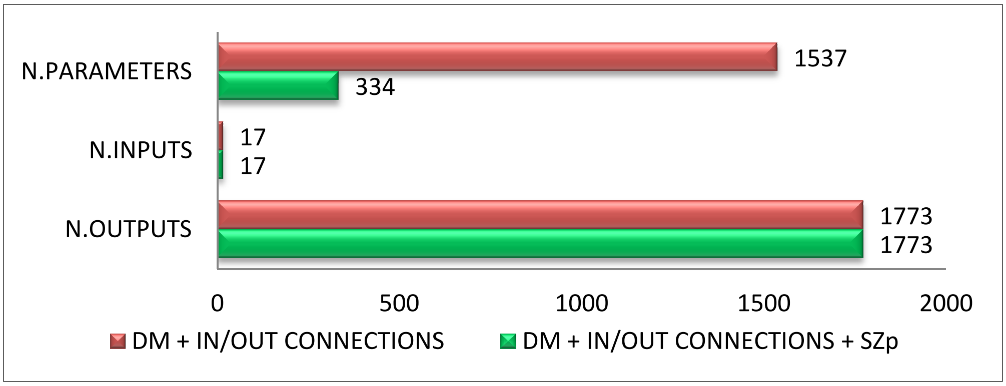
and for the common part of the plant:

- η_s= annual storage efficiency;
- $Q_{ssol-in}$ (kWh)= $(Q_{s-out}+ Q_{dhw})/\eta_s-Q_{s-in}$= annual solar energy introduced in the DHW storage, i.e. annual DHW+ heating energy demand covered by the solar collectors (with η_s =1);
- η_{dsol}= annual solar distribution efficiency;
- Q_{sol} (kWh)= $Q_{ssol-in}/\eta_{dsol}$= annual energy provided by the solar collectors;
- η_{gsol}= annual solar generation efficiency;
- Q_{rad} (kWh)= Q_{sol}/η_{gsol}= annual incident radiation on the solar collectors;
- Q_{s-in} (kWh)= $(Q_{s-out})/\eta_d$= annual energy introduced in the storage from the generation, i.e. annual DHW+ heating energy demand covered by the generation (with η_s =1);
- η_g= annual overall efficiency of the generation subsystem;
- EP (kWh)= Q_g/η_g= annual primary energy introduced in the generation;

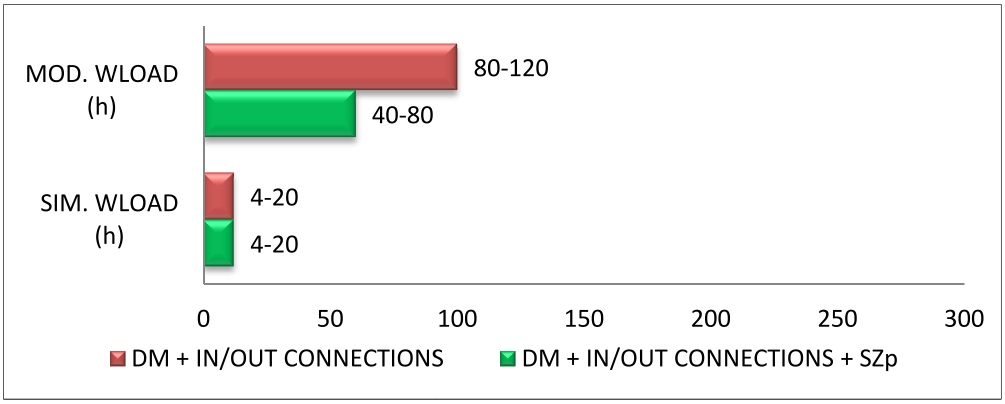
The performance indicators of each single hydraulic scheme, extracted as main outputs from the dynamic integrated model and summarized in the SZp4, are specifically represented in Appendix B.

3.3.5 SZp variable and workload advantages

About the advantages that the SZp is able to give in terms of variable and workload savings, starting from the last characterization of the integrated model with fixed input-output connections (Section 3.2.3) and as previously introduces in the Section 3.3.1, we can say that the sizing protocol, in particular through the SZp1 and SZp3, allows a big reduction of the number of the TRNSYS parameters to be set for the simulation (from around 1500 to around 330) and so another reduction of the modeling workload, now around 40-80h (Graph 3-3 and Graph 3-4), starting to make the new modeling support tool more compatible with the common design times and needs.



Graph 3-3: Sizing protocol variable savings



Graph 3-4: Sizing protocol workload savings

3.4 Simplification protocol (SMp)

The simplification protocol is the second protocol created in order to have the final modelling and simulation workload reductions related to the use of the integrated and dynamic building-plant system model described before, allowing the latter to be easily used during every design stage. As introduced in the Section 3.1, the protocol allows to apply, depending even on the design phase, specific simplifications that can further reduce the modeling implementation and simulation runtime of the TRNSYS dynamic model, still maintaining an acceptable degree of accuracy of the results.

With the simplification protocol, the concept of accuracy assumes a great importance as it is not possible to simplify renouncing completely to the accuracy of the results, essential to consciously evaluate the design choices previously made.

With respect both on the computational results and the real energy consumptions, the case studies shown in the Chapter 4 have been used to create the simplification protocol, composed of two different main kind of simplification:

- Building envelope simplification (SMp1);
- Heating plant simplifications (SMp2);

In particular the second one can be divided into the three independent and different possible simplifications, called:

- Heating plant resizing (SMp2.1);
- Emission control with ideal energy load (SMp2.2);
- Standard efficiency for emission and control subsystems (SMp2.3);

The use of the four identified simplifications may depend on the design phase, thus by the specific and available time and information. In fact, they can be used alone or in any combination of one or more of them (except the SMp2.1, connected to the SMp1) and they are placed into the methodological structure of the tool, described in Section 3.3, in the following way:

<u>SZp1 - DHW sizing</u>;

Second section - DHW simulation;

Building ideal load simulation: **possible application of SMp1**;

SZp2 - Building ideal load and DHW simulation results analysis;

SZp3 - Heating plant sizing: **application of SMp2.1 if SMp1 has been previously applied**;

First + Second section - DHW + HS simulation: **possible application of SMp2.2 and/or SMp2.3**;

SZp4 - Integrated simulation results analysis;

In the next Sections the detailed description of each simplification constituting the simplification protocol is reported.

3.4.1 SMp1 - Building envelope simplification

The first simplification is the building envelope simplification, thus related only to the “Trnsys3d” and “TRNBuild” modeling phase of the modeling support tool (see Section 3.2.1). The simplification is composed of eight consecutive steps to generate a simplified building model from a detailed building model and where each step tackles one major aspect of the building model description.

In particular the whole simplification process has been already tested and validated by Picco *(Picco, 2014)*, and can be considered as the best simplification in order to reduce both the modeling and simulation workloads, especially in the early design phases.

The eight consecutive steps are the following:

Step 01: Simplified constructions

The first step in the simplification process concerns the building constructions of the opaque and transparent surfaces. The simplification is based on the identification of a single construction type for each kind of surface present in the model. In fact, the simplified construction scheme is based on the identification of only six construction types:

exterior walls, exterior roof, exterior floor, fenestrations, interior walls, interior floors (Figure 3-24).

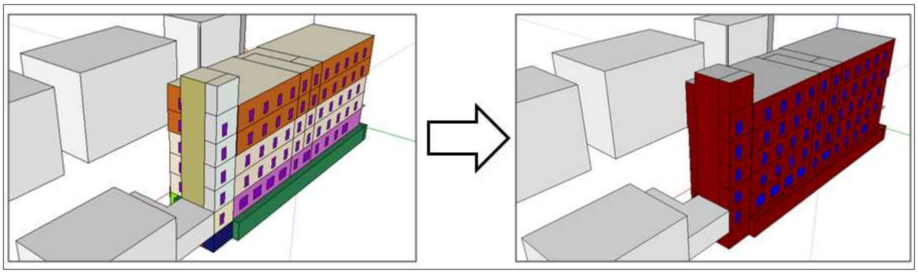


Figure 3-24: SMp1 - Simplified constructions

The simplification step constitutes a relevant reduction in the number of input data for the building envelope, due to a not complete required description of each construction type and all the materials present in the building, in accordance with the information available during especially the early design phases, when the detailed constructions are not yet known and typically only the general structural type and target transmittance are defined.

Note that in the case studies analysed during the research, for each construction type previously mentioned the reference transmittance has been identified by a weighted average of the transmittance of all the construction elements present, in function of their individual surface area as detailed in the following formula (1).

$$\bar{U} = \left(\sum_{i=1}^{n} U_i \times A_i\right) \Big/ \left(\sum_{i=1}^{n} A_i\right) \quad (1)$$

Where:
$\bar{U}$ = Average thermal transmittance of the surface type [W/m^2K];
U_i = Thermal transmittance of the i-th surface [W/m^2K];
A_i = Total area of the i-th surface [m^2];
n = Total number of surfaces of the considered type;

Step 02: Removal of external obstructions

The second simplification step is identified by the removal of all external obstructions modeled (Figure 3-25), like surrounding buildings or other external elements.

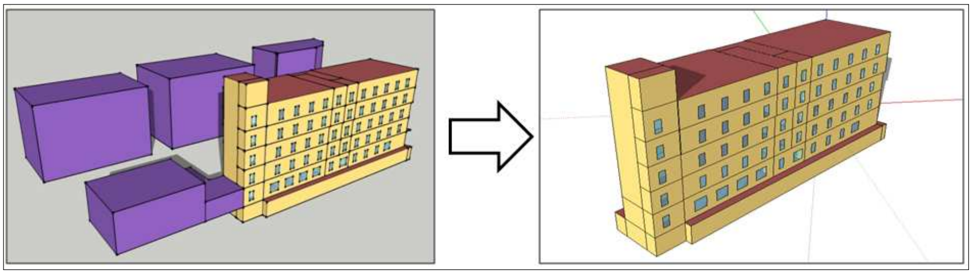


Figure 3-25: SMp1 – Removal of external obstructions

It consists in the deletion of any shadowing surface implemented in the detailed model, with the exclusion of specifically designed obstructions that can be a specific design choice with significant impact on energy needs and requires to be modelled even if the exact dimensions of each shadowing element are probably not yet known. This step is not dictated by the unavailability of needed information, as the position of the building and its surroundings are one of the first information known, but by the observation that the modeling of external obstructions would be a too cumbersome and detailed work especially in the early design phases, and is in fact one of the most common simplifications applied in practice without noticing.

Step 03: Zone lumping

Lumping of zones per floor consists in the characterization of each floor of the building with one single thermal zone (Figure 3-26).

This simplification, together with the one that provide simplified constructions, allows defining an entire building floor with a really limited number of building surfaces and layers, and therefore a limited number of inputs. Also limiting the number of zones per floor to one impacts on the need for definition of zone archetypes, removing all the accessory zones and characterizing each floor, and therefore the building itself, by its main zone destination.

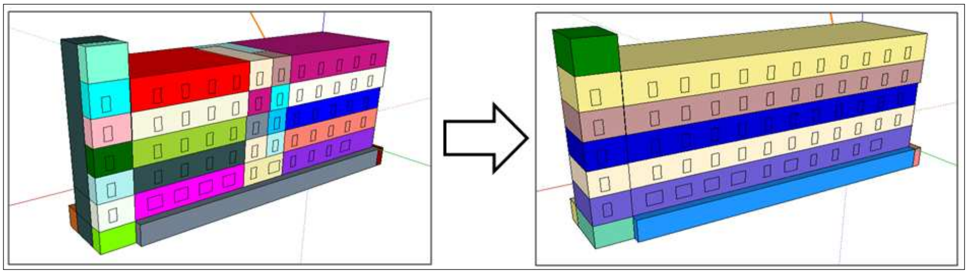


Figure 3-26: SMp1 – Zone lumping

The simplification is greatly in accordance with the available data during the design phases where the interior space distribution is typically not known until the final stages of design, and even when known, it is usually only a rough hypothesis highly subject to future continuous changes. In addition to this, the majority of information required for a complete characterization of each zone archetype is not available during the design process and often until the commissioning of the building.

A database of pre-constructed archetypes can be also used in this step to set-up internal gains, air infiltrations and time schedules (occupancy, lighting and so on).

Step 04: Simplified transparent surfaces

This simplification step is meant to reduce the data input needed to fully model the transparent surfaces of the entire building. It requires the previous simplification step, namely the lumping of zones per floor. The idea at the base of this step is to model the sum of all transparent surfaces on each floor with only four transparent surfaces or windows, one for each relative cardinal direction. For each building floor and for each compass direction only one transparent surface is identified with the purpose to model all the surfaces oriented in that direction. In other words the step provides the modeling, for each building floor and direction, of one single surface with a total area equal to the total area of all transparent surfaces of the detailed model, generated with a reference fenestration height. A total of two data input (total area and height) for each surface and a total of eight data input for each floor (total area and height in the four building vertical plane directions) are required.

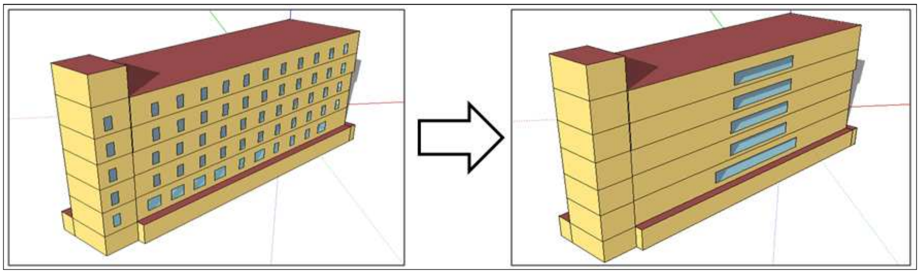


Figure 3-27: SMp1 – Simplified transparent surfaces

Step 05: Single floor standardization

The purpose of this simplification step is to be able to geometrically describe one single floor element to represent the entire building, greatly reducing the number of input required for the model especially in the case of multiple storey buildings. This is achieved by removing all accessory spaces and by standardizing the different floor plans to a reference one. This simplification permits the implementation of a subsequent simplification step called "zone squaring" (see Step 6).

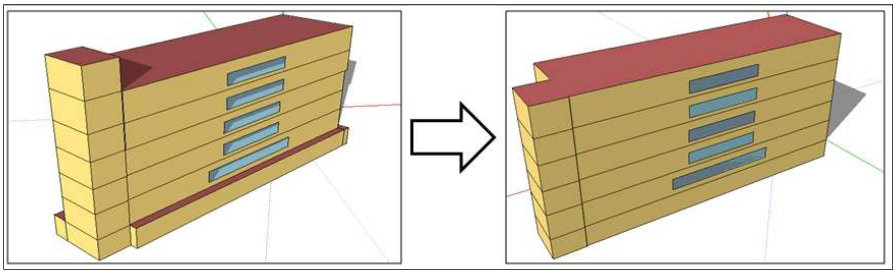


Figure 3-28: SMp1 – Single floor standardization

Step 06: Zone squaring

In conjunction with the previous step, this simplification is meant to allow the full geometrical description of the building with a limited number of inputs. More in detail the “zone squaring” intent is to describe the geometry of a single zone with a simple rectangular box. As this step represent a strong departure of the model from the real building, accurate evaluations must be carried on to determine the best modelling technique to minimize the differences generated by the simplification.

The major geometrical aspect impacting the thermal behaviour of the building can be identified as the area of the vertical diabatic surfaces, therefore maintaining them as similar as possible as in the complete model is the first priority of the simplified model. The simplified zone box is therefore modeled equalling the relative South-North and relative east-west exposed surfaces area to the ones of the complete model.

The second major aspect that influences thermal behaviour is the zone floor area, which is a dispersant surface for the terminal zones and characterizes all internal gains and air changes. Modelling the zone as a simple box can lead to important errors in the estimation of floor area, so an additional input is required for the average floor area of the building. The final simplified model is characterized by four data inputs: South-North face length, east-west face length, medium floor height and total floor area.

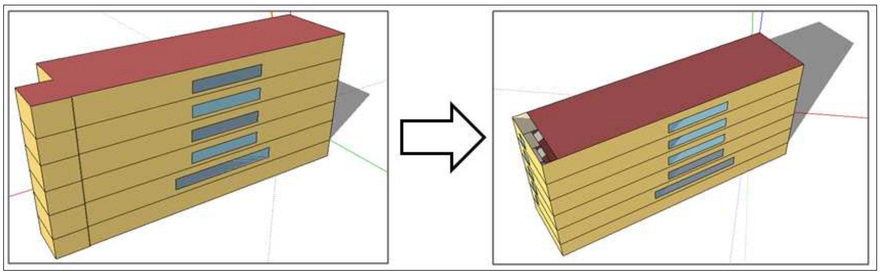


Figure 3-29: SMp1 – Zone squaring

Step 07: Standardization of transparent surfaces

During simplification Step 04, concerning transparent surfaces, the calculation of total surfaces for each cardinal direction was made singularly for each floor. In this simplification step this calculation is carried out for the entire building and then divided by the number of floors, obtaining the same surface area for each floor and therefore significantly further reducing the number of inputs required.

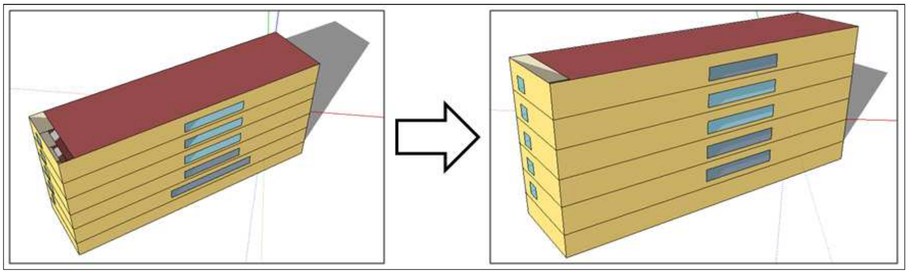


Figure 3-30: SMp1 – Standardization of transparent surfaces

- Step 08: Number of modelled floors

The last simplification step is meant to model a building through a fixed number of floors, and therefore thermal zones, regardless of the actual number of floors of the real building, considering them as multipliers of the modelled zones.

This simplification is implemented by modelling a maximum total of three zones, or floors, one for the lower floor, one for the top floor and one for the middle floors. For the latter, a multiplier number (equal to the middle floors number in the test case) is applied to consider all the building floors.

The following Figure 3-31 summarizes and represents all the mentioned steps of the building envelope simplification.

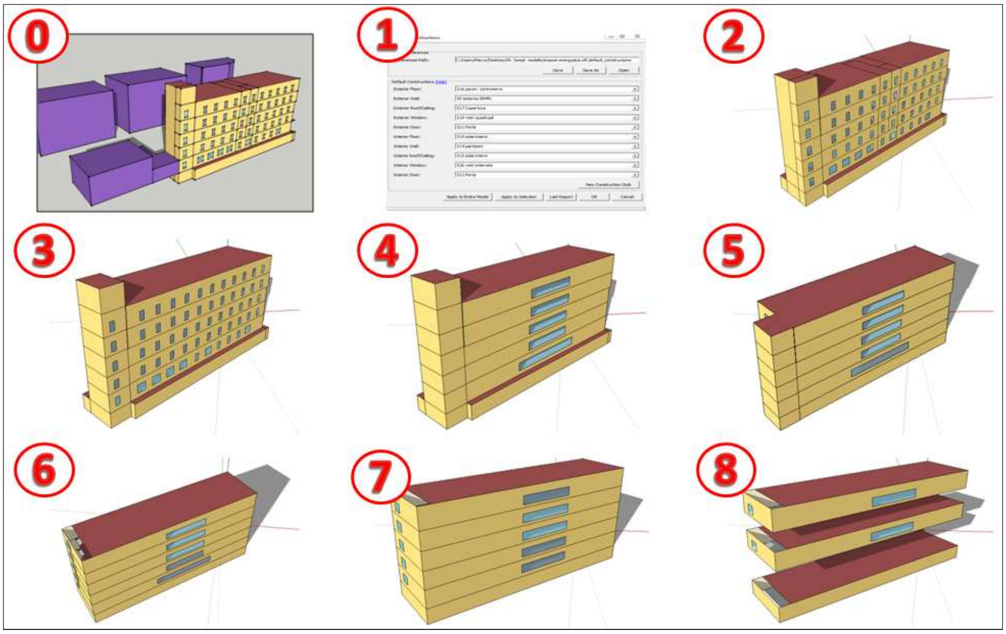


Figure 3-31: SMp1- Building envelope simplification process

3.4.2 SMp2.1 - Heating plant resizing

The first heating plant simplification is called “Heating plant resizing” and it’s closely related to the building envelope simplification previously described.

In fact the reduction of a certain number of real zones to a single thermal zone through the Steps 03 and 08 of the building envelope simplification process, is necessarily accompanied by a new sizing of the plant, in particular of the emission and distribution subsystems, now sized starting from the sum of the loads related to the real zones (Figure 3-32).

Due to the less number of thermal zones that has to be sized, the simplification permits to reduce the modelling workload related to the sizing of the heating plant, still allowing at the same time to describe in an effective way the behaviour of the specific emission, control and the distribution subsystems proposed, each characterized by a specific mass, materials, thermal inertia, and to quickly evaluate, during the design process, the adoption of different alternatives (plant components flexibility Section 3.2.2).

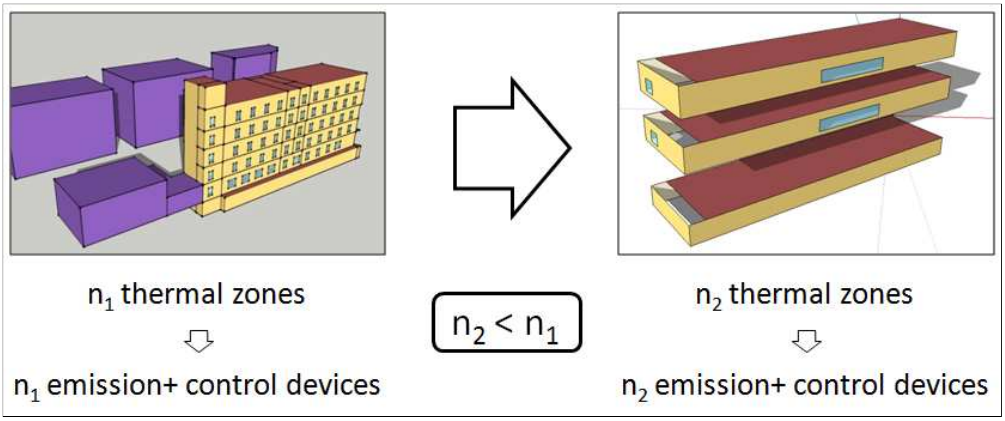


Figure 3-32: SMp 2.1 - Heating plant resizing

3.4.3 SMp2.2 - Emission control with ideal energy load

The second heating plant simplification, called "Emission control with ideal energy load" involves the replacement, in the detailed model, of the component related to the simulation of the building behaviour (Type 56) with a TRNSYS Type constituted by an external data file that gives, at each time-step, the ideal thermal useful energy demand of each zone considered.

The latter, coming from the "Building ideal load simulation", i.e. the third step of the tool design process (see Section 3.3), represents the new input of the environmental control subsystem, no longer based on the internal temperature of the zone, assumed equal to the set point temperature as boundary condition for the emission subsystem.

The simplification allows a control of the heating system in terms of power, satisfying the energy needs (thus also the thermal comfort conditions) of the building, whose simulation is carried out separately. In this way a great reduction not only of the modeling but also of the simulation workloads is provided.

3.4.4 SMp2.3 - Standard η_e η_c efficiency*

The third and last heating plant simplification is called "Standard efficiency for emission and control subsystems". This simplification allows to characterize all the different kinds of emission and control subsystems only with their constant or variable efficiency, derived from standard values universally adopted.

With this simplification the heating plant has a more simplified emission subsystem and a constant flow rate but no time should be spent in order to tune the control subsystem, often with an iterative "trial and error" process, through the P, PI or PID gains (Figure 3-33).

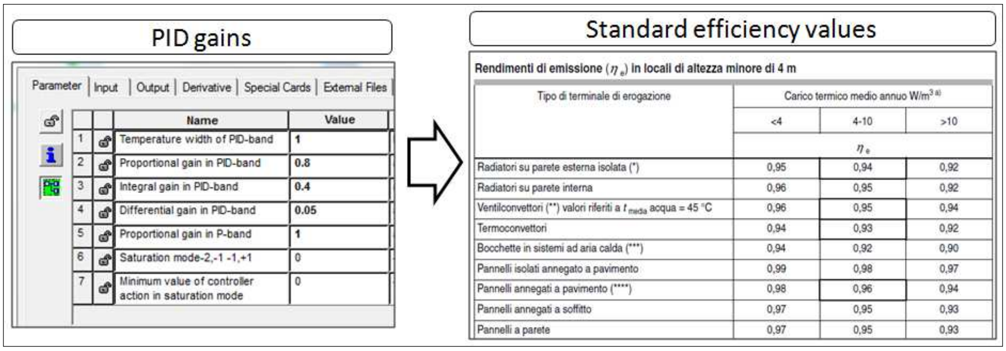
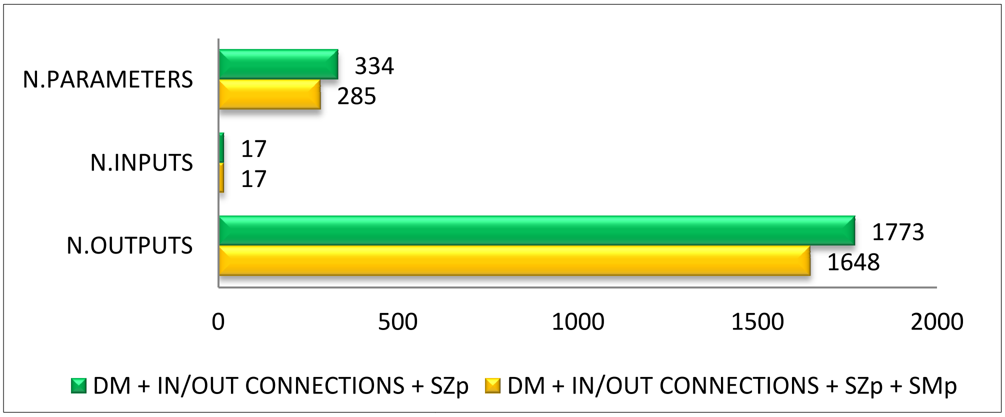


Figure 3-33: SMp 2.3 - Standard η_e*η_c values

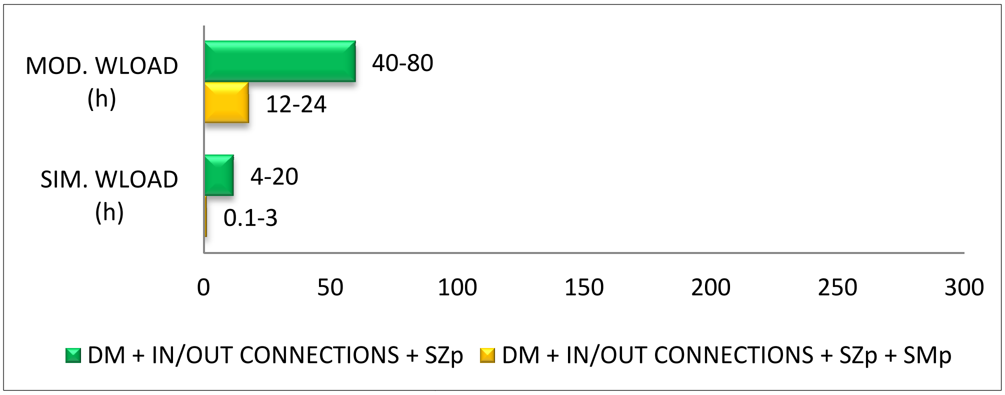
The product of the emission and control subsystems efficiencies η_e*η_c become a parameter to be set and not an output coming from the simulation, but it is absolutely justified by the great modelling and simulation workloads savings that this simplification is able to produce, especially during the early phases of the design process when the attention is more focused in evaluating design alternatives concerning the generation and storage subsystems rather than the emission or the indoor environmental temperature control subsystems.

3.4.5 SMp variable and workload advantages

As done for the sizing protocol, following are reported the graphs showing the advantages that the simplification protocol SMp is able to give in terms of variable and workload savings during the use of the new modeling support tool, starting now from the last characterization of the Section 3.2.3. The first Graph 3-5 shows that the complete application of the simplification protocol allows another small reduction of the number of the TRNSYS parameters to be set for the simulation, accompanied by a small reduction of the number of outputs, that remains in any case vary high compared to the required inputs and parameters.



Graph 3-5: Simplification protocol variable savings

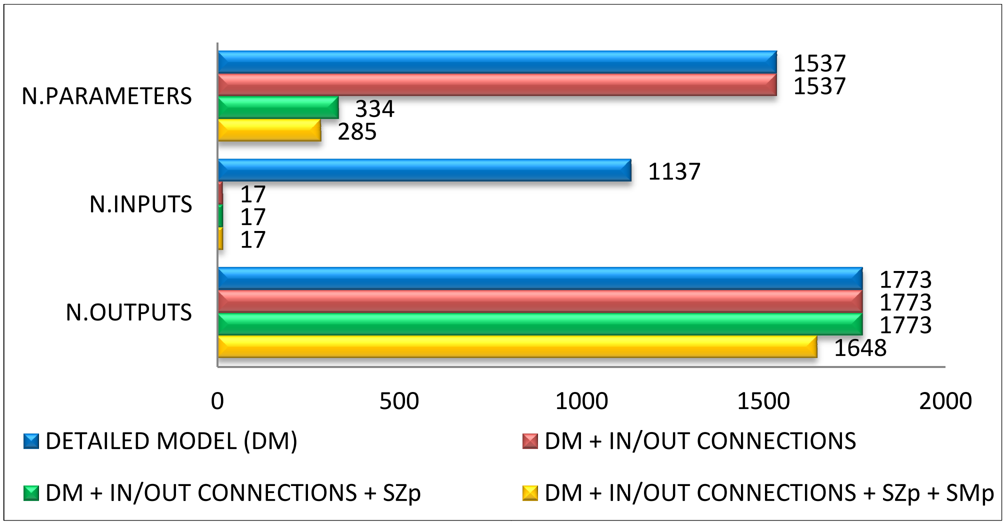


Graph 3-6: Simplification protocol workload savings

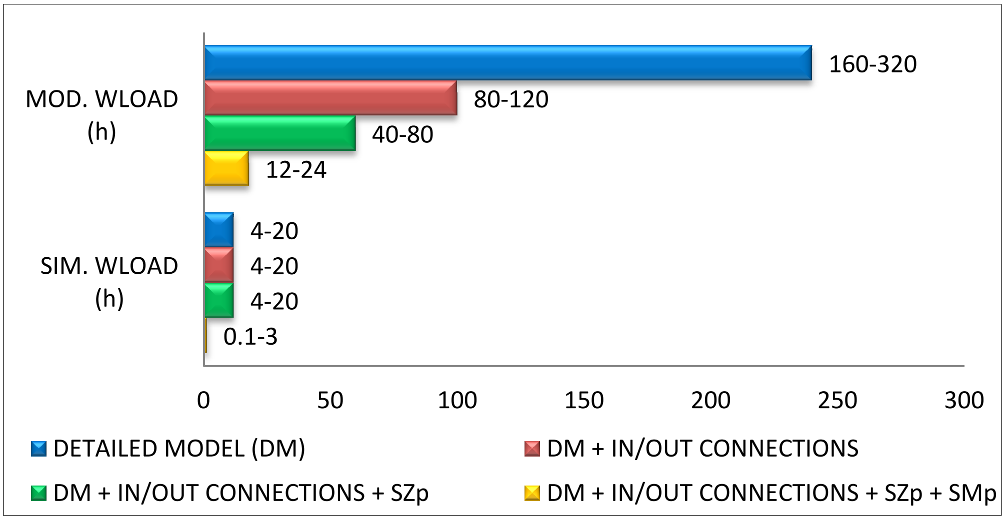
The big advantage given by the simplification protocol is actually shown in the Graph 3-6, where it is clear that the protocol permits a very big reduction of both the modeling workload, that passing from 40-80hours to 12-24 hours it became compatible with the design times, and the simulation workload, that can now range from 0.1 to maximum 3 hours for the most complex cases, far less than the 20 previously required.

But not only because, as specified before, with the simplification protocol the concept of accuracy assumes a great importance and the case studies analyzed and reported in the Chapter 4 (from which also derive all the results shown so far in terms of variable and workloads savings) indicate that the accuracy of the most simplified dynamic model in terms of energy needs, power curves and subsystems efficiencies (the main simulation results extracted by the SZp4) is very high, with a difference from the most complete model always below the 16% for all the output parameters.

Summarizing then the **total workload savings** achieved through the creation of the modeling support tool described until now into the Graph 3-6 and Graph 3-7:



Graph 3-7: Tool progressive variable savings



Graph 3-8: Tool progressive workload saving

considering the mentioned accuracy, it can be stated that, starting from a very detailed but time-expensive dynamic model:

- The fixed input-output connections has highly improved the number of inputs to be set for the simulation, therefore the associated modeling workload;
- The sizing protocol has highly improved the number of parameters to be set for the simulation, therefore it has further reduced the modeling workload;
- The simplification protocol has further improved the modeling workload and highly reduced the simulation workload, that can become even negligible.
- All together the fixed input-output connections and the protocols have highly improved all the variables related to the time requirements and available information of integrated design reaching the creation of a flexible, fast but still accurate tool for the integrated building-plant system design.

PART 3

Case studies

Chapter 4

4 Case studies and results

4.1 Selection criteria

In this chapter the case studies that have been selected for this research are reported, in order to demonstrate the results shown before about the time-accuracy balance in the utilization of the new modeling support tool.

In particular the attention has been focused around two main different case studies, able to reflect the great flexibility of the tool:

- The CS1 is a single residential unit located in a semi-detached existing house, subjected to a renovation design, where:

- The hydraulic scheme is A15;
- The model scale is 1 thermal zone equal to 1 room, so a Small scale & High resolution design;

This case study has been used for the development of the flexible, detailed, integrated and dynamic building-plant system TRNSYS simulation model and for the development and application of the sizing and simplification protocols to a building with common concrete structure and medium energy performances;

- ➢ The CS2 is a recently built apartment building comprising 15 flats, three of which subjected to a complete monitoring of all energy consumptions and activities;

For this case study two different approaches have been followed:

- ➢ The first approach CS2.1 means the dynamic simulation of the whole building-plant system for each single unit with monitored activities and consumptions, where:
  - The hydraulic scheme is A5;
  - The model scale is 1 thermal zone equal to 1 room, so a Small scale & High resolution design;

The case study CS2.1 has been used in particular for the validation of the tool modeling and simulation process with the development and the application of the sizing and simplification protocol to a building with steel-wood structure and very high energy performances;

- ➢ The second approach CS2.2 means the dynamic simulation of the building-plant system for the entire apartment building, supposed to have a heating and domestic hot water central plant, where:
  - The hydraulic scheme is B15;
  - The model scale is 1 thermal zone equal to 1 apartment, so a Medium scale & Medium resolution design;

This third case study has been used for the application of the whole modeling and simulation process to a building with very high energy performances;

In the following Sections 4.2-4.3-4.4 the detailed description of each of the three case studies is presented, while the Section 4.5 shows other examples of how the tool can be used, examples that don't give further results in terms of time/accuracy ratio but that prove the great flexibility of the tool itself, adaptable in a very short time, even with some modifications to the basic simulation model, to various different building, plant or building-plant system design.

4.2 Case study 1- stationary VS dynamic tool

4.2.1 Building description

The case study 1 regards a standard residential unit situated in a building built in 1989 in Bergamo, Italy (Figure 4-1). The building consists of three floors, the basement for garage and winery, ground and first floors each intended for residential purposes. In particular, as opposed to the one on the first floor, the apartment on the ground floor is not currently used and needs a renovation in order to make it habitable.

Retrofit design and simulations focus just on this portion of the building, characterized by an usable floor area of 86.25 m^2, a total net volume of 232.88 m^3, 7 heated spaces/rooms and a central unheated stairwell necessary to connect the basement to the ground floor apartment (Figure 4-2).

Currently the building envelope, except the ceiling adjacent to the upper apartment, is only composed of the structural part made of reinforced concrete, and the renovation design provides the thermal insulation of the 311 m^2 internal surface, through wall and window layers able to ensure both high energy performances and the access to the tax benefits expected for this kind of building work.

Figure 4-1: CS1 building

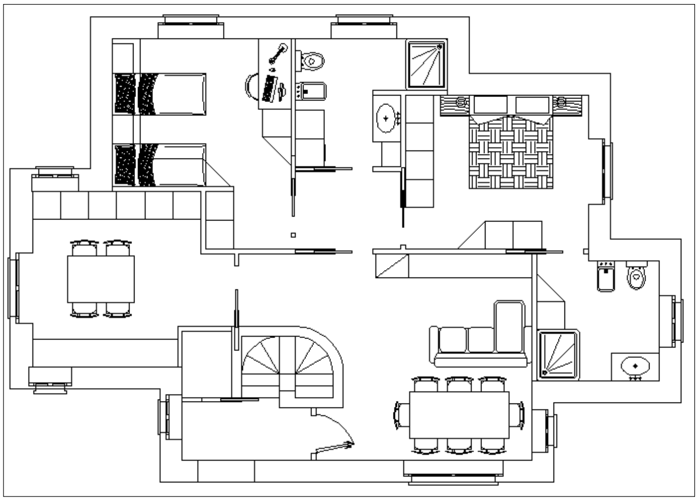


Figure 4-2: Design of the interior layout of the apartment

In particular, as provided by retrofit design, the opaque vertical surfaces will have a transmittance equal to 0.262 W/m^{2}K, while the floor adjacent to the basement a transmittance of 0.285 W/m^{2}K and for the 14.88 m^2 of transparent surfaces a global average transmittance of 1.5 W/m^{2}K is set for the simulations. The HVAC plant is expected to meet only the winter thermal load through a heating system composed of 7 aluminum radiators (one for each room) powered by a 5 kW condensing natural gas boiler.

A climate control for the supply temperature of the heating plant is provided, together with an internal regulation composed by thermostatic valves able to reduce or increase the flow rate of the heat transfer fluid to the radiators. The isolated distribution network piping will be placed inside the heated environments in order to reduce losses to a minimum value.

4.2.2 Stationary simulation model

For the first case study not only a dynamic simulation (required to apply the tool) has been carried out, but even a stationary simulation, with the Italian commercial software Termus (produced by ACCA software S.p.a., M. Cianciulli road - 83048 Montella (AV), Italy), in order to test the differences between the two kind of simulations.

The Termus model consists of a single thermal zone divided into 7 rooms and of all the other heated areas (first floor apartment) and unheated spaces (basement, stairwell and the boiler room) necessary to establish, with monthly time-steps, the average boundary temperatures of all the surfaces (Figure 4-3).

The wall layers of the model consist in 22 different types identified with 15 different materials. A basic time schedule for the heating system has been defined as input and the following quantities have been estimated:

- Losses related to thermal bridges;

- Geometric shadowing objects and obstruction due to the building and its urban context;
- Standard values for infiltration and internal contributions (values recommended by current legislation);
- Standard efficiency values for the emission (η_e) , control (η_c), distribution (η_d) and generation (η_g) subsystems (even for these, the software considers values recommended by current legislation);

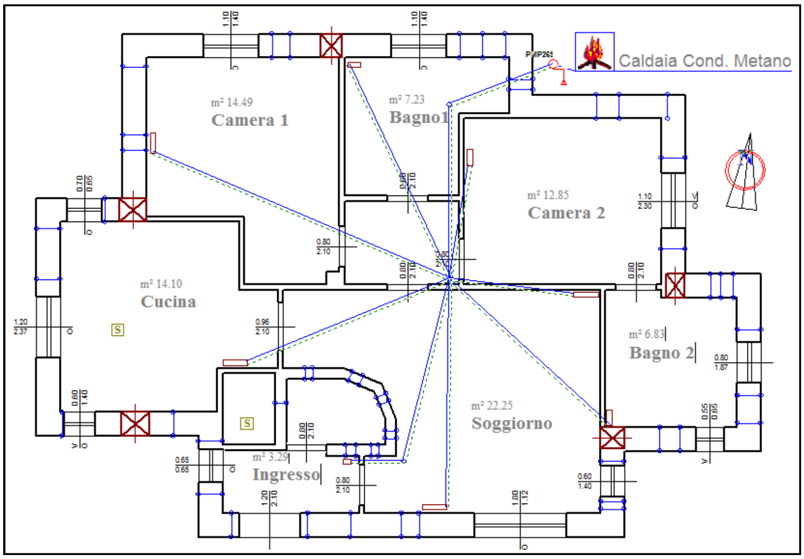


Figure 4-3: Termus simulation model and heating plant design

The software generates as main output results the following parameters:

- Maximum thermal power required from each room in the design conditions (kW);
- Monthly thermal energy demand of the whole zone simulated (kWh);
- Monthly primary energy demand of the entire simulated zone (kWh);

- Annual thermal energy demand of the whole zone simulated Q_h (kWh);
- Annual primary energy demand of the entire simulated zone EP (kWh);

Then, based on the first output described, it proceeds to the heating plant design, sizing the components and verifying their operation in the maximum load condition (Figure 4-3).

The software, all based on standard values and conditions and with the plant subsystems efficiencies given as an input, does not consider the possible presence of a storage tank and does not take into account the recovery of the potential distribution losses.

4.2.3 Dynamic simulation model

After the stationary simulation, the whole tool dynamic simulation process has been applied to the building, starting from the building envelope ideal load simulation (the DHW production is not provided for this case study), passing from the SZp2 and SZP3 to end with the integrated simulation of the first section of the TRNSYS dynamic model and the analysis of the results through the SZp4 (see Section 3.3 for the detailed description of the tool design process).

In particular, in terms of building envelope, as seen for the stationary simulation, the detailed model consists in seven homogenous thermal zones, fully describing all conditioned rooms, underground non-conditioned space, and all accessory not conditioned volumes like stairwell, boiler room and attic.

Through the specific "Trnsys3d" tool, the three-dimensional detailed modeling of the entire building has been created (Figure 4-4), while in the TRNBuild tool, in order to characterize the various zones in terms of materials, walls and windows layers, thermal bridges, internal gains, temperature set-points and time heating schedule, the same data of the previous stationary simulation have been used, adding all the parameters not considered by this kind of design, as the heat capacity of the materials or external and boundary conditions with hourly rather than monthly time-step.

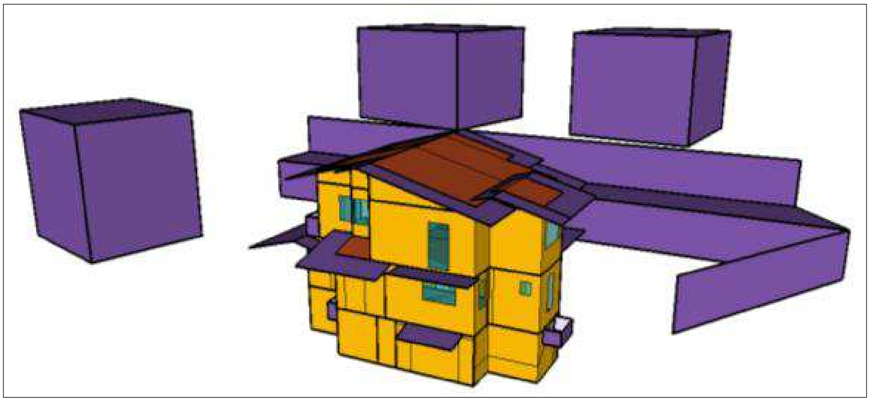


Figure 4-4: CS1 “Trnsys 3d” detailed model

With reference to the hydraulic scheme A15, the heating plant modeling through the Types of the first section of the TRNSYS integrated model (the characterization of all TRNSYS Types used for the plant components has been made from all the data resulting from the stationary plant design made previously in Termus and in the SZp3, both reporting the same results), has been synthetically structured as follows:

- Generation + storage sub-systems: natural gas boiler whose operation is governed on the basis of the temperatures measured inside the buffer tank placed downstream;
- Distribution sub-system: three-way diverter and mixing valves able to ensure at each moment the correct flow temperature regulated depending on the outdoor temperature (climate control), variable speed pump, distribution piping from the storage tank to the supply/return manifold and from the latter to radiators;
- Emission subsystem: aluminium radiators;

- Control subsystem: individual room PI type able of acting on the flow of the heat transfer fluid to the single radiator, with feedback constituted by the actual ambient temperature recorded.

About the outputs, the clear and very big difference respect on the stationary model is that the dynamic model created with the tool allows checking the actual operation of the entire building-plant system at any variation of all the possible internal and external conditions, taking into account each instant the interaction of all the components, result that the stationary approach is not absolutely able to return.

Now, those just mentioned are the features of the detailed dynamic simulation model, but what about the simplification protocol?

The latter has been applied in consecutive simulations where all the simplifications constituting the simplification protocol has been used (except the last simplification SMp2.3 introduced with the next case studies), progressively enhancing the level of simplification and giving, together with the stationary model and the ideal loads conditions for both the dynamic and stationary approach, all the simulation combinations shown in the following Section 4.2.4 (Table 4-I).

In particular the output of the building envelope simplification SMp1 has been the one shown in the Figure 4-5, where the building become a rectangular box with only one heated thermal zone.

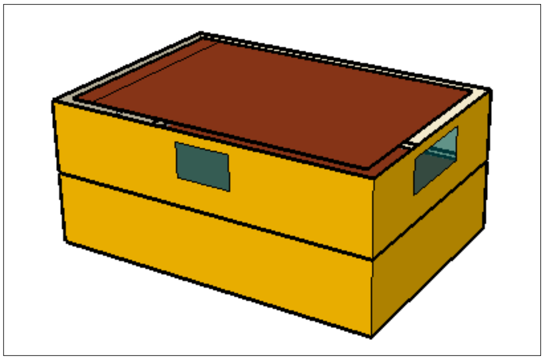


Figure 4-5: CS1 building envelope simplification

4.2.4 Simulation cases and results

As introduced above, thanks to the stationary model, the detailed dynamic simulation done for the entire building-plant system, and the progressive application of the simplifications considered by the simplification protocol, 8 different annual simulations have been identified and carried out for the CS1, summarized in the Table 4-I:

Table 4-I: CS1 simulation cases

SIMULATION CASES		ENVELOPE		
		TERMUS	TRNSYS	
		DETAILED MODEL	DETAILED MODEL	DETAILED MODEL +SMp1
HVAC	IDEAL LOADS	1	2	3
	DETAILED MODEL	4	5	/
	DETAILED MODEL+SMp2.2	/	6	/
	DETAILED MODEL+SMp2.1	/	/	7
	DETAILED MODEL +SMp2.1+SMp2.2	/	/	8

The simulation number 5 is the most complete and detailed simulation, while the case study number 8 is the most simplified simulation.

As introduced before the aim of the progressive increase in the level of simplification has been the comparison between the results of the most detailed model and the simplified models, in order to test the quality/accuracy of the energy results respect on the time and information requirements dictated by each specific simulation case.

In particular, the articulation of the simulations is the following:

<u>Case 1</u>: a complete stationary energy simulation of the building, through Termus software (time-step 1 month), i.e. a stationary simulation only for the building envelope, or, in other words, the determination of ideal loads through a stationary model (ideal loads means that all the thermal efficiencies of the heating plant subsystems are set equal to one);

Case 2: a complete dynamic energy simulation of the building system, through TRNSYS software (time-step 1 hour), i.e. a detailed model only for the building envelope, without the integration of all the subsystems of the heating plant (determination of the ideal loads through a complete dynamic model);

Case 3: dynamic energy simulation of the simplified building system through TRNSYS software (time-step 1 hour), i.e. Case study 2 + Building envelope simplification SMp1;

Case 4: stationary energy simulation of the entire building-plant system, through Termus software (time-step 1 month) = Case study 1 + application of standard efficiency values for all the subsystems of the heating plant;

Case 5: dynamic energy simulation of the entire building-plant system, through the TRNSYS integrated model (time-step 5 min) = the most complete detailed model. This is the case taken as reference for the comparison with the results of all the other simulations analyzed, constituting the highest degree of detailed simulation for both the building envelope and the heating plant;

Case 6: dynamic energy simulation of the entire building-plant system + Emission control with ideal energy load, through the TRNSYS integrated model (time-step 5 min) = Case study 5 + heating plant simplification SMp2.2;

Case 7: dynamic energy simulation of the entire building-plant system + Building envelope simplification + Heating plant resizing, through the TRNSYS integrated model (time-step 5 min) = Case study 5 + simplifications SMp1 and SMp2.1;

Case 8: dynamic energy simulation of the entire building-plant system + Building envelope simplification + Heating plant resizing + Emission control with ideal energy load, through the TRNSYS integrated model (time-step 5 min) = Case study 5 + simplifications SMp1 , SMp2.1 and SMp2.2;

The comparison of the results for all the simulations carried out has been restricted to the output parameters and curves able to describe the annual operation of the building-plant system analyzed, i.e. the most important performance indicators and parameters listed in the Figure 4-6[8], plus the thermal power curves deriving from the indicated energies:

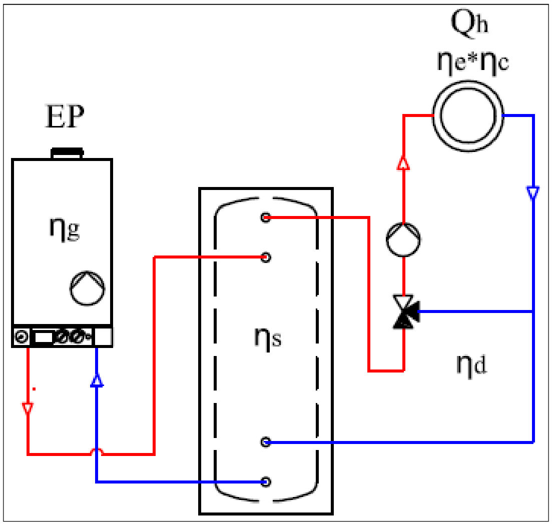


Figure 4-6: CS1 performance indicators

In particular:

- Q_h (kWh)= annual heating useful energy demand of the apartment;
- EP (kWh)= annual primary energy introduced in the generation;
- ηx = annual average efficiencies of all the heating subsystems;

[8] The performance indicators are extracted from the ones listed in the section 3.3.4 for the specific hydraulic scheme analyzed, omitting those which can be directly derived from the relationships shown in the same section and in Appendix B;

while the thermal power curves (pay attention that this curve cannot be obtained for the stationary models) are related to the annual trend of the useful thermal power Q_h introduced in the apartment.

To test the loss of accuracy of the energy results respect on the modeling workload and simulation workload savings deriving from the progressive simplifications, the results of the 8 simulations carried out, in absolute values and percentage differences compared to the reference Case study 5 (highest degree of detailed simulation for both the building envelope and the heating plant), are summarized in the following tables and graphs, adding the modeling and simulation workloads required to perform each case.

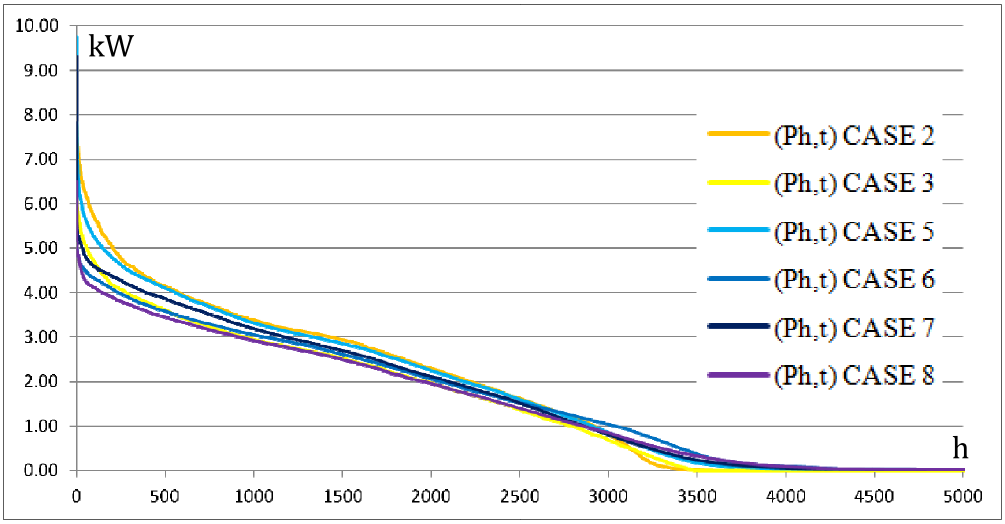
Note that, as specified in the Section 3.2.3 and for all the case studies of this research, the modeling workload and simulation workload has been estimated from repeated attempts through the case studies shown. In particular the modeling workload can be defined as the time spent to prepare the simulations, considering already available all the data needed to characterize the various building thermal zones. Simulation workload consist on the simulation runtime in the software TRNSYS.

Table 4-II: CS1 results - absolute values

CS1 RESULTS - ABSOLUTE VALUES									
Symbol	**U.m.**	**CASE 1**	**CASE 2**	**CASE 3**	**CASE 4**	**CASE 5**	**CASE 6**	**CASE 7**	**CASE 8**
Timestep	h	744.00	1.00	1.00	744.00	0.08	0.08	0.08	0.08
Q_h	kWh	8151	8243	7739	8151	8243	8243	7739	7739
EP	kWh	8151	8243	7739	9266	10049	9403	9562	8864
$\eta_e*\eta_c$	/	1.00	1.00	1.00	0.94	0.90	1.00	0.90	0.99
η_d	/	1.00	1.00	1.00	0.96	1.00	1.00	1.00	1.00
η_s	/	1.00	1.00	1.00	1.00	0.91	0.90	0.90	0.90
η_g	/	1.00	1.00	1.00	0.97	0.97	0.97	0.97	0.97
Mod Wload	h	20	28	8	24	48	40	32	24
Sim Wload	h	0.02	0.08	0.05	0.03	4.50	0.18	1.00	0.10

Table 4-III: CS1 results - absolute values

CS1 RESULTS - RELATIVE VALUES									
Symbol	**U.m.**	**CASE 1**	**CASE 2**	**CASE 3**	**CASE 4**	**CASE 5**	**CASE 6**	**CASE 7**	**CASE 8**
Q_h	kWh	99%	100%	94%	99%	100%	100%	94%	94%
EP	kWh	/	/	/	92%	100%	94%	95%	88%
η_e*η_c	/	/	/	/	105%	100%	111%	100%	110%
η_d	/	/	/	/	95%	100%	100%	100%	100%
η_s	/	/	/	/	110%	100%	99%	99%	98%
η_g	/	/	/	/	100%	100%	100%	100%	100%
Mod+ Sim Wload	h	42%	58%	17%	50%	100%	83%	67%	50%



Graph 4-1: CS1 power curves

Considering the results just shown, it can be stated that:

- Observing the thermal power curves (Ph, t) at the time t=0, the value of the maximum useful thermal power introduced in the building to ensure the temperature set point, has a fairly high variation, with peak values higher for cases 5 and 7, i.e. for dynamic simulations where the feedback of the control subsystem is constituted by the interior temperature of the simulated zones. However it is possible to note that such peak values are required for a number of hours per year absolutely negligible, while the curves indicates the presence of a peak around the mean power of 5.5 kW, however higher to that returned by the first stationary simulation, equal to 4.67 kW.

- For the rest of the time, all the thermal power curves have a very similar trend. In the central part of the curves there are constant differences between cases 2-3, 5-7 and 6-8, due to the simplification SMp1, which slightly underestimates the useful energy requirements of the building envelope. There are small opposite deviations in the intervals near the maximum and minimum power in particular for the cases 5-6 and 7-8, where the simplifications adopted for the plant become more important, going to affect in particular the operation of the emission and control sub-systems (simplification SMp2.2), which are more stressed for low and high thermal powers;
- The value of the annual heating useful energy demand of the apartment Q_h has a maximum variation of 6%. In particular, by adopting for both the stationary model and the dynamic simulations the same characterization of zones (note that thermal bridges on a small building play a very important role and in both simulations are estimated with stationary algorithm), the values of Q_h for these simulations are very close. The building envelope simplification SMp1 causes an acceptable underestimation of the 6%, equal to the difference of the areas under the thermal power curves of the cases 2 and 3.
- The energy efficiencies of the distribution (η_d), storage (η_s) and generation (η_g) sub-systems, for all the dynamic simulations concerning the whole building-plant system (cases 5, 6, 7, 8), are

almost constant. They assume quite different values in the stationary simulation (case 4), which does not take into account the possible recovered distribution losses and the storage subsystem.

In particular the efficiency of the distribution network piping for dynamic simulations assumes high values, due to the total recovery of distribution losses and the partial thermal recovery of the energy consumed by the distribution pump.

- Both in the stationary simulation (case 4) and in the dynamic simulations 6 and 8, in which the controller feedback is an external energy data file reporting the ideal heating requirements of the simulated zones, the emission and regulation efficiency (η_e* η_c) is overestimated compared to cases 5 and 7, where the feedback is more realistically represented by the internal ambient temperature.

  As expected, the heating plant simplification SMp2.2 has a stronger effect on the control, bringing the plant to provide almost perfectly the ideal energy requirements of the building.

- Finally, the primary energy demand of the building EP has a fairly limited variability, with an underestimation of up to 12% for the case 8, i.e. for the dynamic simulation characterized by the highest degree of simplification. Even the stationary simulation underestimates the EP value compared to the case 5.

- About the modeling and simulation workload, it is possible to note how, compared to a maximum loss of accuracy of 12% of the most simplified case 8, the time required to perform a simplified dynamic simulation of the entire building-plant system is reduced to one half, and becomes equal to the time required to perform a complete stationary simulation (case 4). However, the latter is not absolutely able of ensuring benefits that only a dynamic simulation is able to guarantee, such as the full control of the integrated operation of all the heating plant components at any variation of internal and external conditions.

Therefore it can be concluded that:

- Even if stationary and dynamic simulations may lead to close global results when a lot of same standard inputs are used, the results for individual components and subsystems may differ because of the more accurate algorithms and assumptions used during the development of dynamic simulations. (Furthermore often the real cases differ from standard conditions and only a dynamic simulation is able to consider any type of possible different condition.)
- The dynamic simulations are able to provide a number of output far greater than those given by a stationary approach and therefore allow a more precise evaluation of the power loads (the stationary model is not able to give the thermal power curves).
- A simplified dynamic approach provides a complete energy simulation with a very high accuracy and workloads equal than the time necessary to perform a complete stationary simulation.
- The CS1 just described is a first example that, with the proper modeling support tool it can be reached, with a dynamic simulation, a very high number of accurate results with low workloads, compatible with the ones required by all the stages of the integrated design.

4.3 Case study 2.1 – tool validation

4.3.1 Building description

The building analyzed in the case study 2 is an apartment building comprising 15 flats, built in 2012 and situated in Torquay, UK (Figure 4-7).

Figure 4-7: CS2 building

The building consists of four floors, the basement for the car park, ground, first and second floors intended for residential purposes and each composed of five apartments along a central hallway (Figure 4-8).

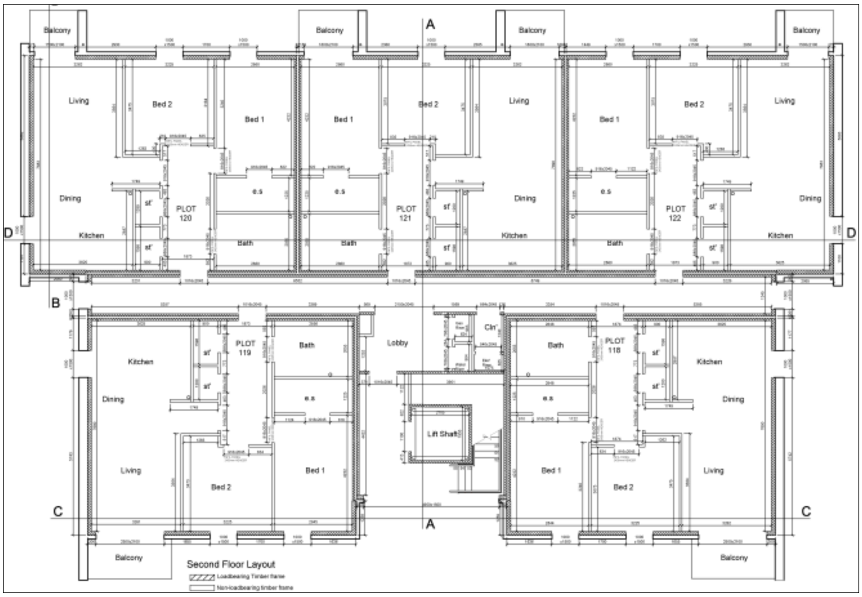


Figure 4-8: CS2 Building second floor plant

The whole building is characterized by a net total floor area of 1921 m^2 and a net total volume of 5255 m^3, while each apartment is composed of 8 heated rooms, with a useful floor area of 77 m^2 and a net total volume of 208 m^3.

It has also an innovative steel-wood structure able to reduce thermal bridges and especially construction times like the one shown in the Figure 4-9.

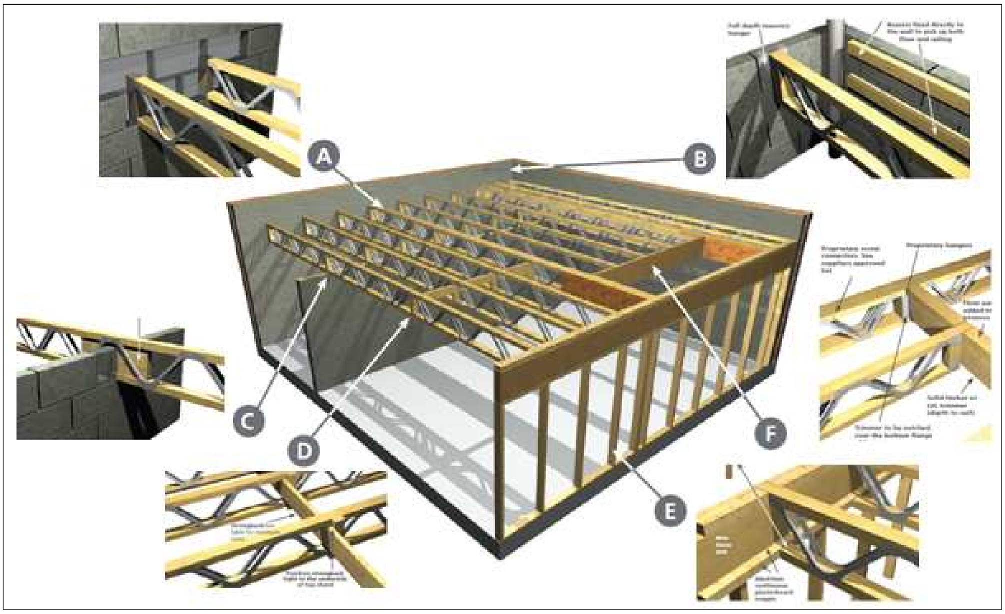


Figure 4-9: CS2 building steel-wood structure

The building layers are also uncommon, designed to have the best thermal, hygrometric and acoustic performances.

In particular, the external surfaces have been designed in order to have high thermal and hygrometric performances.

In fact all the surfaces are composed by several different layers and materials, with a transmittance equal to 0.10 W/m^{2}K for the external walls, 0.11 W/m^{2}K for the external ceilings, 0.13 W/m^{2}K for the external floors, 0.55 W/m^{2}K for the external doors and 1.2 W/m^{2}K for the external windows or transparent surfaces.

In addition, the internal partitions have been designed to have the best acoustic performances, based on the so called “Robust details”, an online handbook that brings together the best layers in terms of acoustic performances, already tested and recognized by the English building legislation.

The separating walls and floors are composed by multiple layers and they have low transmittance, equal to 0.21W/m^{2}K and 0.18 W/m^{2}K respectively. The HVAC plant provided for each apartment is composed by an independent mechanical ventilation system (whose main aim is to ensure proper air change in the winter season and to avoid overheating during the summer) and an independent aluminum radiators heating system, powered by a 28kW combined condensing natural gas boiler, used even for the instantaneous production of the domestic hot water.

A climate control for the supply temperature of the heating plant is provided, together with an internal regulation composed by thermostatic valves able to reduce or increase the flow rate of the heat transfer fluid to the radiators. All the insulated distribution network piping is placed inside the heated environments in order to reduce losses to a minimum value.

4.3.2 Monitored data

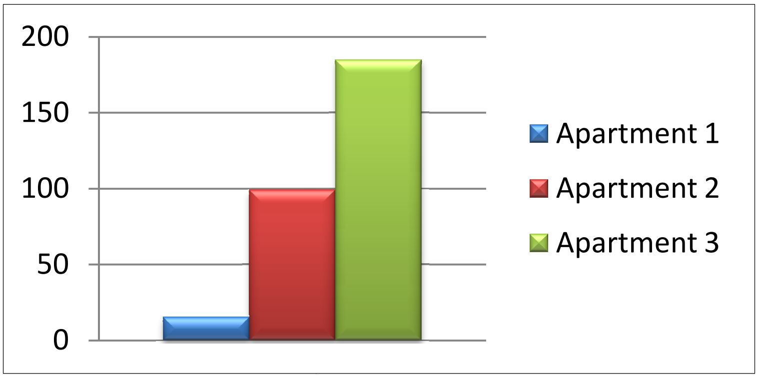
As previously specified, for the CS2 two different approaches have been followed. The first approach discussed here CS2.1 provides the dynamic simulation of the whole building-plant system for each of the three single units with monitored activities and consumptions (hydraulic scheme A5, Small scale & High resolution design). In fact, the case study CS2.1 has been used for the validation of the created tool modeling and simulation process because the availability of metered data provides a baseline for the validation which is not available for any hypothetical cases.

Furthermore, using a high performance building permits to ensure that the tool is able to represent even advanced dwellings.

Now, what are the energy and activity data of which three apartments of the building, situated on the second floor, have been subjected to monitoring? In addition to the outside temperature and relative humidity, for each apartment the following data, with a five minutes timestep, have been monitored:

- Occupancy (with Passive InfraRed sensor) of central hallway and living room;
- Window opening in main and second bedroom;
- Balcony door opening in living room;
- Temperature and Relative Humidity in living room and main bedroom;
- Total gas and electricity consumptions;

About the tool validation, it's important to note that even if the apartments have the same dimensions, structural, thermal and HVAC features, and even if the consumptions are very low respect when compared with a standard residential unit, the occupant's influence during the real management of the apartment is very high, as shown by the monitored gas consumptions for the heating system, completely different for the three users (Graph 4-2).



Graph 4-2: CS2.1 Total monitored gas consumption (m^3)

4.3.3 Dynamic simulation model

In order to apply the tool simulation process to the three apartments with monitored data, the three-dimensional modeling of the entire building has been created in “Trnsys3d” tool, as shown in the following Figure 4-10. In particular every room has been modeled for the three apartments while only one thermal zone has been created for the other apartments and boundary zones.

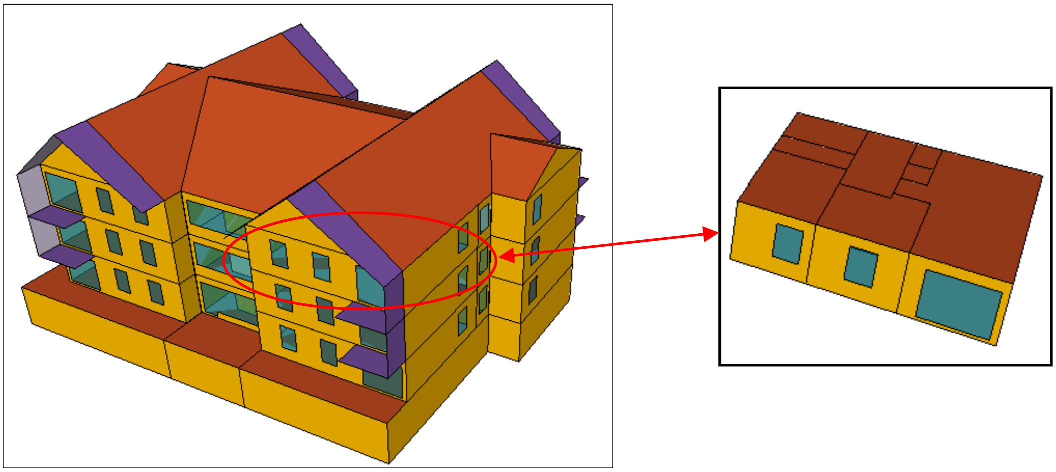


Figure 4-10: CS2.1 Trnsys3d building modeling

After, the characterization of the entire building envelope in “TRNBuild” tool has been performed and finally three different dynamic simulations have been carried out, each one applying the integrated model only for one apartment, simulating the other boundary thermal zones with an “ideal load” approach (i.e. no HVAC systems really simulated).
In particular the main assumptions made in the whole process have been the following:

- Plymouth 2002 weather file has been used (the closest available weather file), correcting it with the real temperature and relative humidity coming from the monitored data.

- Set point temperature for the heating system of each apartment equal to the average internal temperature monitored in the same unit (for the three apartments) or equal to the global average internal temperature monitored (for the other apartments);
- Solar factor or g-value of all the transparent surfaces equal to 0.265 and internal shading devices able to considerably reduce the external solar radiation fraction directly transmitted to the internal environment;
- Continuous air change due to infiltrations equal to 0.06/h and increase of the latter to 0.15/h when the inside temperature is higher and the outside temperature is lower than the one monitored, in order to reflect the real opening and closing of the external doors and windows.
- Continuous air change volume due to the mechanical ventilation, for all the apartments except the apartment 3, equal to 85.1 kg/h, and increase of the latter to 170.2 kg/h in the summer. For these apartments the temperature of the incoming air in the winter season is equal to the one coming from an heat recovery with an efficiency of 87%, while in the summer season is equal to the one coming either from the heat recovery or directly from the outside, when the conditions for the activation of the heat recovery bypass are satisfied (note that air change volume, heat recovery efficiency and bypass logic have been derived from the constructor details);
- Continuous air change volume due to the mechanical ventilation, for only the apartment 3, equal to 170.2 kg/h, both in the winter and in the summer season. For this apartment the temperature of the incoming air is always equal to the one coming either from the heat recovery or directly from the outside, the latter when the conditions for the activation of the heat recovery bypass are satisfied (in this case the temperature set point for the activation

of the bypass is supposed lower than the same for the other apartments in order to permit the bypass to be activated even in the winter season);

- Internal electric gains of each apartment equal, for the three apartments, to the total electric consumptions monitored in the same unit, minus the energy related to the electric showers, whose activation is supposed for the monitoring timesteps with higher consumptions. For the other apartments the internal electric gains are supposed equal to the average of the three above.
- Internal occupancy provided, for each apartment, only for the two thermal zones with PIR sensor, the central hallway and the living room. When the PIR sensor has registered a positive occupation of the area during the monitoring timestep, it has been supposed to have one person in the hallway and two people in the living room. As for the other variables the occupancy on-off value for the three main apartments derives directly from the monitored data, while for the other apartments an average value of the latter is provided.
- The monthly gas consumption of the three main apartments, used to compare real and simulations results, is directly derived from the monitored data, removing from the global monthly consumption the one related to the domestic hot water, this equal to the average gas consumption of the summer months (from May to September);
- Applying of the integrated and dynamic building – plant system model to the three apartments with monitored data with the adoption of the heating plant simplifications SMp2.2 (Emission control with ideal energy load) and SMp2.3 (Standard efficiency for emission and control subsystems) and recovery of all the losses and internal energy changes related to the distribution

subsystem because the isolated distribution network piping is placed inside the heated environments.

4.3.4 Results

Despite the high number of available simulation outputs, the comparison between the simulation results and the monitored data has been restricted to the parameters able to describe the main thermal behavior of the building. So, the comparison has been proceeded, for each of the three apartments, for:

- Trend of the average internal temperature during the winter season (controlled temperature) and during the summer season (temperature controlled only through the mechanical ventilation without any cooling system);
- Monthly gas consumption for heating;

The results are shown in the following figures and graphs:

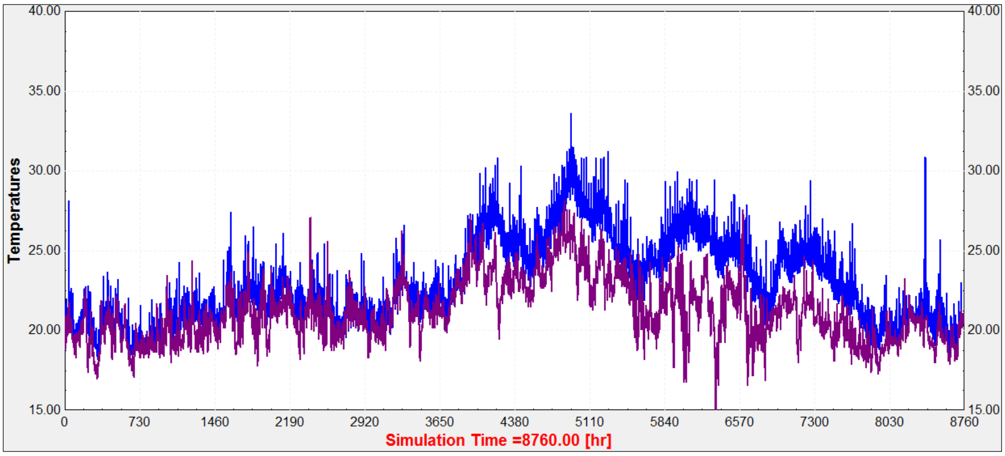


Figure 4-11: Apartment 1 internal monitored (violet line) and simulated (blue line) average temperature (°C)

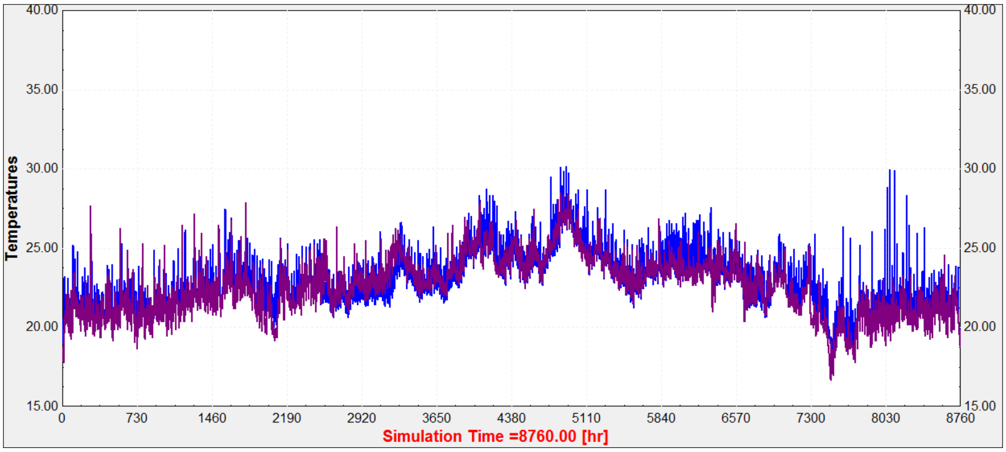


Figure 4-12: Apartment 2 internal monitored (violet line) and simulated (blue line) average temperature (°C)

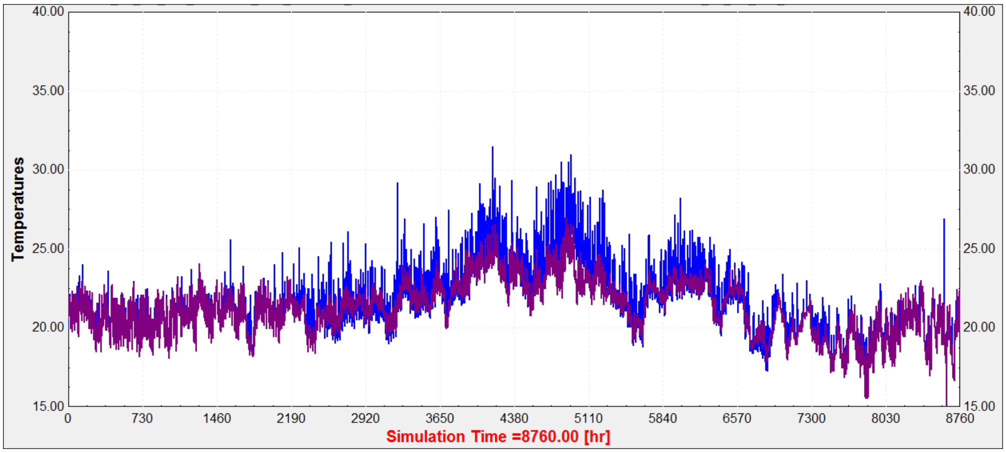
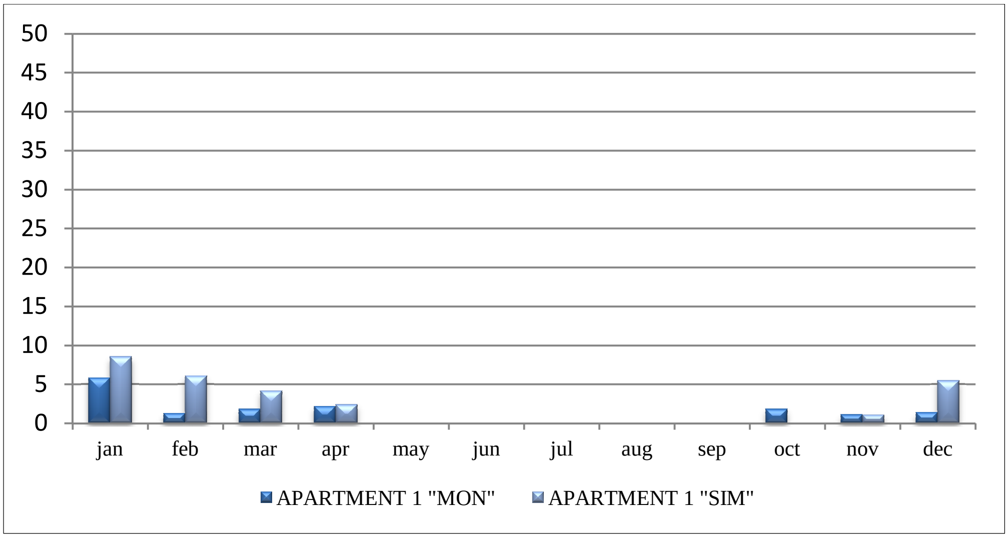
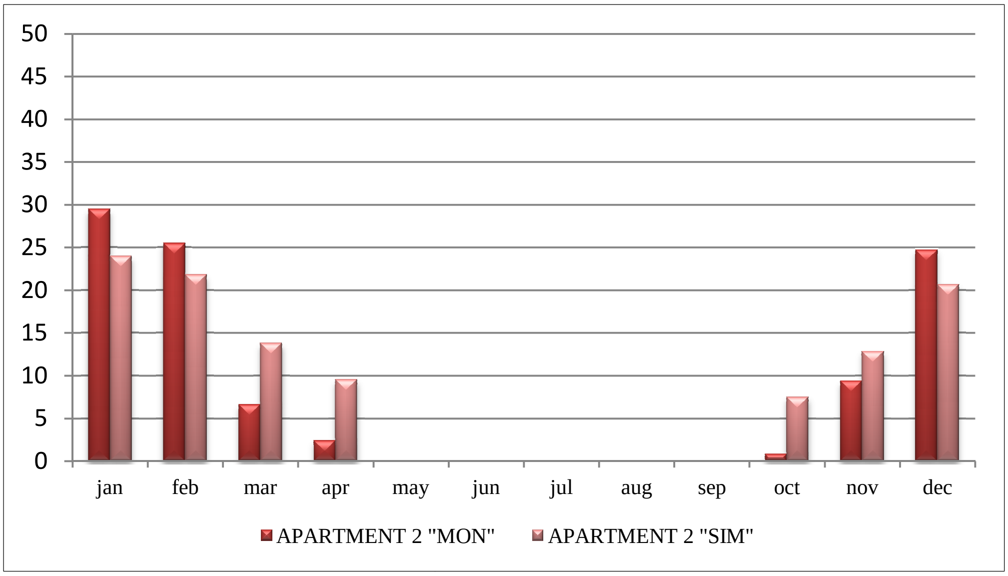


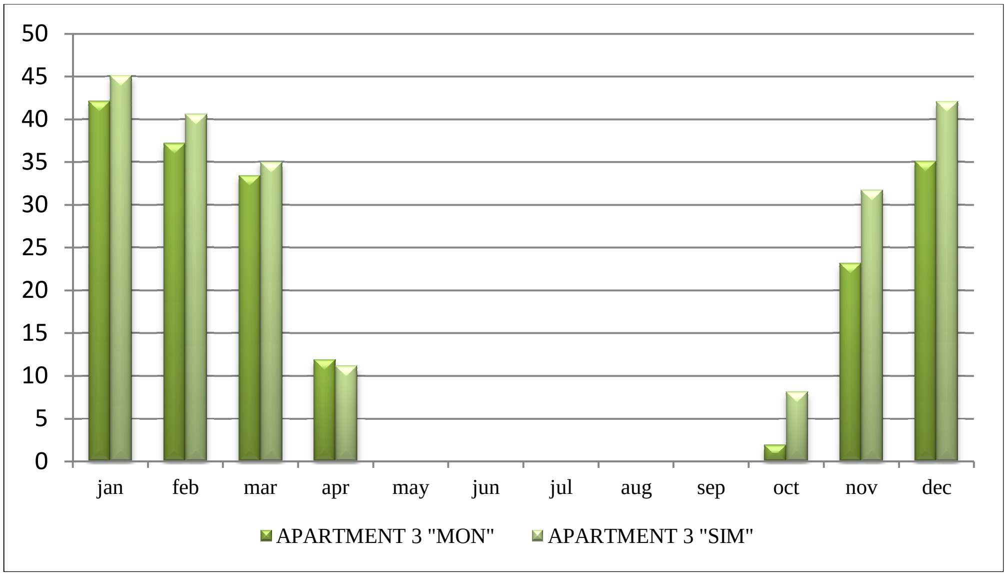
Figure 4-13: Apartment 3 internal monitored (violet line) and simulated (blue line) average temperature (°C)



Graph 4-3. Apartment 1 monitored ("MON") and simulated ("SIM") monthly gas consumptions (m^3)



Graph 4-4: Apartment 2 monitored ("MON") and simulated ("SIM") monthly gas consumptions (m^3)



Graph 4-5: Apartment 3 monitored ("MON") and simulated ("SIM") monthly gas consumptions (m^3).

Considering the results just shown, it can be stated that:

- The simulation trend of the average internal temperature during both the winter and the summer season reflect in a very reliable way the same as in the monitored data, especially for apartments 2 and 3. Only for the first apartment the simulation sometimes overestimates the internal temperature.
- Even the trend of the monthly gas consumption between the simulated and monitored data is similar for all of the apartments. In particular the average annual consumption coming from the simulation is 11% overestimated compared to the real one for the apartment 2, while 16% overestimated for the apartment 3. The percentage overestimation of the gas consumption for the apartment 1 is higher but it doesn't matter because the consumption of that unit is practically zero both in the monitoring and in the simulations.

Then taking into account that:

- The simulated building is characterized by very high thermal performances and low energy consumptions (the gas consumption for heating of the apartment 3 is approximately equal to one-tenth of that for a common residential unit);
- The heat balance that describes each unit is very sensitive even to small variations of each component, from the different solar gains due to different exposures to the presence or absence of people, the management of the electrical equipment and to the different possible adjustments of all HVAC components;
- The apartments are indeed characterized by very different consumption from each other, showing how the occupant's influence during the real management of the apartment is very high;
- Nonetheless the assumptions made for the applying of the dynamic simulations have been extended without distinctions to all the apartments;

the results obtained through the application of the tool can be considered extremely positive in terms of its validation, as it is able to predict the behavior of the whole building-plant system for extreme cases such as the one presented above.

Considering also a modeling workload around 24h and a simulation workload equal to 0.5h to apply the entire tool process to each apartment, it can be concluded that the CS2.1 is another example that demonstrate that the new modeling support tool created gives the possibility to perform dynamic simulations able to return a very high number of accurate results with low workloads, compatible with the ones required by the integrated design.

4.4 Case study 2.2 – whole tool application

4.4.1 Dynamic simulation model

The second approach of CS2 provides the dynamic simulation of the building-plant system for the entire apartment building described in the Section 4.3.1, without using the monitored data (except for the external temperature and humidity) but standard internal activities and set point temperatures and supposing to have now a heating and DHW central plant, instead of an independent heating system for each apartment.

In this case, as shown in the Figure 4-14, each apartment is a thermal zone (Medium scale & Medium resolution design) and the hydraulic scheme provided is B15.

In fact, as already specified, the case study has been used for the application of the whole tool modeling and simulation process, including the simulation of the DHW production with solar integration.

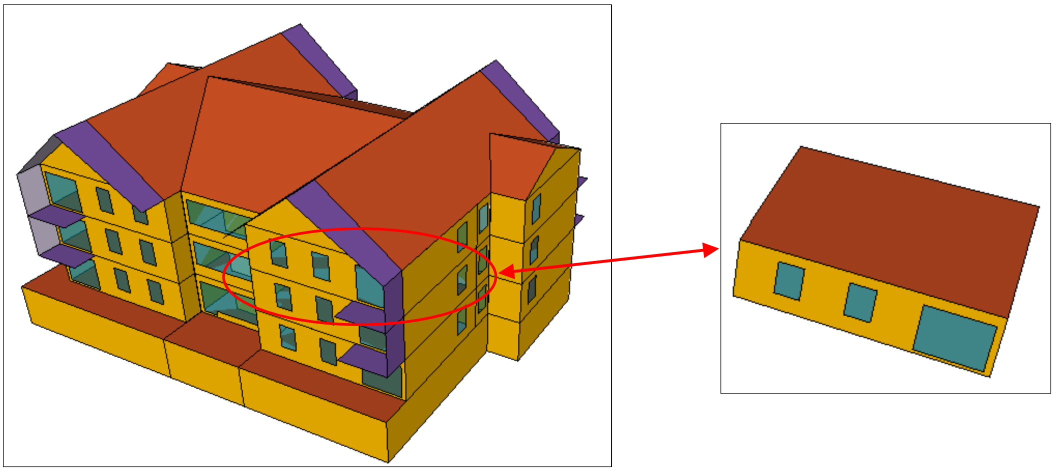


Figure 4-14: CS2.2 Trnsys3d building modeling

The heating and DHW system is in particular the one shown in the Figure 4-15, composed by a 80kW natural gas boiler and a heating storage of around 1000l, able to satisfy the 15 apartments heating and domestic hot water demand. For the latter, a storage of 2000l is provided, with a solar integration composed of 35 square meters collectors. Note that, with the application of the modeling support tool it has been possible to do the new design of the heating system with the 80% reduction of the current generation power.

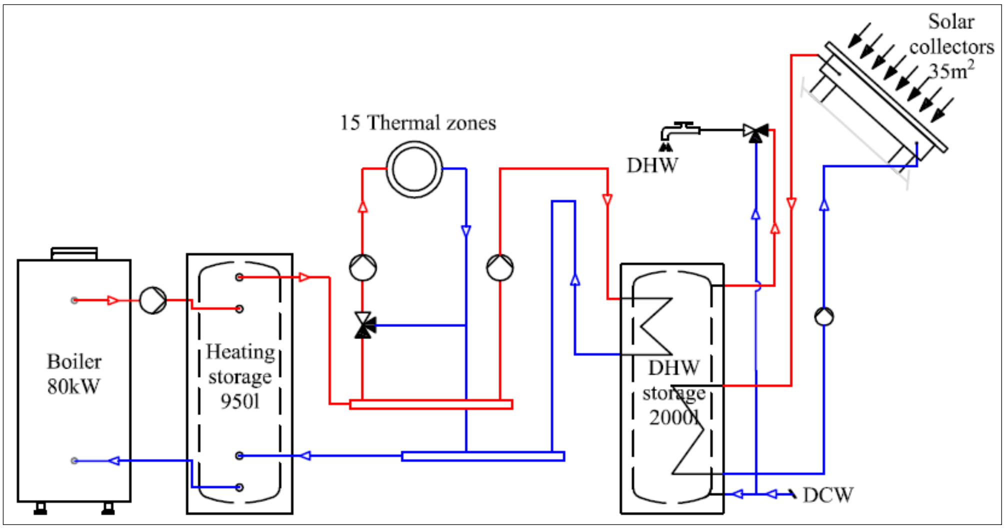


Figure 4-15: CS2.2 hydraulic scheme (B15)

4.4.2 Simulation cases and results

The determination of the simulation cases for the CS2.2 has been made in a very similar way to that performed for the CS1. In particular, starting from the most detailed model, instead of the creation of a competitor stationary model, the complete application in consecutive simulations of the simplification protocol has been performed, including the last simplification SMp2.3. So, even in this case study, the progressive enhance of the level of simplification, together with the building ideal loads condition, has resulted in 8 different simulations listed in the Table 4-IV, where the simulation case 3 is now the most complete and detailed simulation, taken as the reference case, while the last simulation case 8 is the most simplified simulation.

Table4-IV: CS2.2 simulation cases

SIMULATION CASES		ENVELOPE	
		DETAILED MODEL	DETAILED MODEL+SMp1
HVAC	IDEAL LOADS (NO DHW)	1	2
HVAC	DETAILED MODEL	3	/
HVAC	DETAILED MODEL + SMp2.2	4	/
HVAC	DETAILED MODEL +SMp2.2+SMp2.3	5	/
HVAC	DETAILED MODEL + SMp2.1	/	6
HVAC	DETAILED MODEL + SMp2.1+SMp2.2	/	7
HVAC	DETAILED MODEL + SMp2.1+SMp2.2+SMp2.3	/	8

About the simplification protocol, the output of the building envelope simplification SMp1 has been the one shown in the Figure 4-16, where, as for the CS1, the building become a rectangular box with only three heated thermal zone.

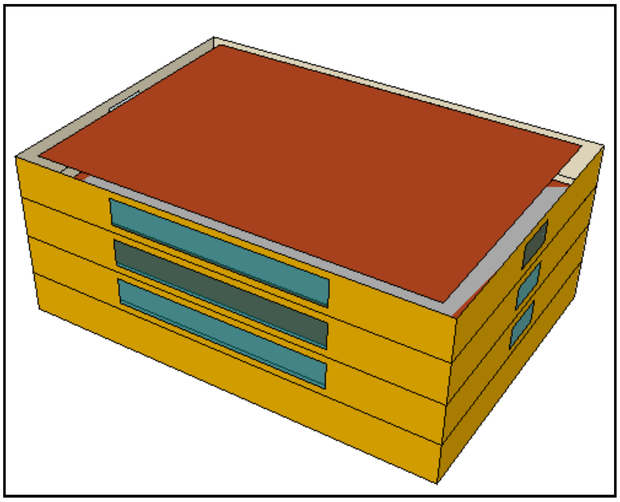


Figure 4-16: CS2.2 building envelope simplification

Now, what are the results extracted and compared for all the simulations carried out in order to test, as previously done for the CS1, the loss of accuracy of the energy results respect on the modeling workload and simulation workload savings deriving from the progressive simplifications?

The results extracted has been restricted to the most important performance indicators and parameters listed in the Figure 4-17[9], plus the thermal power curves deriving from the indicated energies and the modeling and simulation workloads necessary to perform each simulation.

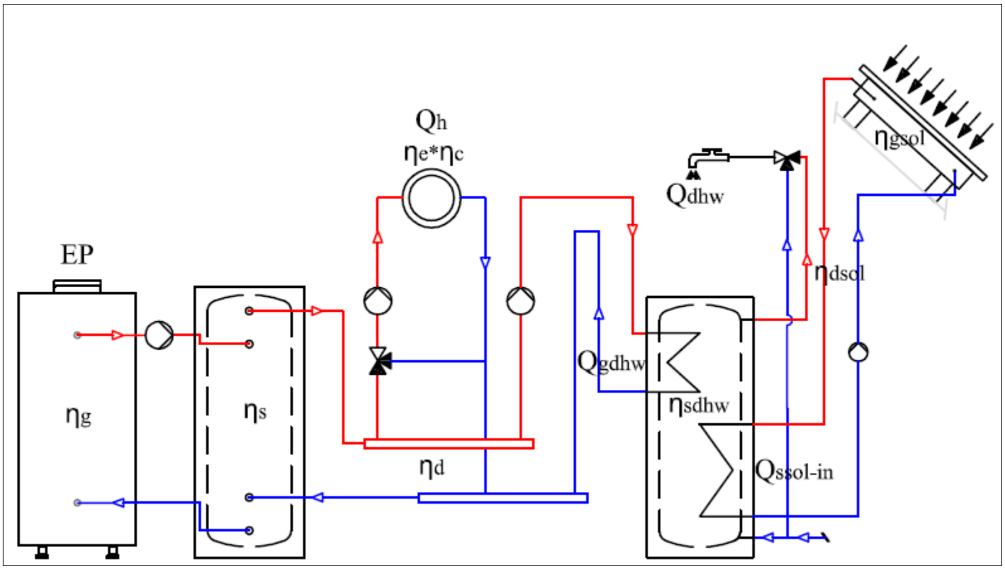


Figure 4-17: CS2.2 performance indicators

In particular the comparison of the energy results has been performed for the ones related to the building envelope, the heating plant and the common part of the plant, and not for the results only related to the

[9] The performance indicators are extracted from the ones listed in the section 3.3.4 for the specific hydraulic scheme analyzed, omitting those which can be directly derived from the relationships shown in the same section and in Appendix B;

DHW production, as no simplifications have been provided for this specific part of the plant, equal for all the simulations carried out.

In the figure 4-17 the performance indicators only related to the production of the DHW are:

- Q_{dhw} (kWh)= annual DHW energy demand;
- η_{sdhw}= annual DHW storage efficiency;
- Q_{gdhw} (kWh)= annual energy introduced in the DHW storage from the generation;
- $Q_{ssol\text{-}in}$ (kWh)= annual solar energy introduced in the DHW storage;
- η_{dsol}= annual solar distribution efficiency;
- η_{gsol}= annual solar generation efficiency;

the ones only related to the heating service are:

- Q_h (kWh)= annual heating energy demand;
- η_e*η_c = annual heating emission efficiency * annual heating control efficiency;

While for the common part of the plant:

- η_d= annual overall efficiency of the distribution subsystem;
- η_s= annual storage efficiency;
- η_g= annual overall efficiency of the generation subsystem;
- EP (kWh)=Q_g/η_g= annual primary energy introduced in the generation;

Following all the results are summarized in tables and graphs.

Table 4-V: CS2.2 DHW general results

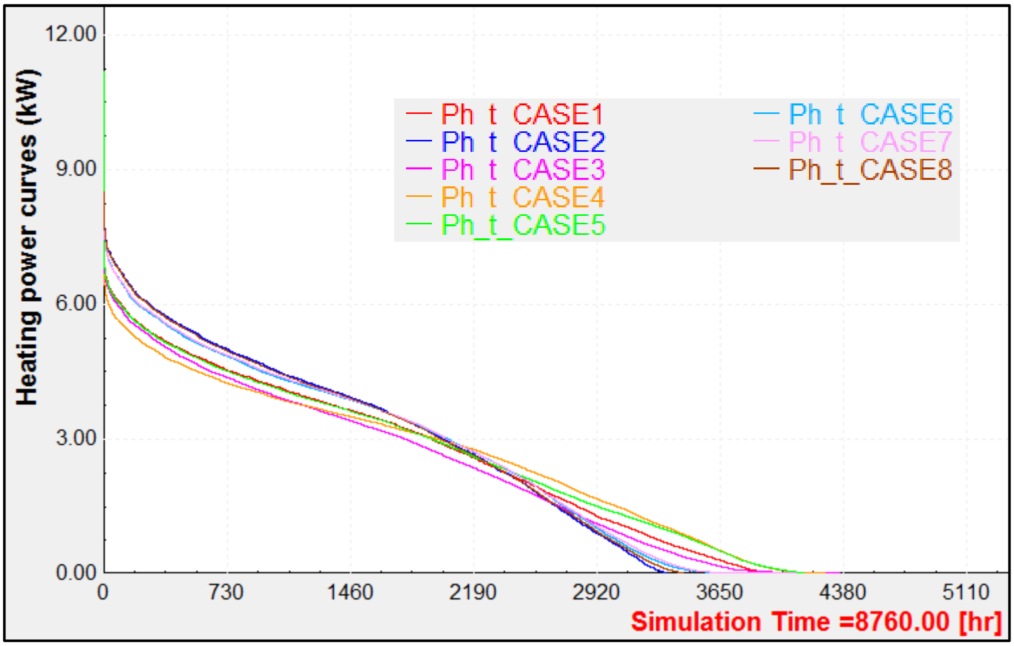
CS2.2 DHW GENERAL RESULTS ABSOLUTE VALUES		
Symbol	**U.m.**	**ALL CASES**
TIMESTEP	min	1.00
Q_{dhw}	kWh	48528
Q_{sol}	kWh	15377
Q_{gdhw}	kWh	33807
η_{gsol}	/	0.50
η_{dsol}	/	0.94
η_{sdhw}	/	0.99
DHW solar coverage	%	31%
Annual solar Energy yield	kWh/m^2yr	440

Table 4-VI: CS2.2 results – absolute values

CS2.2 RESULTS - ABSOLUTE VALUES									
Symbol	**U.m.**	**CASE 1**	**CASE 2**	**CASE 3**	**CASE 4**	**CASE 5**	**CASE 6**	**CASE 7**	**CASE 8**
Timestep	min	60.00	60.00	1.00	1.00	1.00	1.00	1.00	1.00
Q_h	kWh	11266	11545	11266	11266	11266	11545	11545	11545
EP	kWh	11266	11545	47471	47607	48724	48043	48132	49296
η_e*η_c	/	1.00	1.00	1.00	1.00	0.93	1.00	1.00	0.93
η_d	/	1.00	1.00	1.00	1.00	0.99	0.99	0.99	0.99
η_s	/	1.00	1.00	0.98	0.98	0.98	0.98	0.98	0.98
η_g	/	1.00	1.00	0.96	0.97	0.97	0.97	0.97	0.97
Mod Wload	h	64	8	80	78	76	24	22	20
Sim Wload	h	0.66	0.05	19.00	5.00	6.50	3.25	2.50	2.75

Table 4-VII: CS2.2 results – relative values

CS1 RESULTS - RELATIVE VALUES									
Symbol	**U.m.**	**CASE 1**	**CASE 2**	**CASE 3**	**CASE 4**	**CASE 5**	**CASE 6**	**CASE 7**	**CASE 8**
Q_h	kWh	100%	102%	100%	100%	100%	102%	102%	102%
EP	kWh	/	/	100%	100%	103%	101%	101%	104%
$\eta_e*\eta_c$	/	/	/	100%	100%	93%	100%	100%	93%
η_d	/	/	/	100%	100%	99%	100%	100%	99%
η_s	/	/	/	100%	100%	100%	100%	100%	100%
η_g	/	/	/	100%	101%	101%	101%	101%	101%
Mod Wload	h	80%	10%	100%	98%	95%	30%	28%	25%
Sim Wload	h	3%	0%	100%	26%	34%	17%	13%	14%



Graph 4-6: CS2.2 thermal power curves

Considering the results just shown, it can be stated that:

- The energy demand for the DHW production of the 15 apartments, equal to about fifty thousand kWh, is supplied for the 31% by the solar collectors, able to convert the 50% of the incident radiation, and for the rest by the heating system.
- Comparing the absolute value results related to the most detailed model (case 3) and the most simplified model (case 8), it can be seen immediately that there are very high modeling and simulation workload reductions, in particular from 80 hours to 20 hours for the modeling workload and from 19 hours to about 3 hours for the simulation workload.

Regarding to the other outputs, the percentage deviations reveal that:

- The value of the annual ideal heating energy demand (Q_h) has a very low variation (2%), so the building envelope simplification has a very small incidence;
- The total primary energy demand EP is 4% overestimated in the most simplified simulation case, while the highest percentage difference is related to the standard emission and control efficiencies of the heating service, with a 7% difference, due to the application of both the heating plant simplifications SMp2.2 and SMp2.3, directly related to these efficiencies;
- The heating power curves, related to the annual trend of the useful thermal power Q_h introduced in the whole building, have a similar trend for all the simulations, with a small high-power overestimation and low-power underestimation for the cases characterized by the building envelope simplification, low differences that can be considered as a reasonable safety factor during the design process.

Even for this case study it can be concluded that the new modeling support tool is able to give, passing from the most detailed to the most simplified model, high modeling and simulation workload reductions, accompanied by high result accuracy in term of energy needs, subsystem efficiencies and thermal power curves, all parameters able to describe the annual operation of the building-plant system analyzed and to assess its technical and economic feasibility.

4.5 Other applications

In this last section of the Chapter 4 other important examples of the tool application, already performed, are shown.

The aim is not to give further results in terms of accuracy/workload ratios to those given by the case studies previously performed, but to show the great flexibility of the tool in terms of the possibility of its use, even partial, for the fast resolution of different and various design problems and the possibility of subjecting the created dynamic TRNSYS models to small changes to expand, always in a short time, the already high number of hydraulic schemes able to be simulated.

Following each example is described reporting, as well as the main features and objectives, the three-dimensional building model or the hydraulic scheme used for the simulations.

a) "Palazzo Muratori" building – Romano di Lombardia, Bergamo, Italy;

- Main features: built in 1995, for offices and multi-purpose room but poorly used because of the very limited thermal and hygrometric performances and the high maintenance costs.
- Main objectives: determination of the heating and cooling needs in different building utilization conditions, before and after the adoption of energy efficiency measures. Preliminary plant design and investment economic evaluation.
- Real building and Trnsys3d building model:

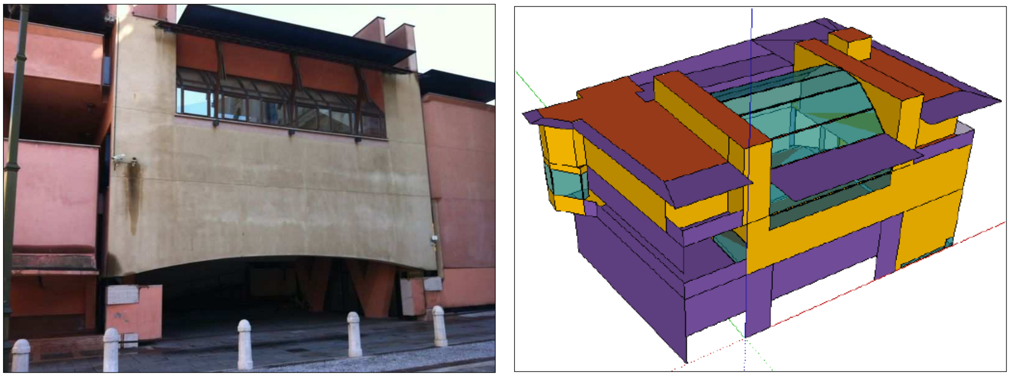


Figure 4-18: “Palazzo muratori” building

b) Apartment building – Mele, Genova, Italy;

- Main features: built in the seventies, composed of 21 residential apartments, still powered by a diesel boiler with high costs for the heating service.
- Main objectives: determination of the heating needs before and after the adoption of energy efficiency measures. Preliminary plant design and investment economic evaluation.
- Real building and Trnsys3d building model:

Figure 4-19: Apartment building – Mele, Genova, Italy

c) “RSA Zogno” – Zogno, Bergamo, Italy;

- Main features: built starting from the fifties, used as a residence for elderly care, still powered by a diesel boiler with high costs for the heating and DHW service.
- Main objectives: determination of the heating and DHW energy and power needs and new plant sizing with investment economic evaluation.
- Real building and Trnsys3d building model:

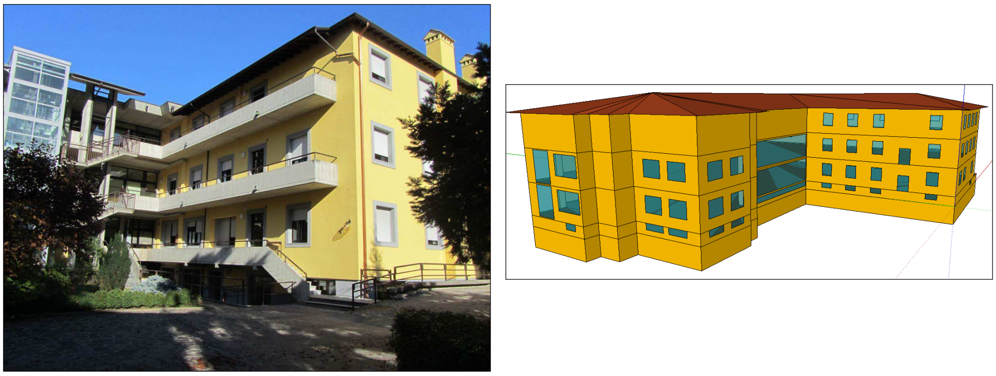


Figure 4-20: “RSA Zogno” – Zogno, Bergamo, Italy

d) “Castelli clinic” – Bergamo, Italy;

- Main features: built starting from the thirties, it consists of many buildings with a central plant for heating, DHW production and cooling services. Used as a private hospital, it has very high costs and consumptions of electricity and thermal energy.
- Main objectives: determination of the heating and DHW energy demand in order to size and evaluate, together with the electricity consumptions, a new cogeneration system for the clinic.
- Real building and Trnsys3d building model:

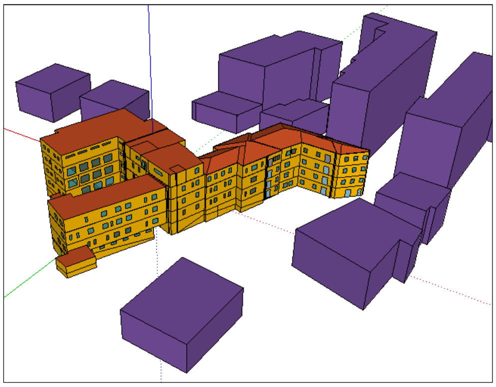



Figure 4-21: "Castelli clinic" – Bergamo, Italy

e) Apartment building – L'Aquila, Italy;

- Main features: new apartment building composed of six residential apartments with very high thermal, hygrometric and acoustic performances.
- Main objectives: determination of the dynamic building envelope behaviour, of the heating and cooling demand, in order to assess different kind of solutions both for the building envelope and the heating and cooling plant.
- Trnsys3d building model:

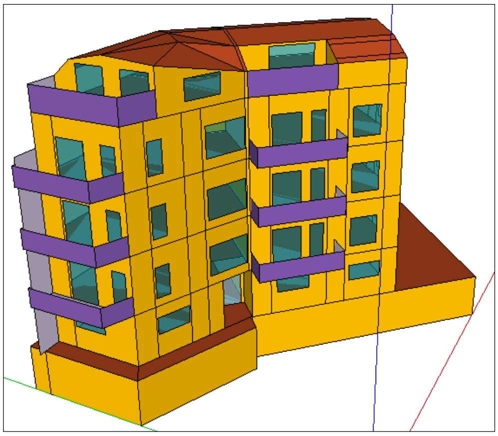
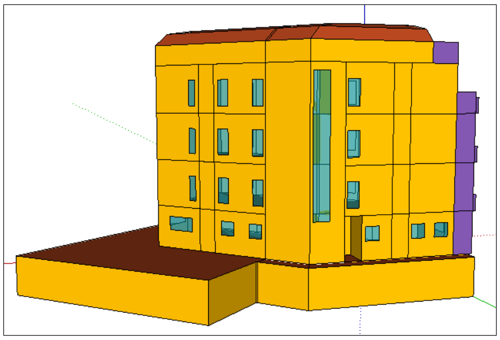



Figure 4-22: Apartment building – L'Aquila, Italy;

f) Residential building – Moio de Calvi, Bergamo, Italy;

- Main features: new residential building with very high energy performances.
- Main objectives: determination of the dynamic building envelope behaviour, of the heating, cooling and DHW energy demand, in order to assess different kind of solutions both for the building envelope and for the plant.
- Trnsys3d building model:

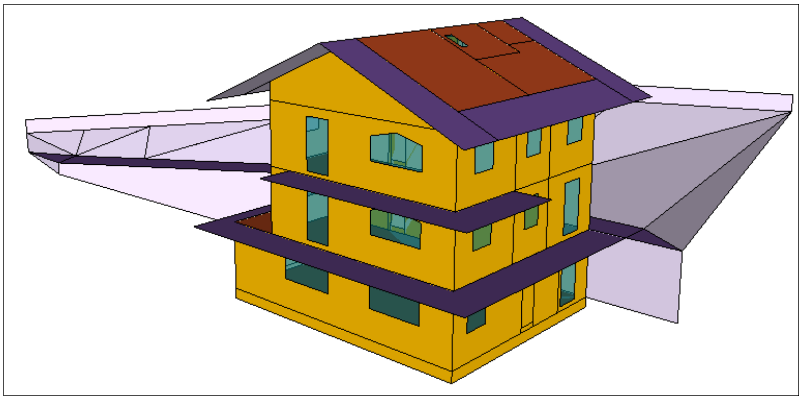


Figure 4-23: Residential building – Moio de Calvi, Bergamo, Italy

g) Drainback compact solar thermal system – Brighton, East Sussex, UK;

- Main features: dynamic simulation of a compact solar thermal system prototype, built to meet approximately the 50% of domestic hot water needs for a family of 3/4 persons and that includes the use of the emptying solar technology (drainback). Utilization of the second section of the tool TRNSYS dynamic model with small changes like the introduction of the drainback vessel and the heat exchanger provided by the prototype.
- Main objectives: test the operation and energy performances of the prototype in a possible wide matrix of different conditions, in

order to give the best design suggestions to the experimental development of the system.

➢ Hydraulic scheme and modified TRNSYS model:

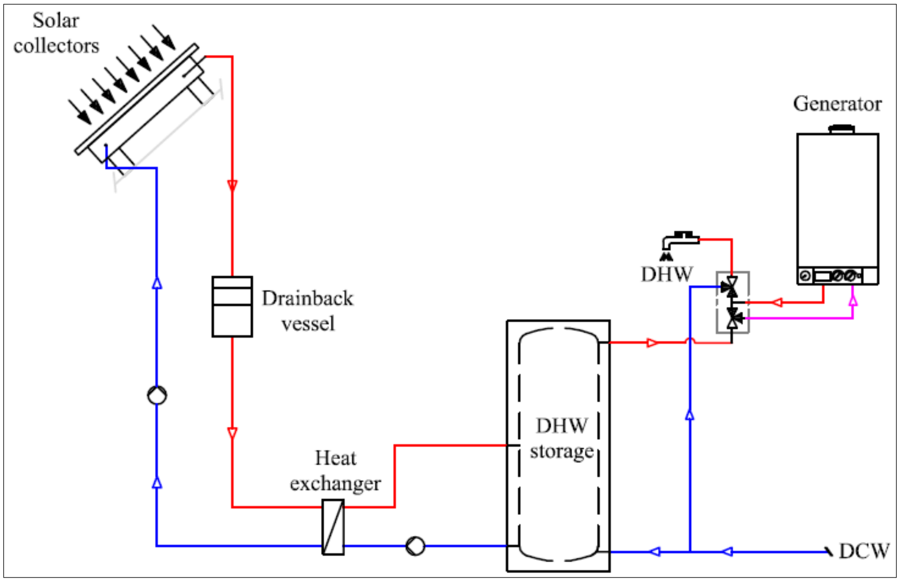


Figure 4-24: Prototype hydraulic scheme

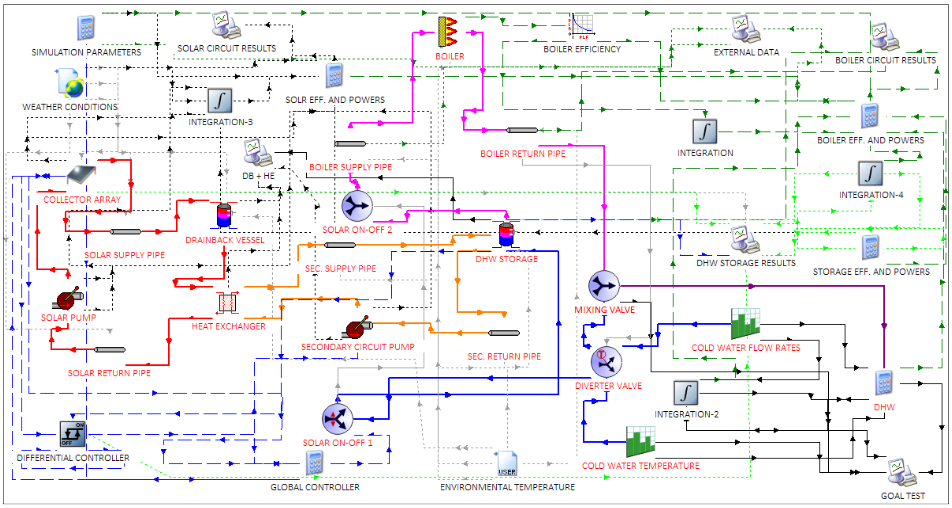


Figure 4-25: Second section modified of the TRNSYS dynamic model

h) Rural building – Gandino, Bergamo, Italy;

- Main features: built starting from the thirties as a typical farm house without any kind of heating and DHW services, composed of several rooms for the countryside activities.
- Main objectives: determination of the heating needs for the part of the building for residential use, before and after the adoption of energy efficiency measures for the envelope. Executive biomass plant design for heating and DHW services.

Real building and Trnsys3d building model:

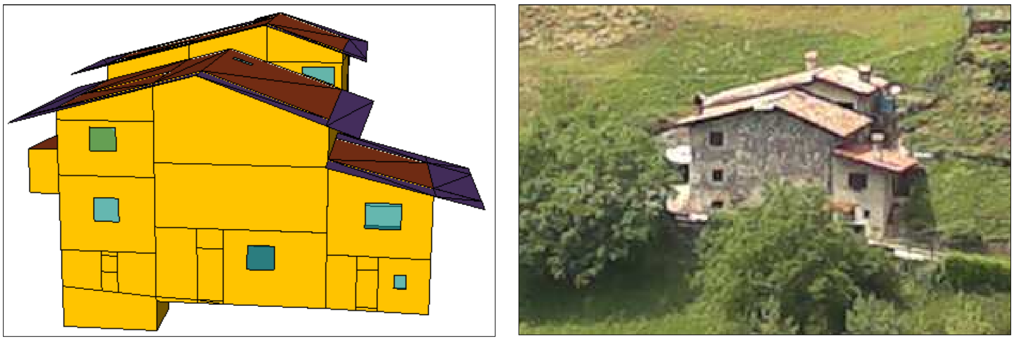


Figure 4-26: Rural building – Gandino, Bergamo, Italy

Chapter 5

5 Conclusions

The research problem addressed in this thesis has been the integration of building performance analysis tools in the building design process. In fact, although building performance analysis can be expected to be an essential part of the building design process, their actual application to provide information to support building design decisions is still limited, due to the high time and expertise that these tools requires to be used.

The research question -Is it possible to obtain a sufficiently accurate simplified modeling support tool compatible with time requirements and available information at all stages of the integrated design?- has been answered with the creation of a new modeling support tool that seeks to meet this need by providing a flexible, guided, fast but accurate way to perform building-plant system dynamic energy simulations.

The development of such a tool has been achieved through a work of reverse engineering applied to one of the most flexible and detailed currently existing analysis tools, TRNSYS.

The tool, validated through real monitored data related to a very high performance building and mainly composed by one dynamic simulation model, a sizing protocol and a simplification protocol, can actually be defined:

- flexible, due to the possibility to be used with several different hydraulic schemes, plant components, building scales, to be adopted in a full or in a partial way, depending on the specific objectives or on the design phase and available information and to be subjected to small variations in order to include more and more different design conditions;
- guided, i.e. easy to use, thanks to the clear and univocal methodological structure created especially through the sizing protocol, able to assist the user throughout the whole design, simulation and results analysis process;
- fast, because the whole application of the simplifications provided by the simplification protocol permits to extremely reduce both the modeling and the simulation workloads to around respectively 12-24 hours and 0.1-3 hours, depending on the complexity of the case study analyzed, times compatible with the ones required by the integrated design and equal or even less to those of the stationary/traditional approach.

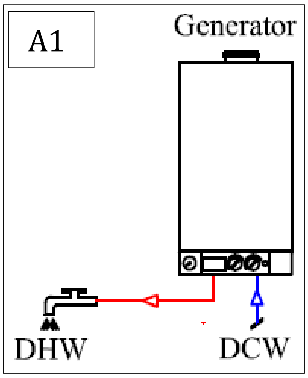
- accurate, due to the fact that, with the whole application of the simplification protocol, the tool gives, as main outputs, the most important performance indicators and variables to understand the behaviour of the building-plant system and to assess its technical and economic feasibility, with an accuracy always below the 16% for all the cases considered in this work.

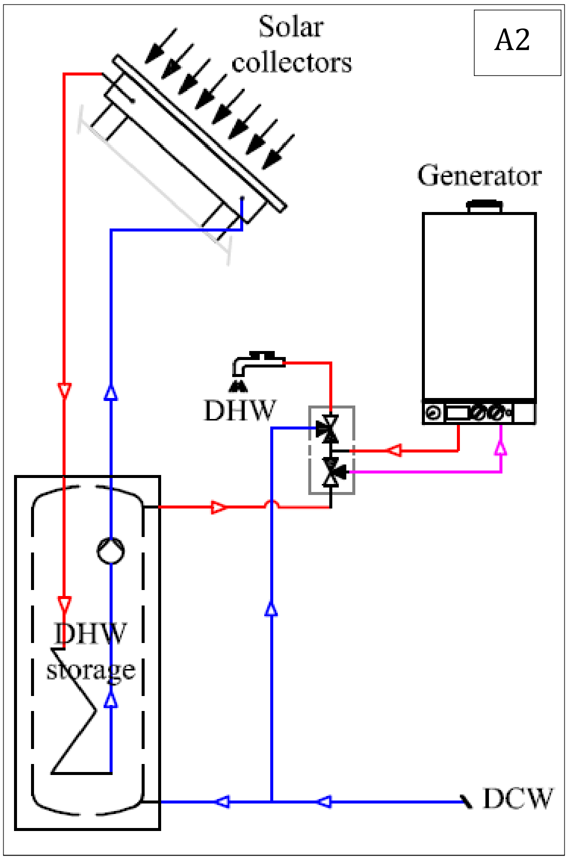
With all this features, it can be surely integrated during all the stages of the integrated design and it has the potential be the perfect answer to the growing demand, both in terms of quality and low engineering costs in retrofit and new building design.

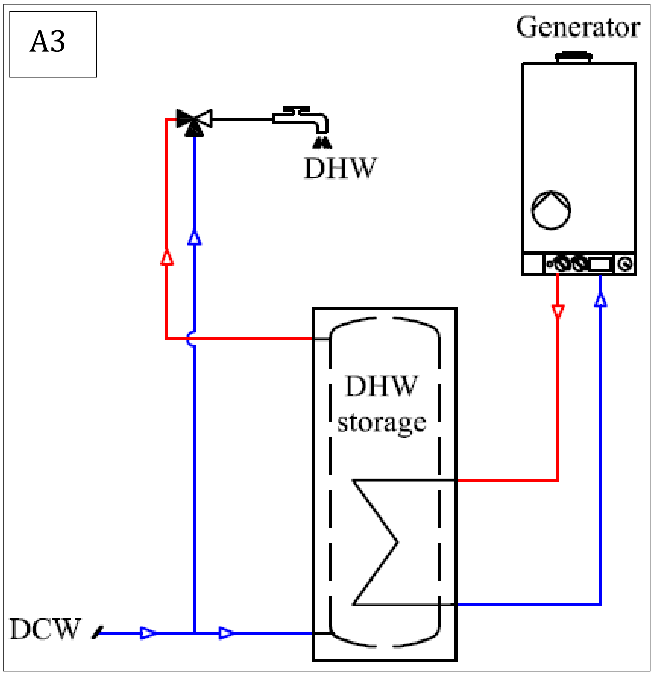
Appendix A

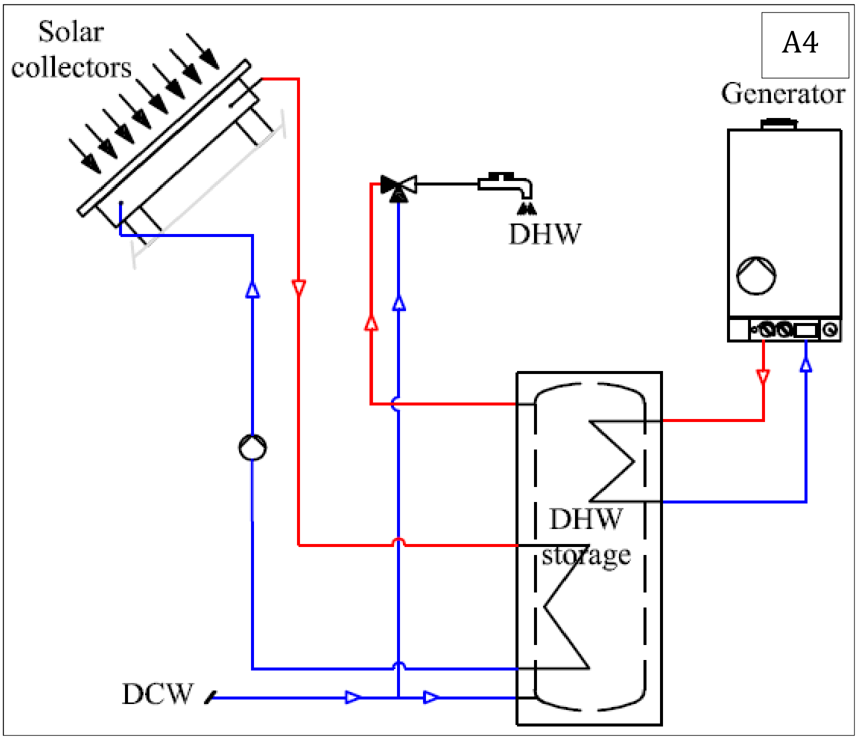
Hydraulic schemes combinations

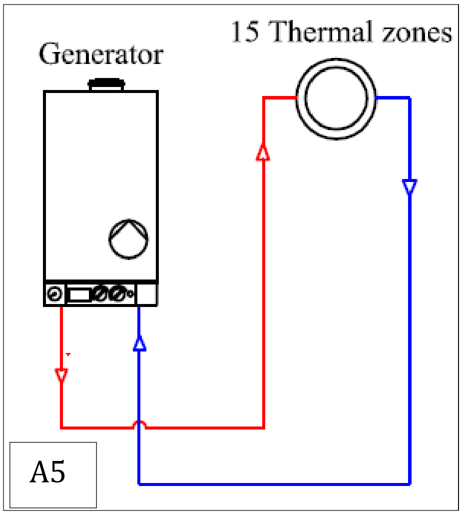
			DOMESTIC HOT WATER (DHW)					
		No HDW	Instantaneous production		Storage production			
			No solar	Solar	No solar		Solar	
			Prior.	Prior.	Prior.	No prior.	Prior.	No prior.
	No HS	/	A1	A2	A3	/	A4	/
HEATING SYSTEM (HS)	Direct HS	A5	A6	A7	A8	/	A9	/
	Hydraulic sep. HS	A10	A11	A12	A13	/	A14	/
	Storage HS	A15	A16	A17	A18	/	A19	/
	Direct HS & DHW	B1	/	/	B2	B3	B4	B5
	Hydraulic sep. HS & DHW	B6	/	/	B7	B8	B9	B10
	Storage HS & DHW	B11	B16	B17	B12	B13	B14	B15

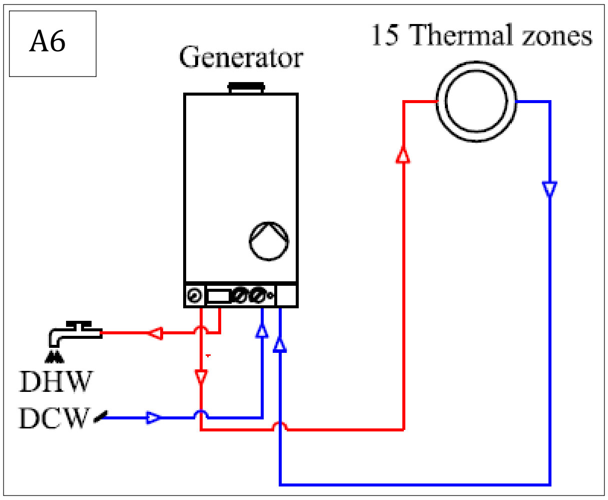

A1
Generator
DHW
DCW

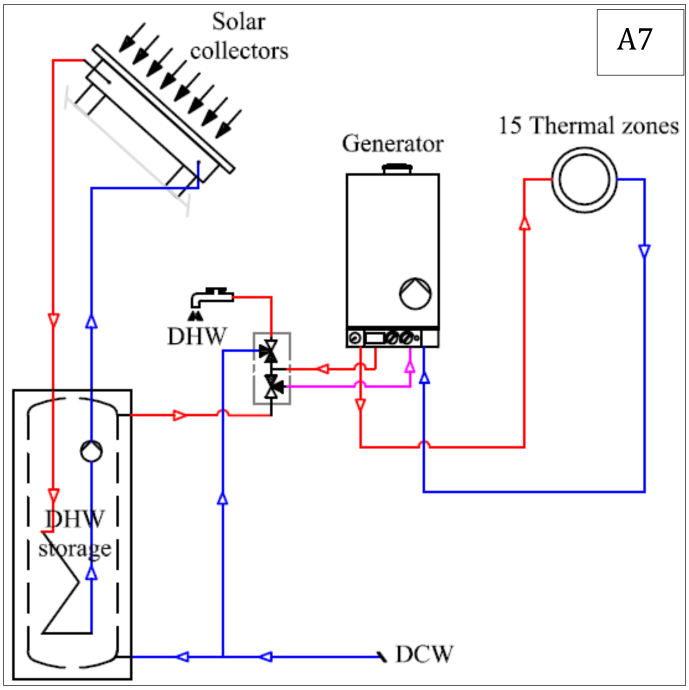

Solar
collectors
A2
Generator
DHW
DHW
storage
DCW

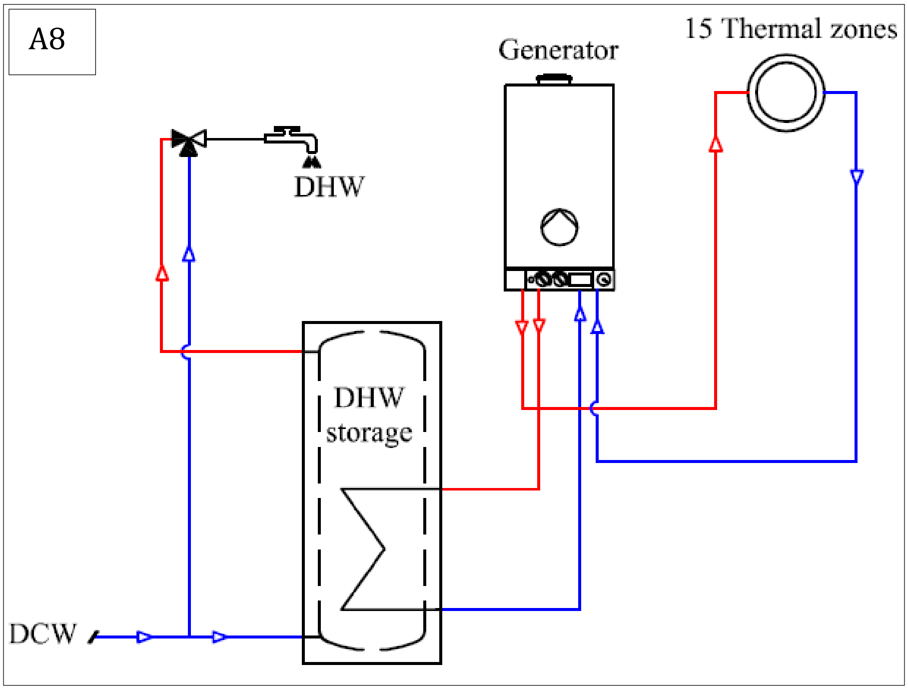

A3
Generator
DHW
DHW
storage
DCW


Solar
collectors
A4
Generator
DHW
DHW
storage
DCW


Generator
15 Thermal zones
A5


A6
Generator
15 Thermal zones
DHW
DCW


A7
Solar
collectors
Generator
15 Thermal zones
DHW
DHW
storage
DCW


A8
Generator
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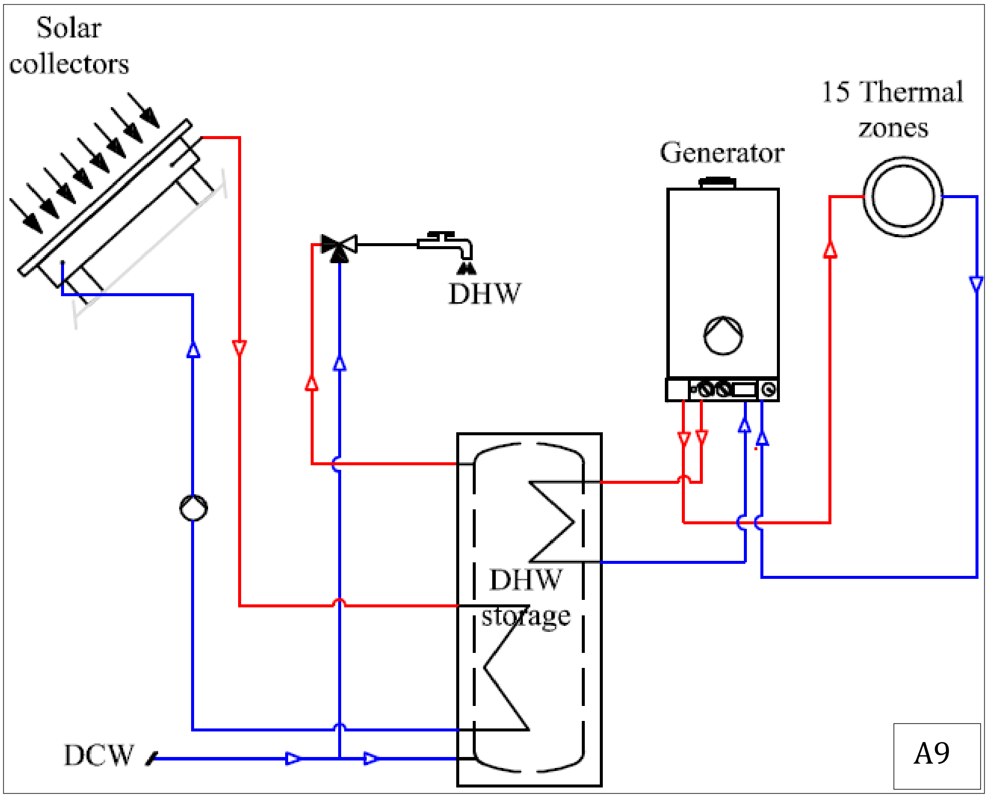
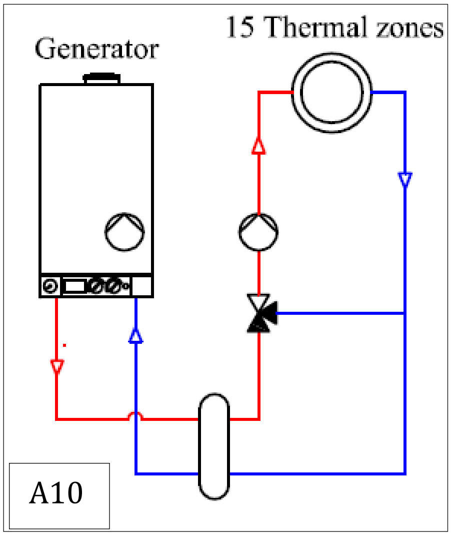
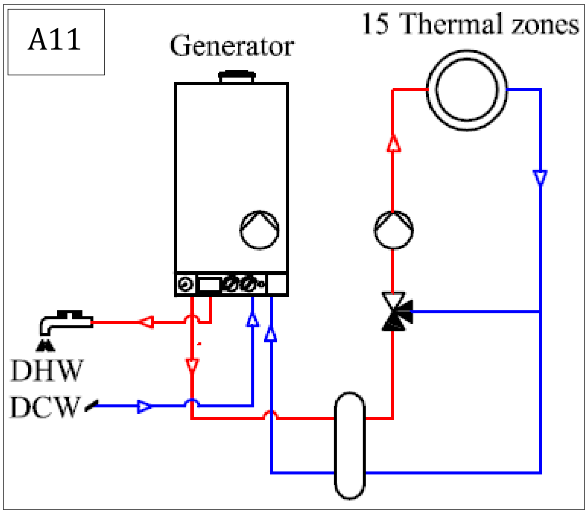
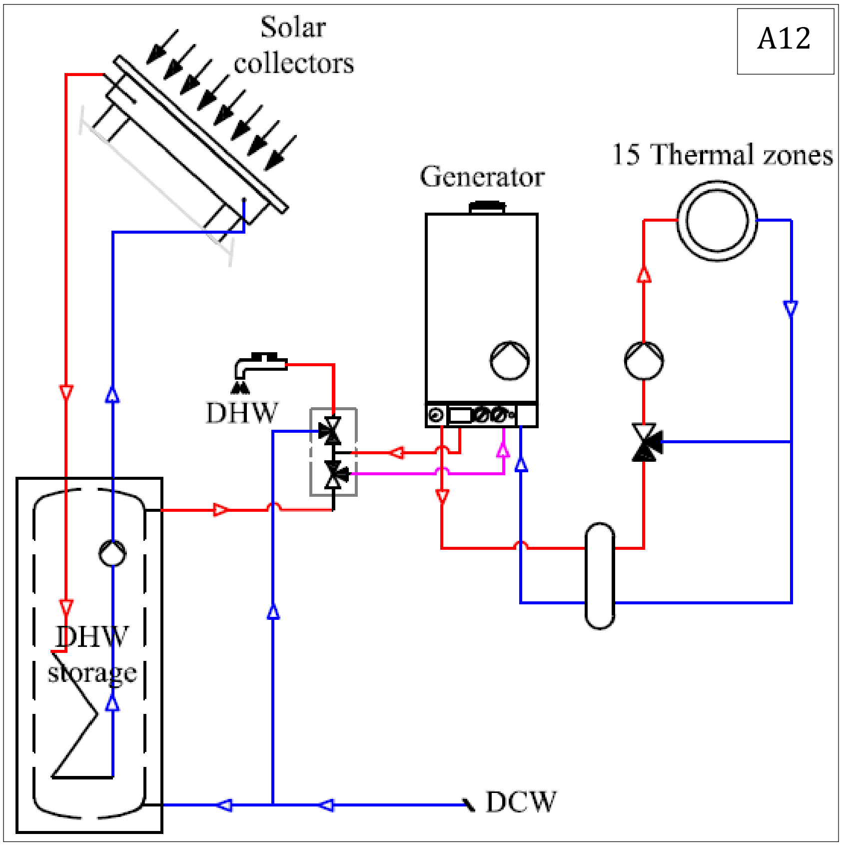
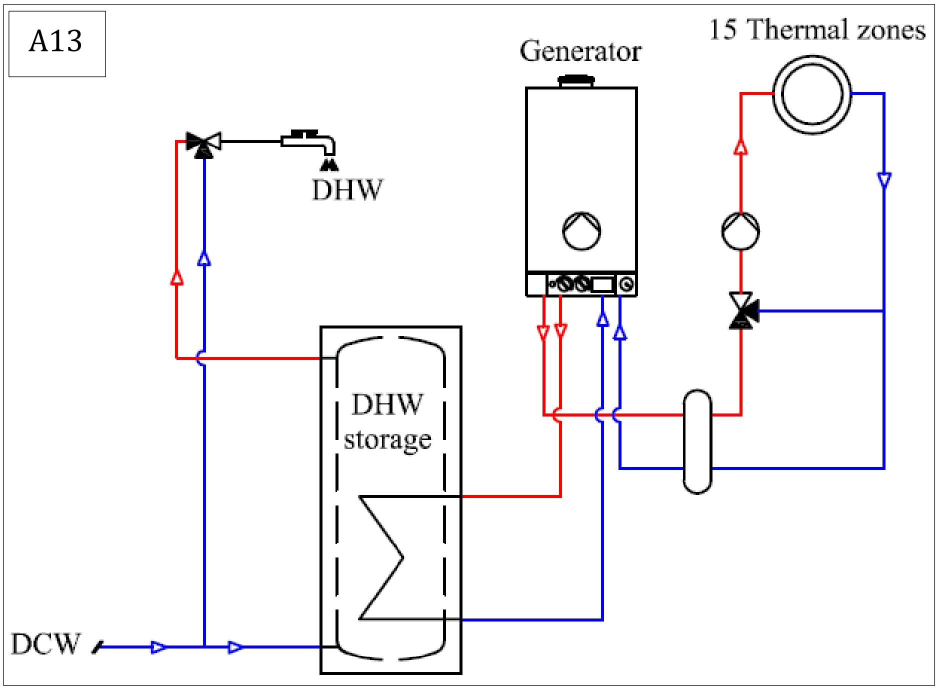
DHW
DHW
storage
DCW


Solar
collectors
15 Thermal
zones
Generator
DHW
DHW
storage
DCW
A9


Generator
15 Thermal zones
A10


A11
Generator
15 Thermal zones
DHW
DCW


Solar
collectors
A12
Generator
15 Thermal zones
DHW
DHW
storage
DCW


A13
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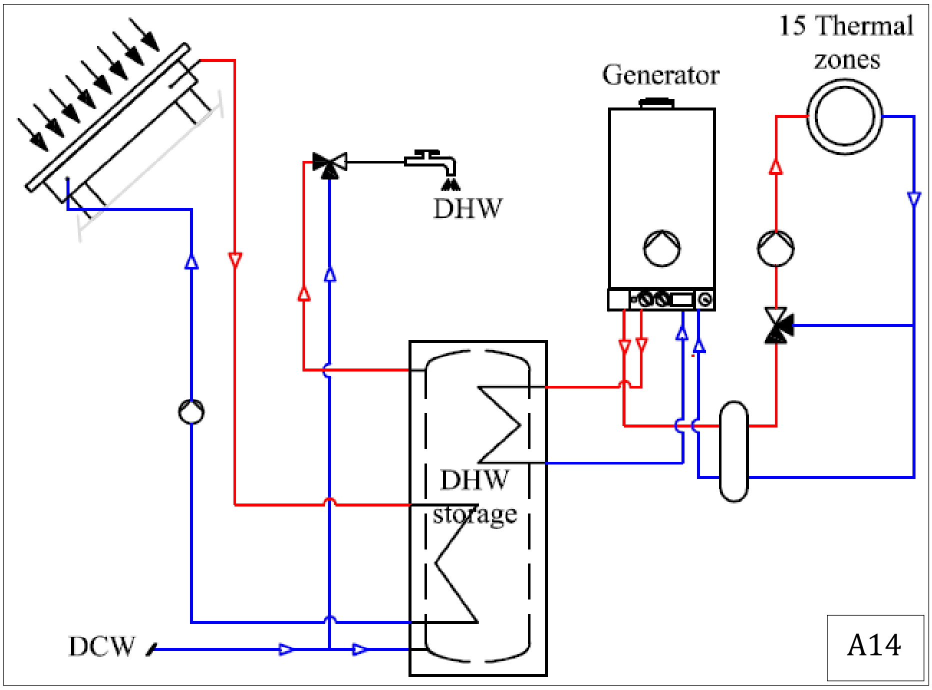
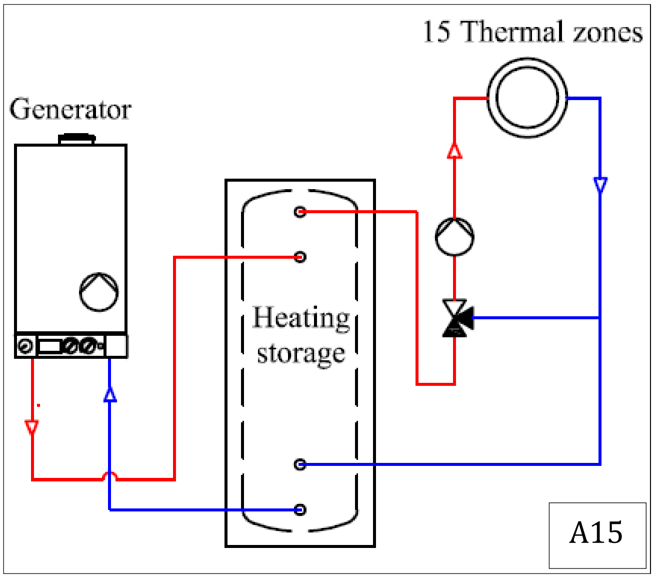
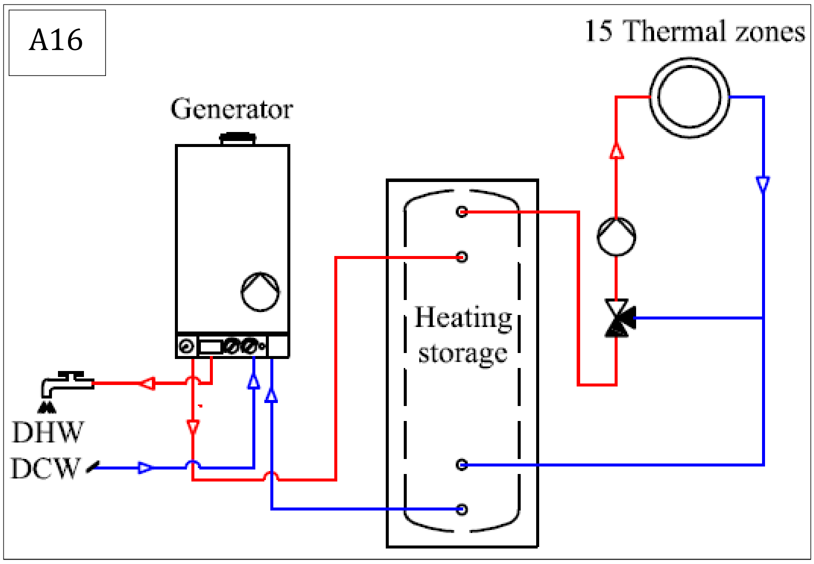
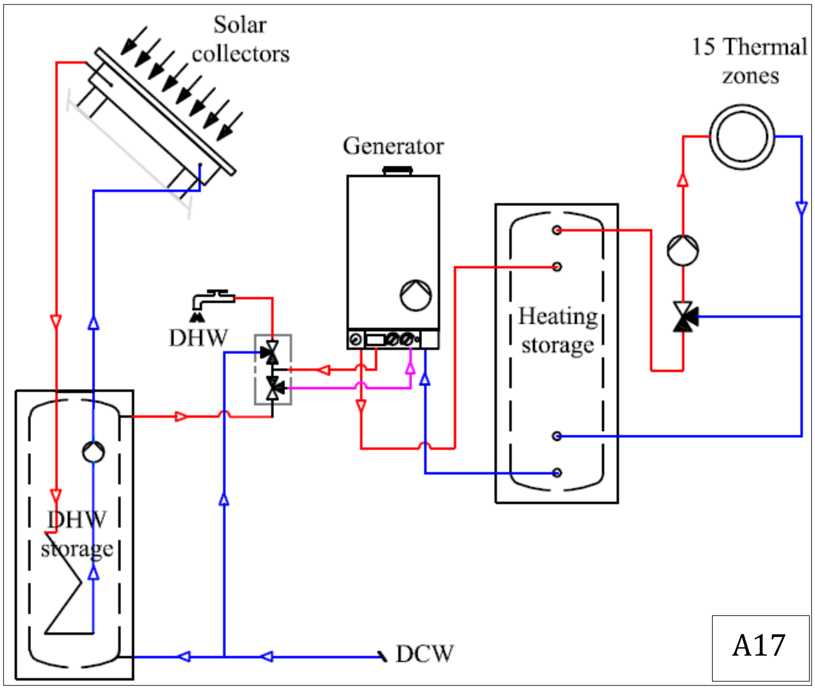
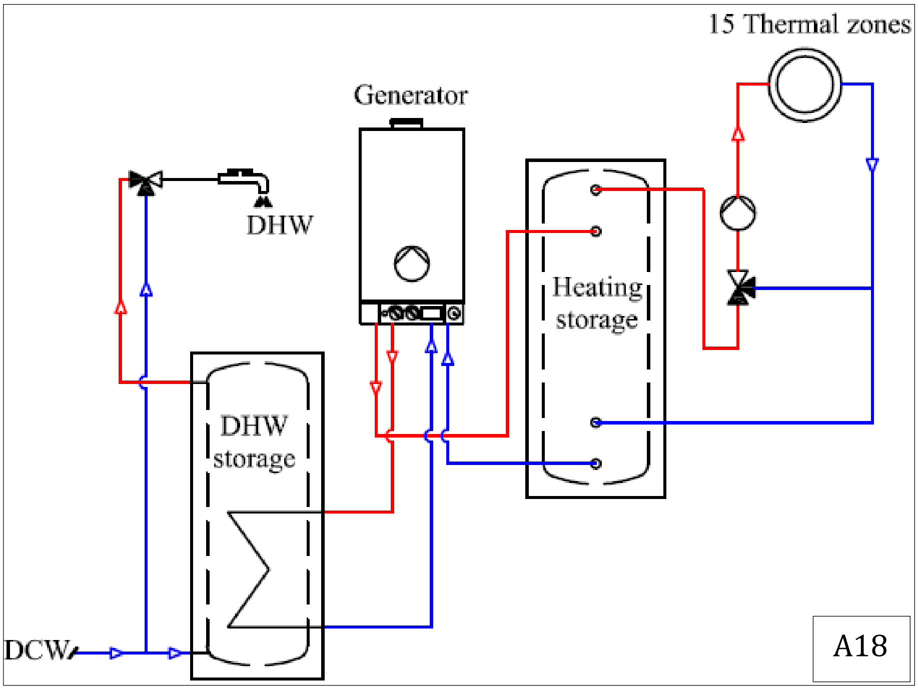
DHW
DHW
storage
DCW

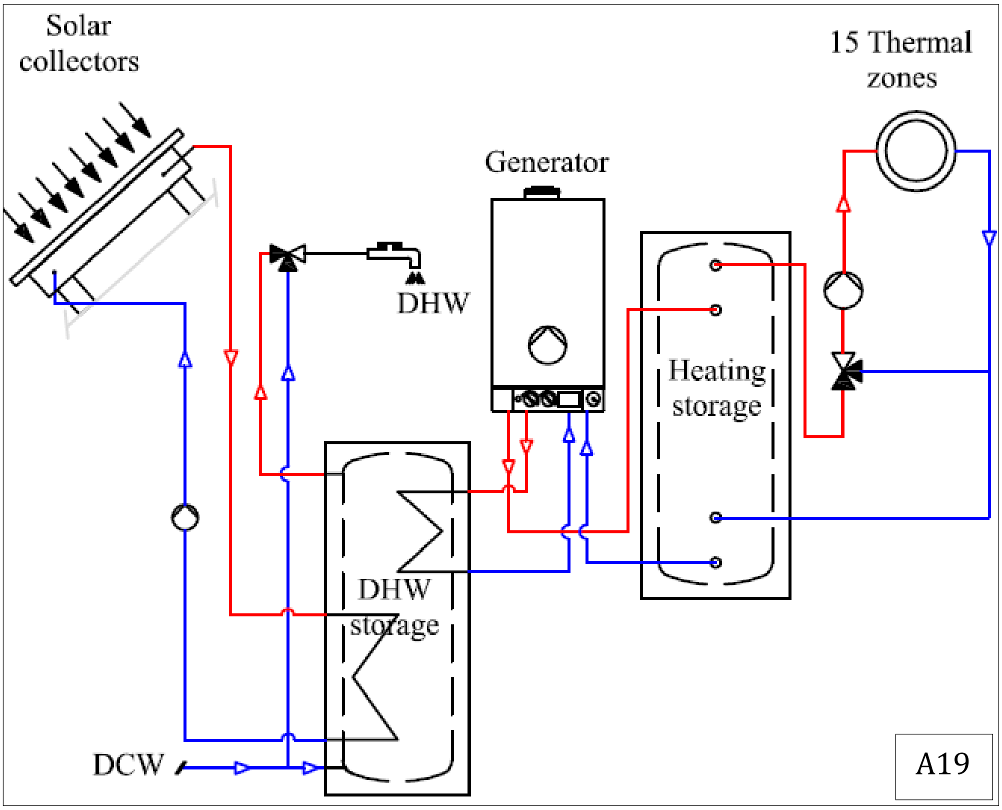

15 Thermal
zones
Generator
DHW
DHW
storage
DCW
A14

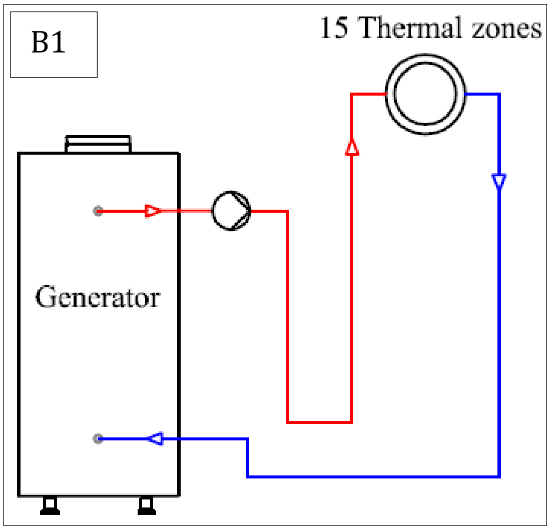

15 Thermal zones
Generator
Heating storage
A15


A16
15 Thermal zones
Generator
Heating storage
DHW
DCW


Solar
collectors
15 Thermal
zones
Generator
DHW
Heating
storage
DHW
storage
DCW
A17


15 Thermal zones
Generator
DHW
Heating
storage
DHW
storage
DCW
A18


Solar collectors
15 Thermal zones
Generator
DHW
Heating storage
DHW storage
DCW
A19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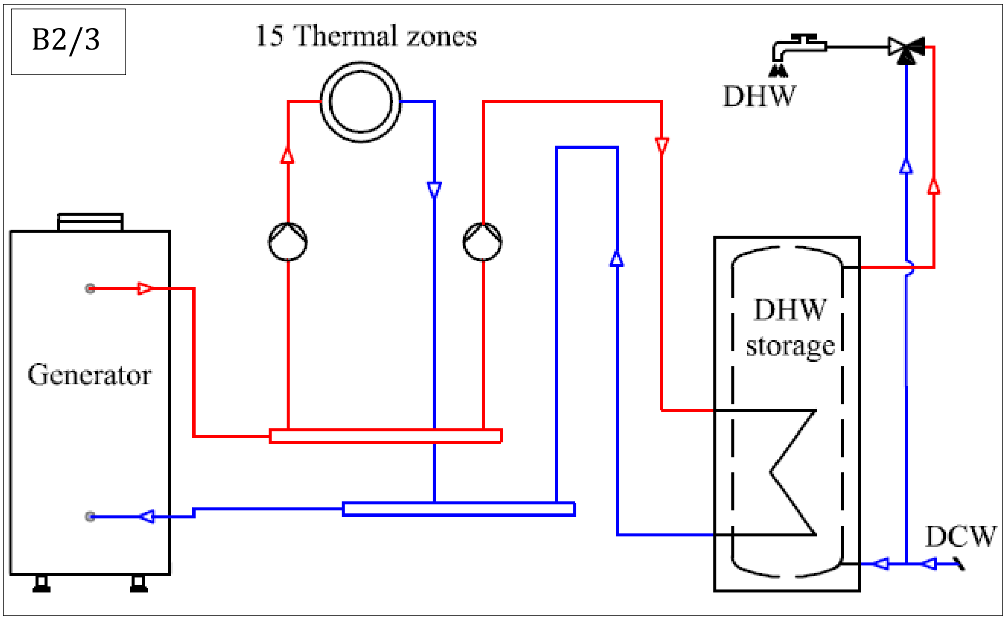
Generator



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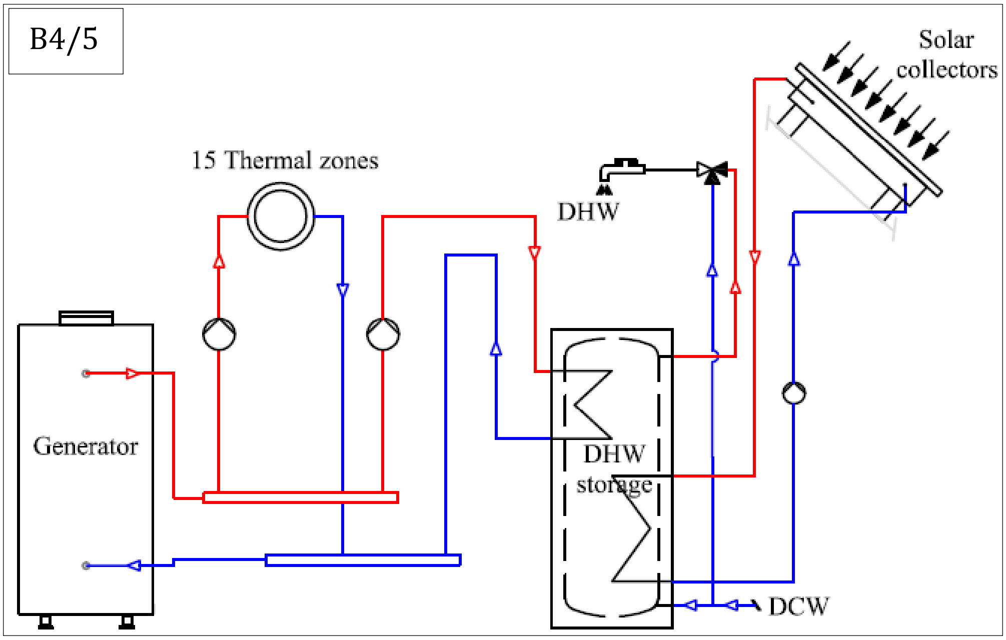
DHW
Generator
DHW storage
DCW



B4/5
Solar collectors
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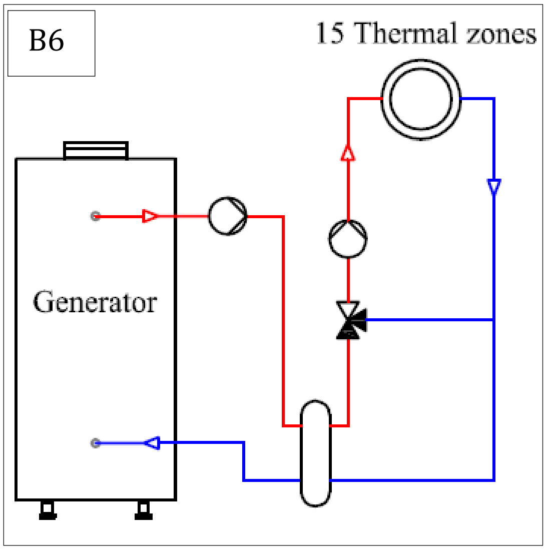
DHW
Generator
DHW storage
DCW


B6
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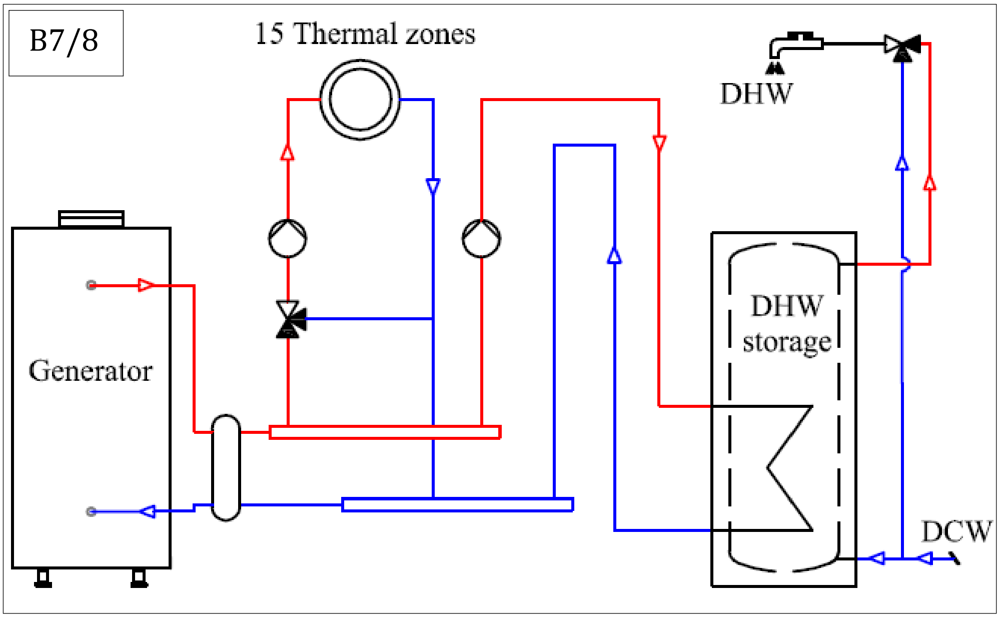
Generator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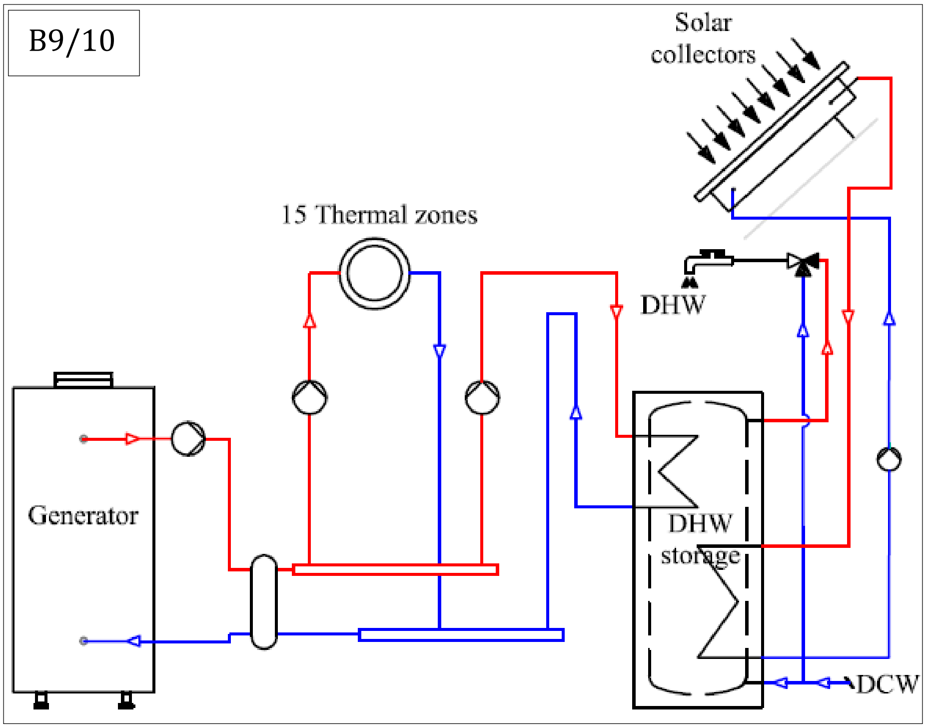
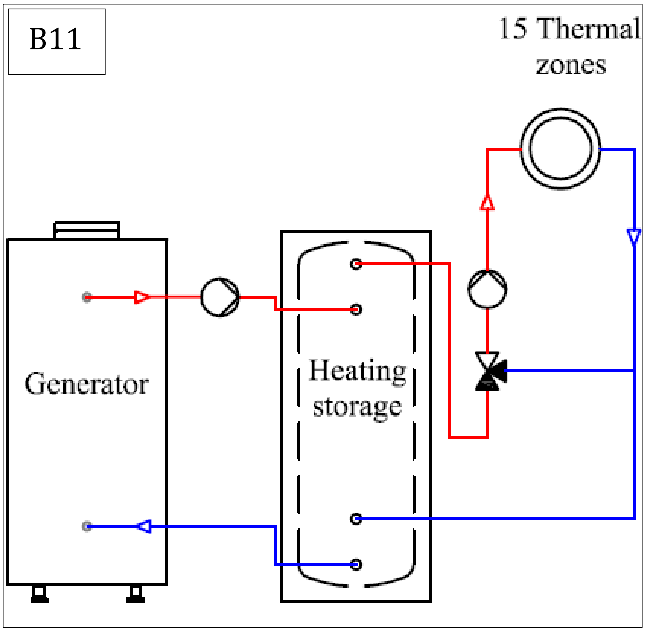
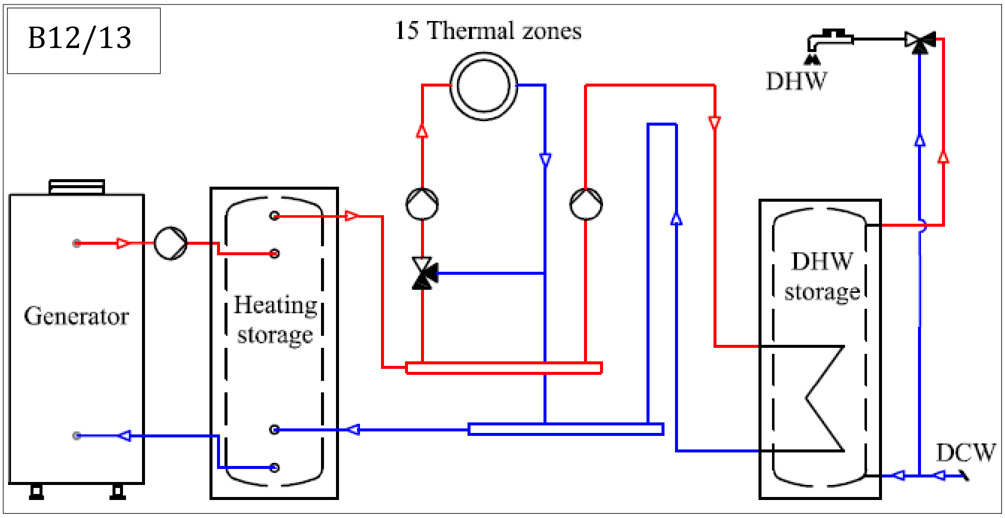
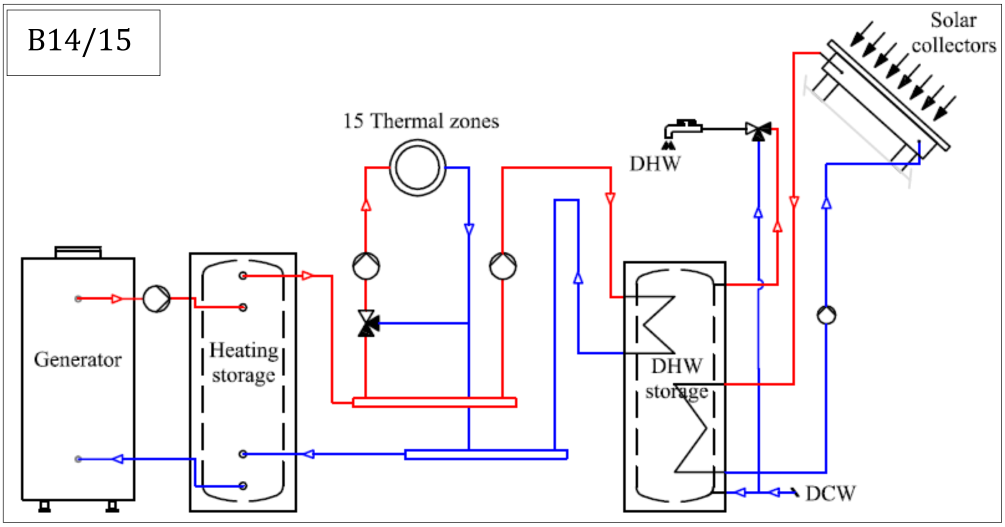
DHW
Generator
DHW
storage
DCW


B9/10
Solar
collectors
15 Thermal zones
DHW
Generator
DHW
storage
DCW

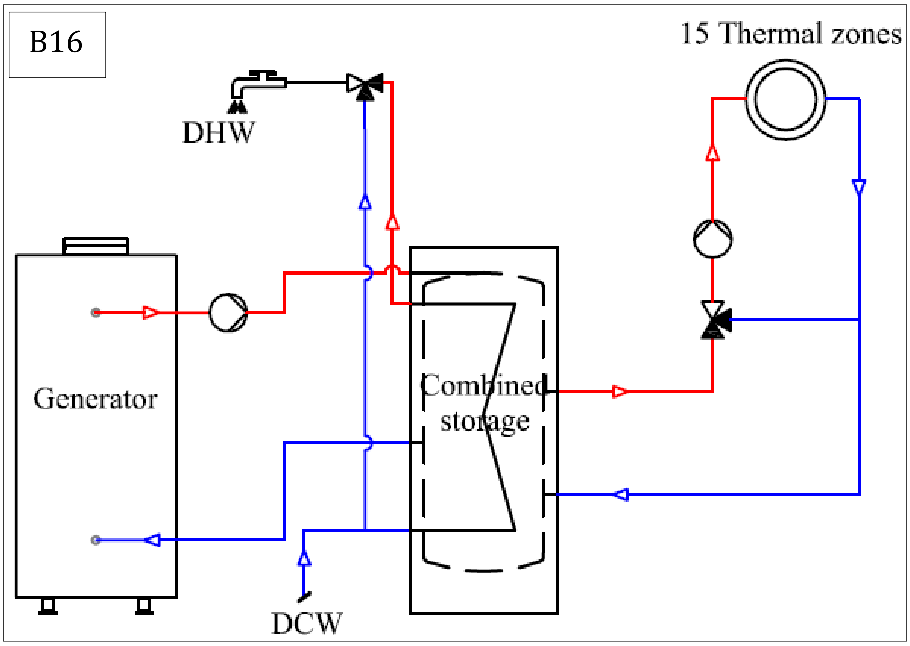

B11
15 Thermal
zones
Generator
Heating
storage

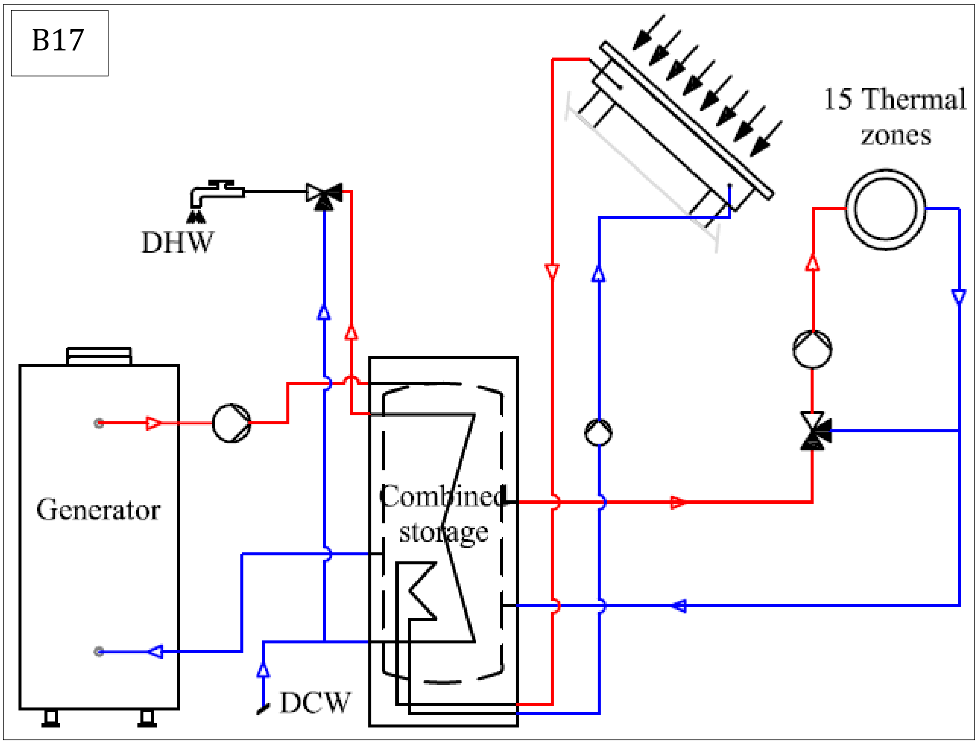


B12/13
15 Thermal zones
DHW
Generator
Heating storage
DHW storage
DCW



B14/15
Solar collectors
15 Thermal zones
DHW
Generator
Heating storage
DHW storage
DCW

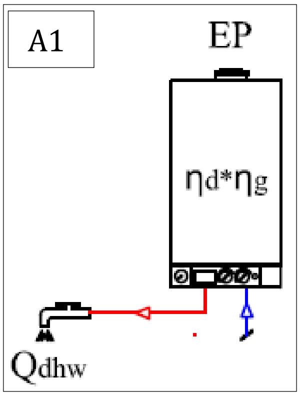

B16
15 Thermal zones
DHW
Generator
Combined storage
DCW

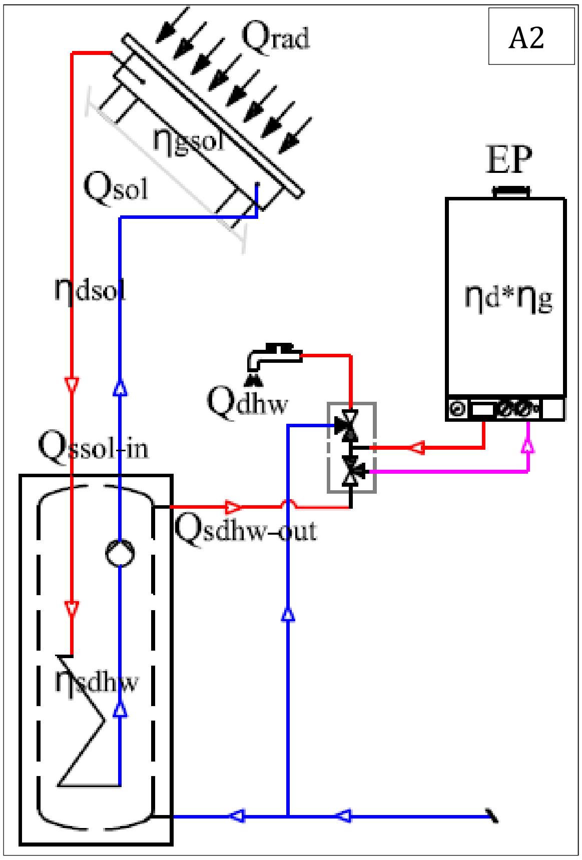

B17
15 Thermal zones
DHW
Generator
Combined storage
DCW

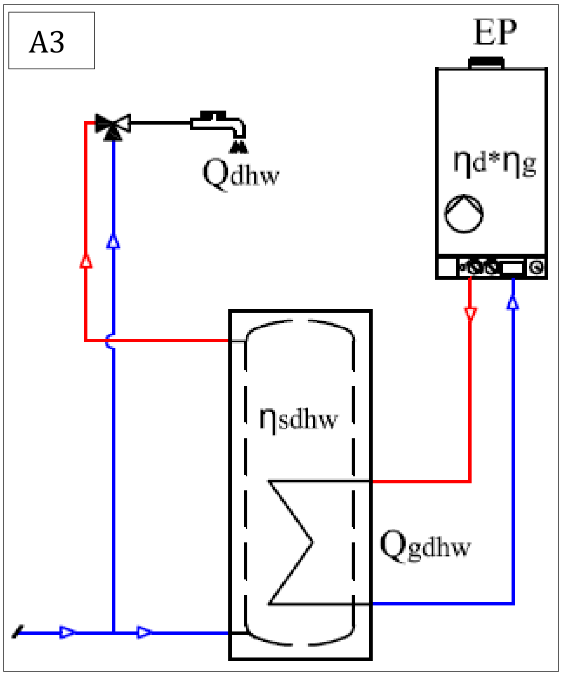
Appendix B

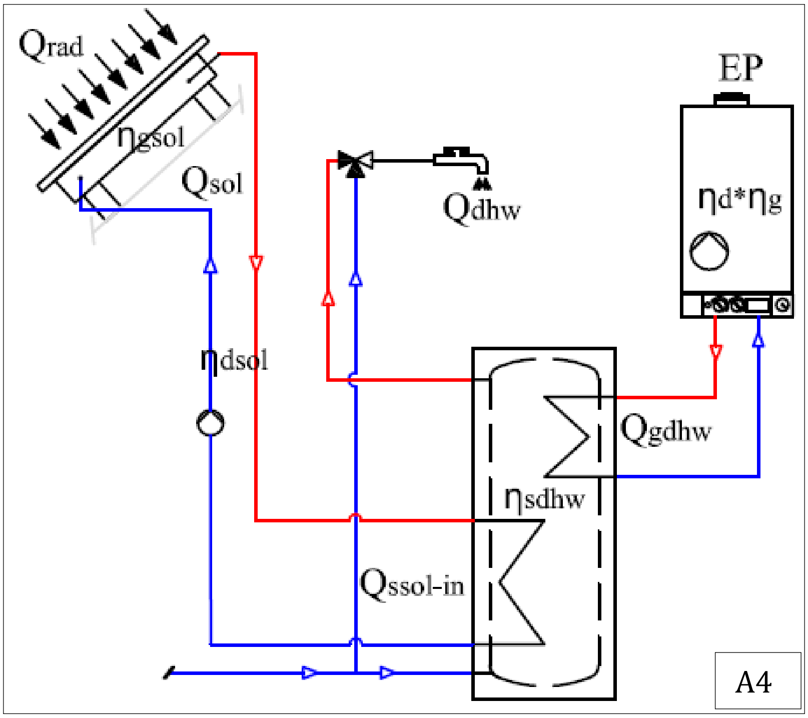
Hydraulic schemes performance indicators

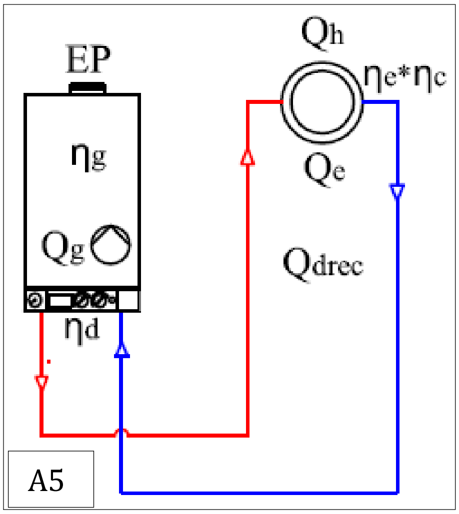
			DOMESTIC HOT WATER (DHW)					
		No HDW	Instantaneous production		Storage production			
			No solar	Solar	No solar		Solar	
			Prior.	Prior.	Prior.	No prior.	Prior.	No prior.
	No HS	/	A1	A2	A3	/	A4	/
HEATING SYSTEM (HS)	Direct HS	A5	A6	A7	A8	/	A9	/
	Hydraulic sep. HS	A10	A11	A12	A13	/	A14	/
	Storage HS	A15	A16	A17	A18	/	A19	/
	Direct HS & DHW	B1	/	/	B2	B3	B4	B5
	Hydraulic sep. HS & DHW	B6	/	/	B7	B8	B9	B10
	Storage HS & DHW	B11	B16	B17	B12	B13	B14	B15


A1
EP
ηd*ηg
Qdhw

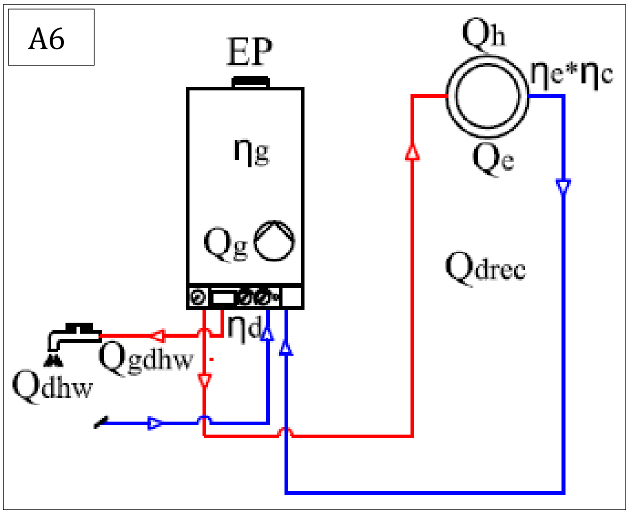

Qrad
A2
ηgsol
Qsol
EP
ηd*ηg
ηdsol
Qdhw
Qssol-in
Qsdhw-out
ηsdhw


A3
EP
ηd*ηg
Qdhw
ηsdhw
Qgdhw

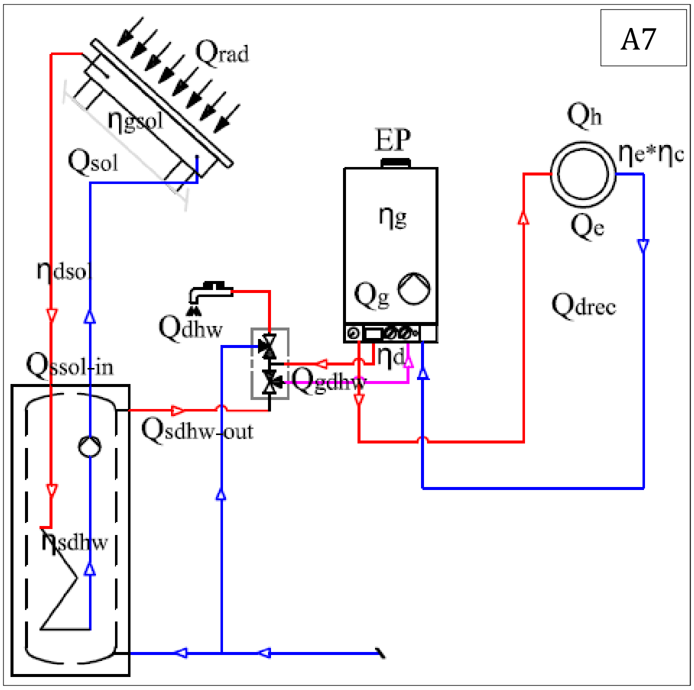

Qrad
ηgsol
Qsol
EP
Qdhw
ηd*ηg
ηdsol
Qgdhw
ηsdhw
Qssol-in
A4

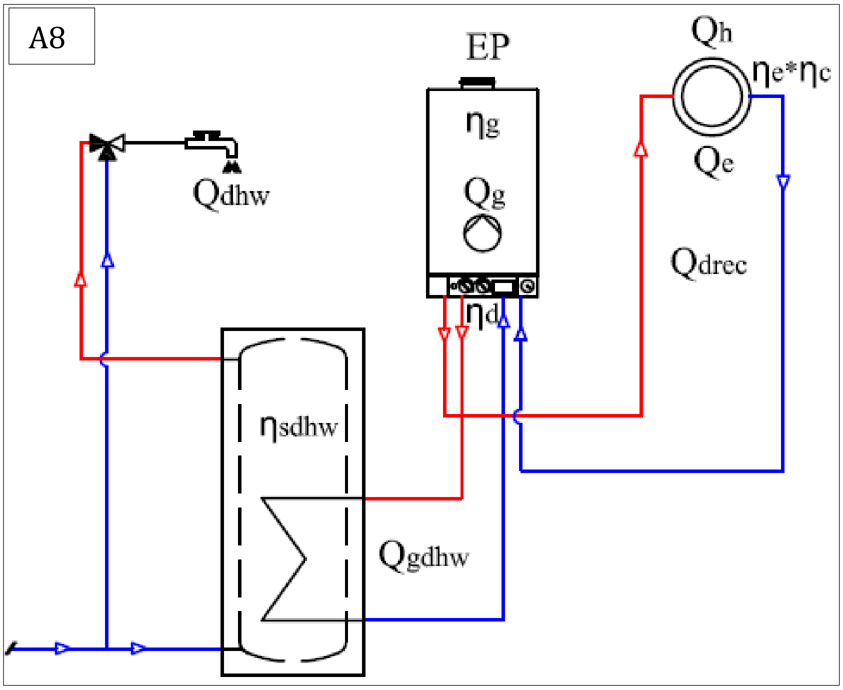


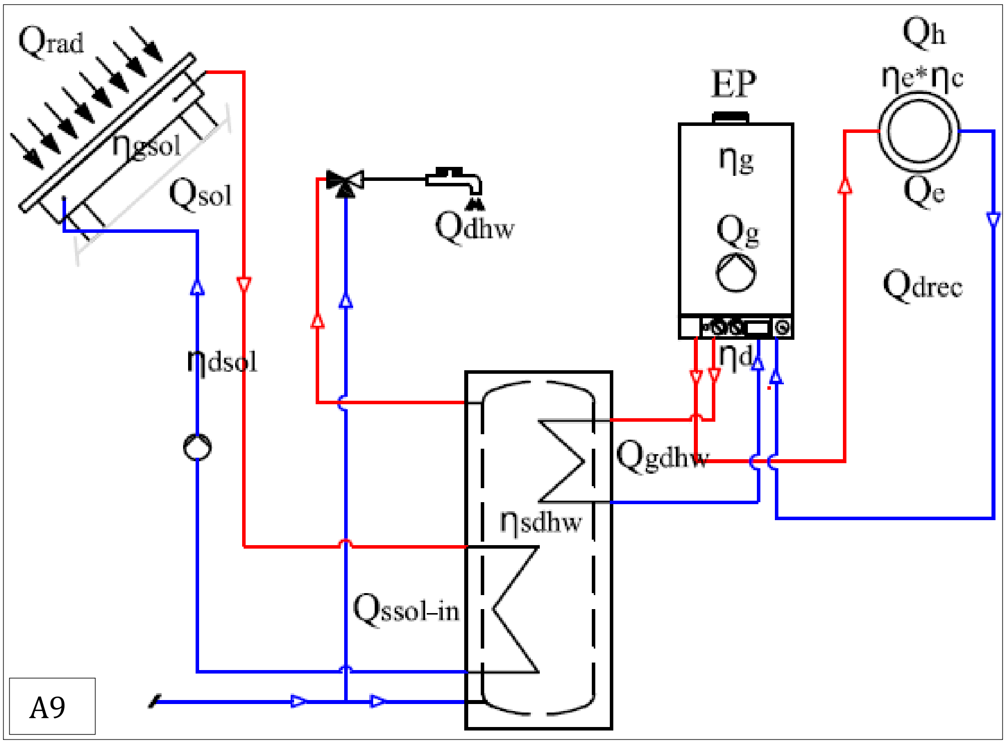
EP
Qh
ηe*ηc
ηg
Qe
Qg
Qdrec
ηd
A5

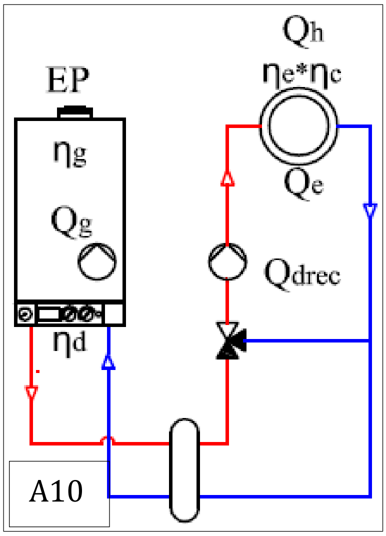


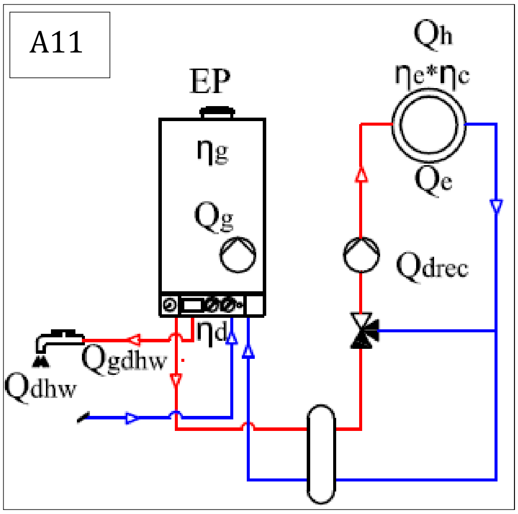
A6
EP
Qh
ηe*ηc
ηg
Qe
Qg
Qdrec
ηd
Qgdhw
Qdhw


A7
Qrad
ηgsol
Qsol
EP
ηg
Qg
Qh
ηe*ηc
Qe
Qdrec
ηdsol
Qdhw
Qssol-in
ηd
Qgdhw
Qsdhw-out
ηsdhw

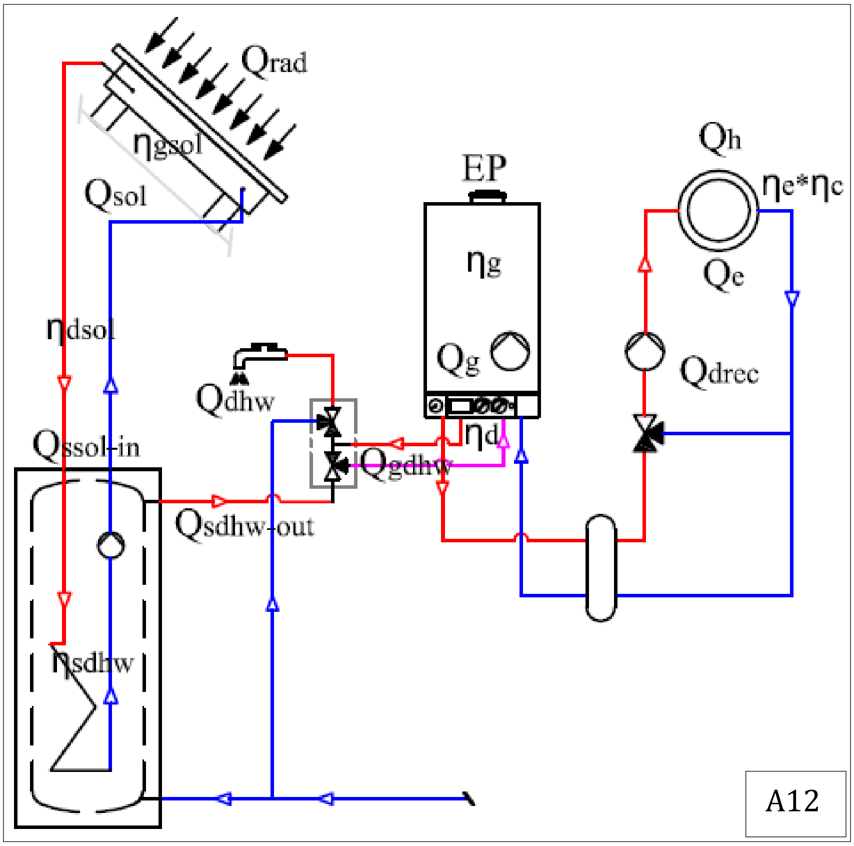

A8
EP
ηg
Qg
Qh
ηe*ηc
Qe
Qdrec
Qdhw
ηd
ηsdhw
Qgdhw


Qrad
ηgsol
Qsol
Qdhw
EP
ηg
Qg
ηd
Qh
ηe*ηc
Qe
Qdrec
ηdsol
Qgdhw
ηsdhw
Qssol-in
A9

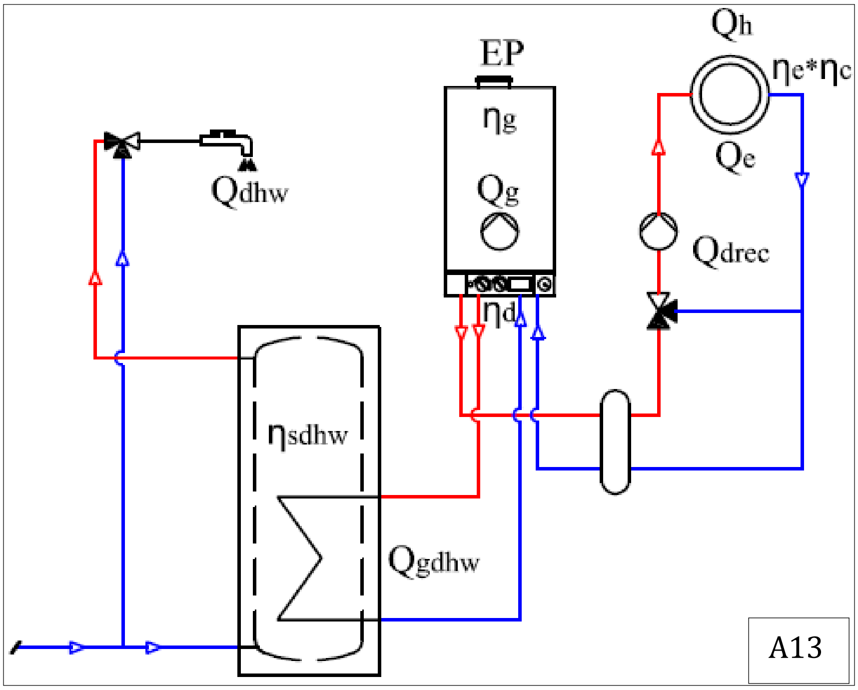

Qh
ηe*ηc
EP
ηg
Qe
Qg
Qdrec
ηd
A10

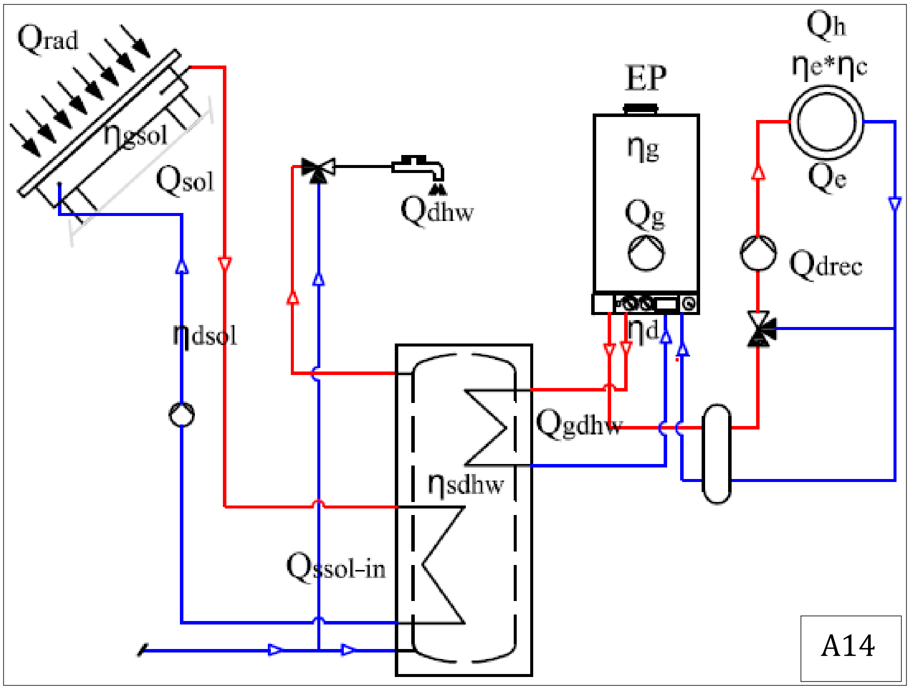


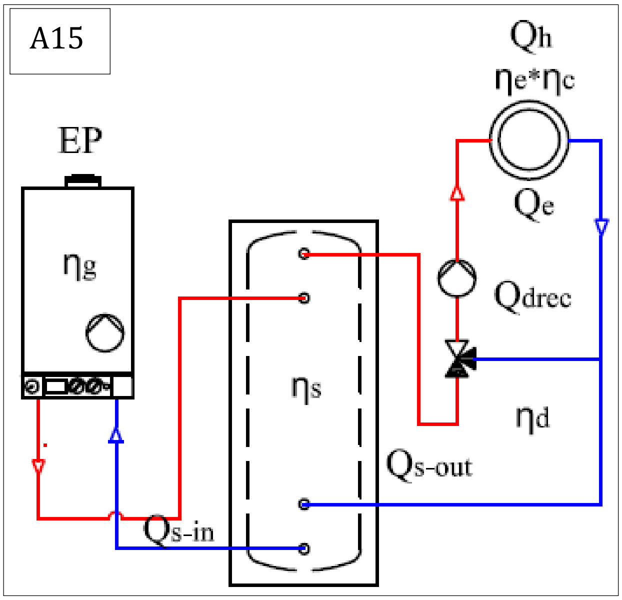
A11
EP
Qh
ηe*ηc
ηg
Qe
Qg
Qdrec
ηd
Qgdhw
Qdhw

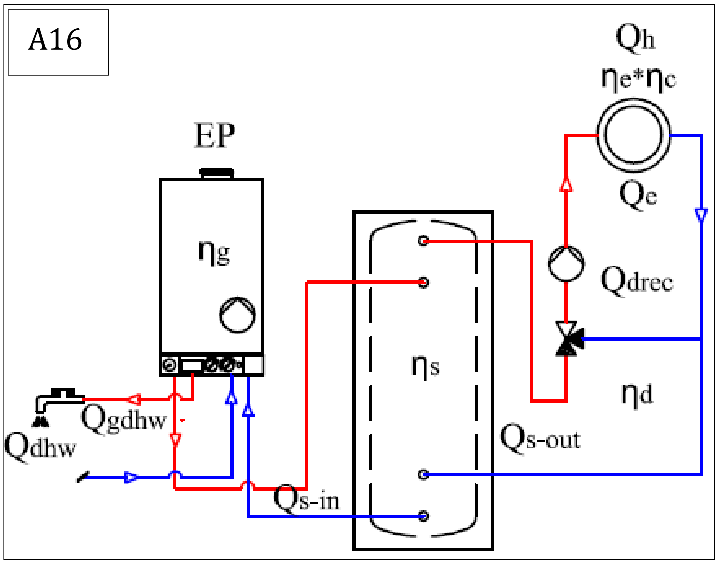


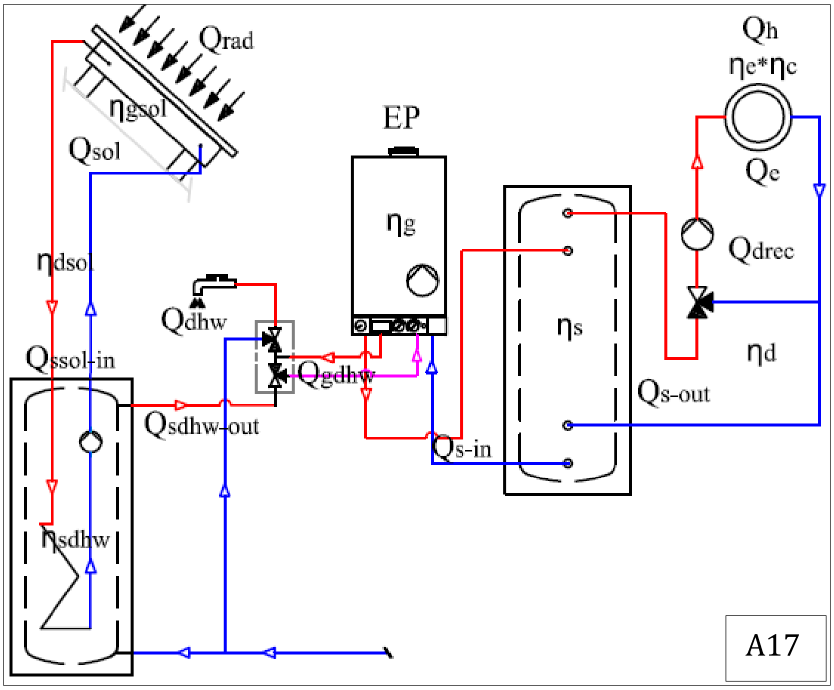
Qrad
ηgsol
Qsol
EP
Qh
ηe*ηc
ηg
Qe
ηdsol
Qg
Qdrec
Qdhw
ηd
Qssol-in
Qgdhw
Qsdhw-out
ηsdhw
A12


EP
Qh
ηe*ηc
ηg
Qe
Qdhw
Qg
Qdrec
ηd
ηsdhw
Qgdhw
A13

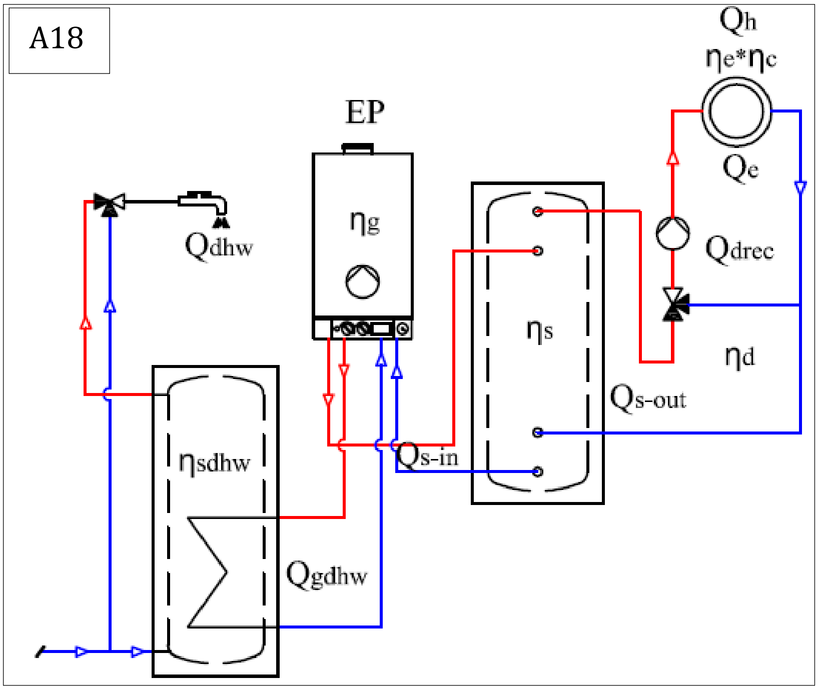

Qrad
Qh
ηe*ηc
EP
ηgsol
ηg
Qsol
Qe
Qdhw
Qg
Qdrec
ηdsol
ηd
Qgdhw
ηsdhw
Qssol-in
A14


A15
Qh
ηe*ηc
EP
Qe
ηg
Qdrec
ηs
ηd
Qs-out
Qs-in

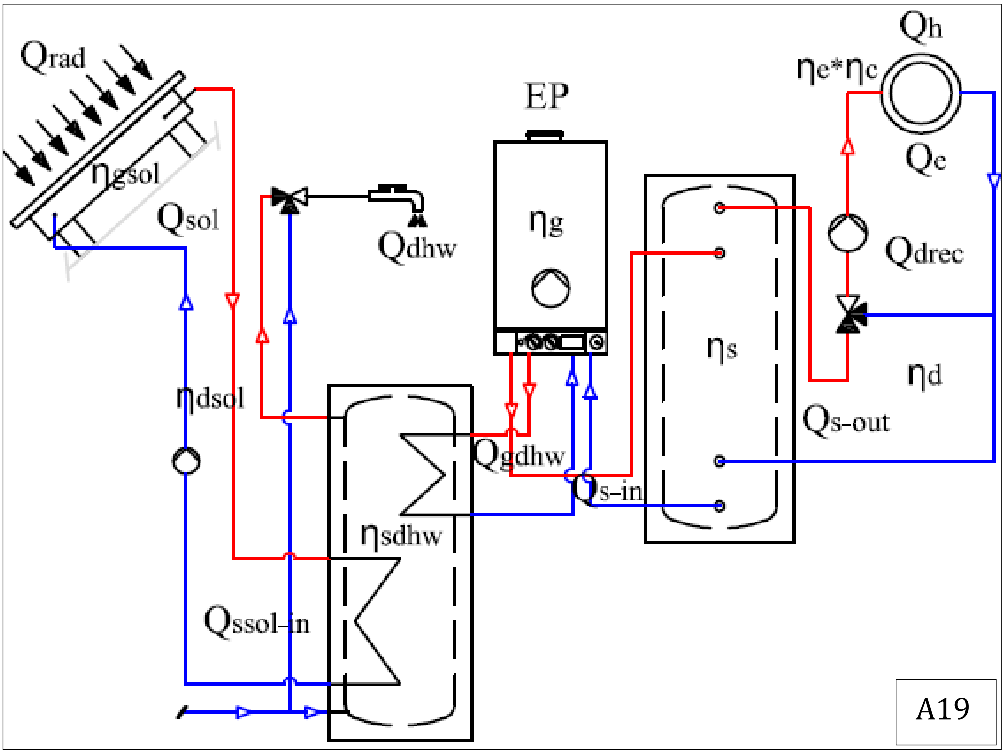

A16
Qh
ηe*ηc
EP
Qe
ηg
Qdrec
ηs
ηd
Qgdhw
Qdhw
Qs-out
Qs-in

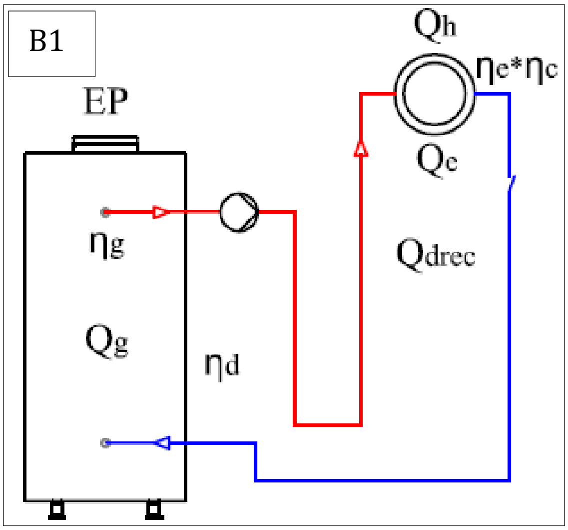


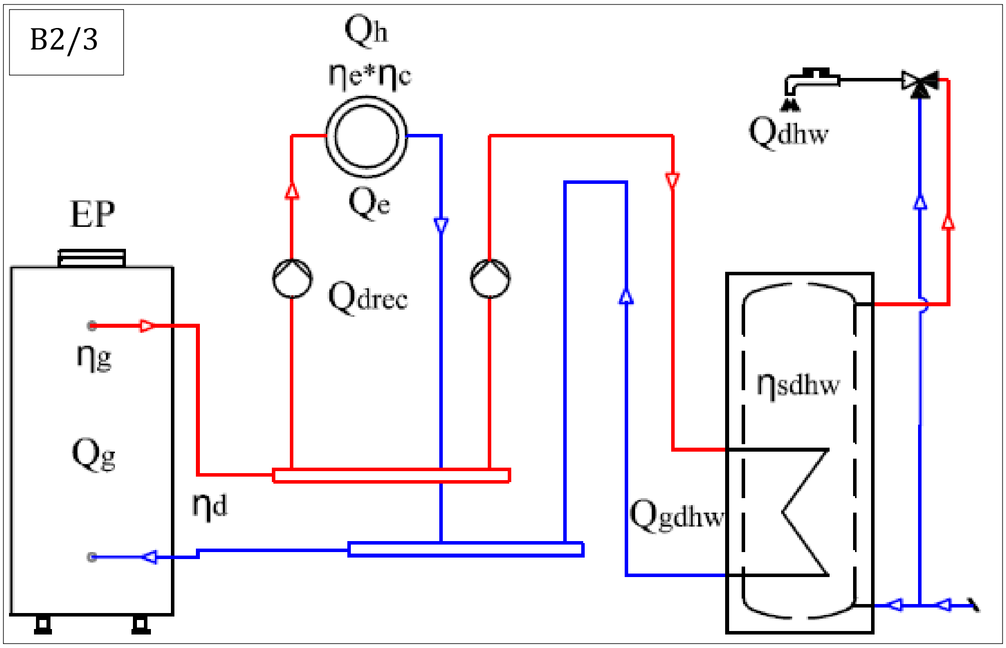
Qrad
ηgsol
Qsol
ηdsol
Qdhw
Qssol-in
Qgdhw
Qsdhw-out
ηsdhw
EP
ηg
ηs
Qs-in
Qs-out
Qh
ηe*ηc
Qe
Qdrec
ηd
A17

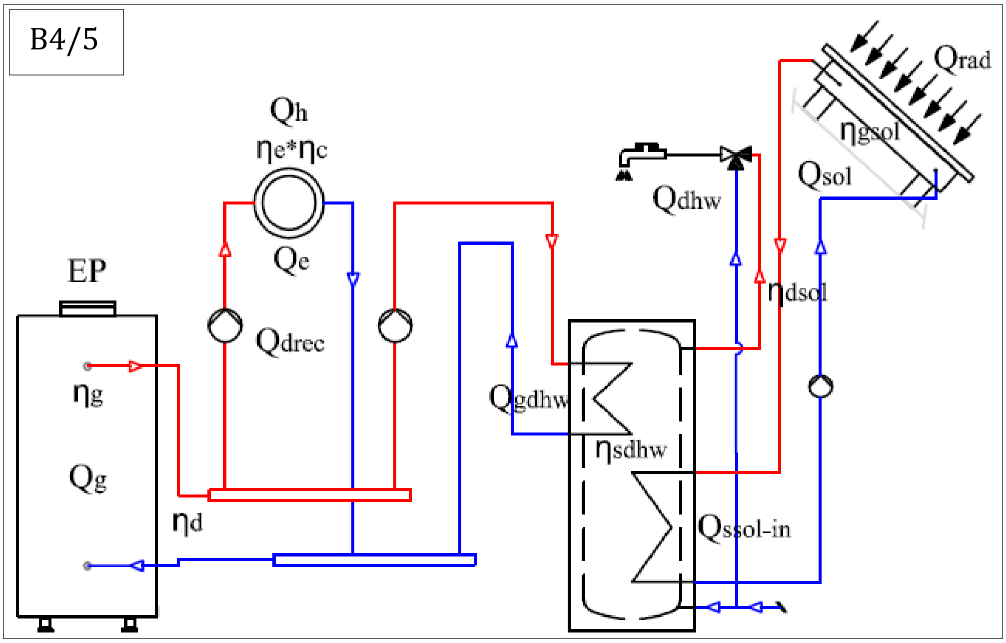


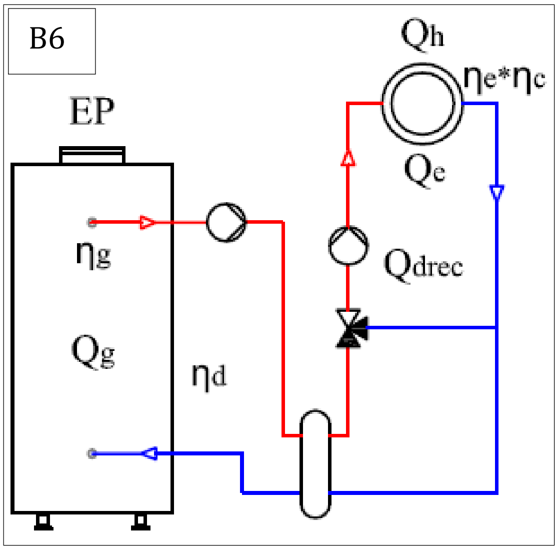
A18
Qdhw
EP
ηg
ηs
ηsdhw
Qgdhw
Qs-in
Qs-out
Qh
ηe*ηc
Qe
Qdrec
ηd

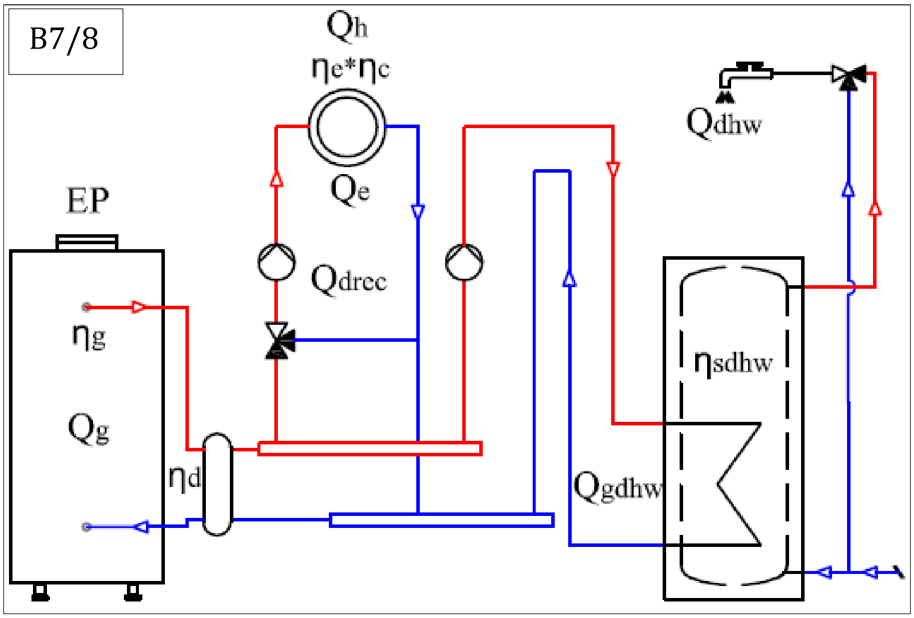

Qrad
ηgsol
Qsol
Qdhw
EP
ηg
Qh
ηe*ηc
Qe
Qdrec
ηs
ηd
Qs-out
ηdsol
Qgdhw
Qs–in
ηsdhw
Qssol–in
A19

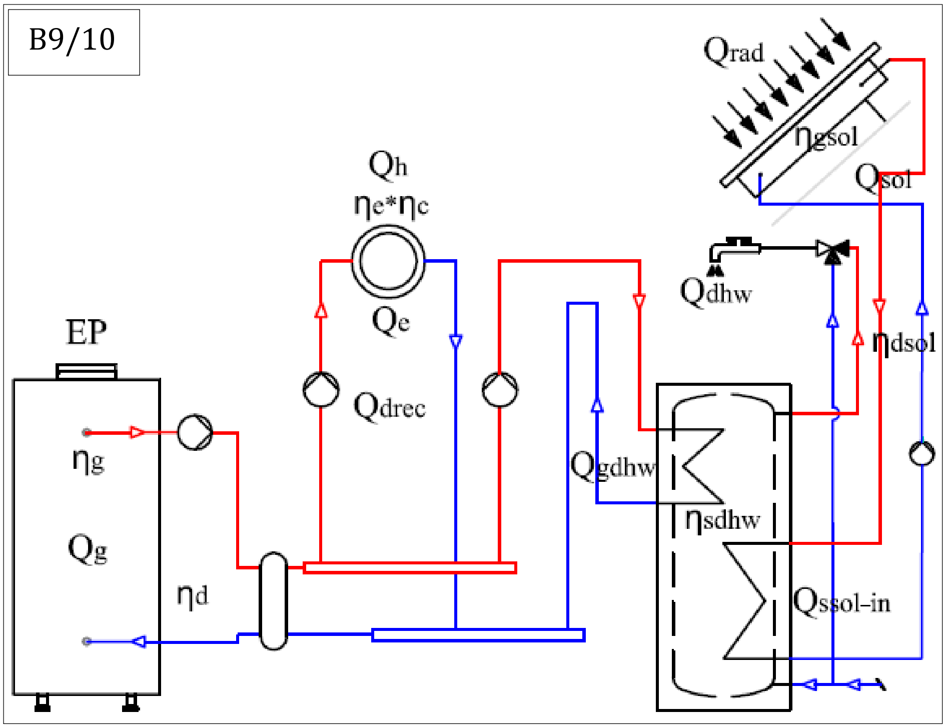

B1
EP
Qh
ηe*ηc
Qe
ηg
Qdrec
Qg
ηd

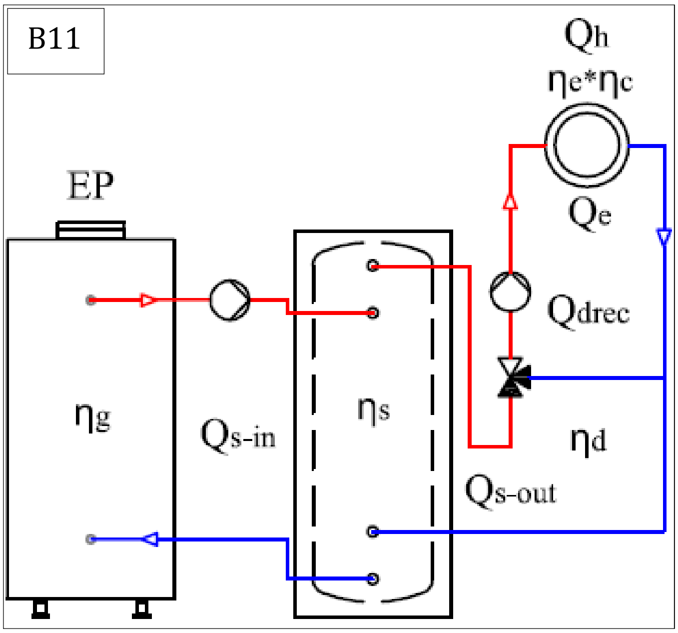

B2/3
Qh
ηe*ηc
Qe
Qdrec
Qdhw
EP
ηg
Qg
ηd
ηsdhw
Qgdhw

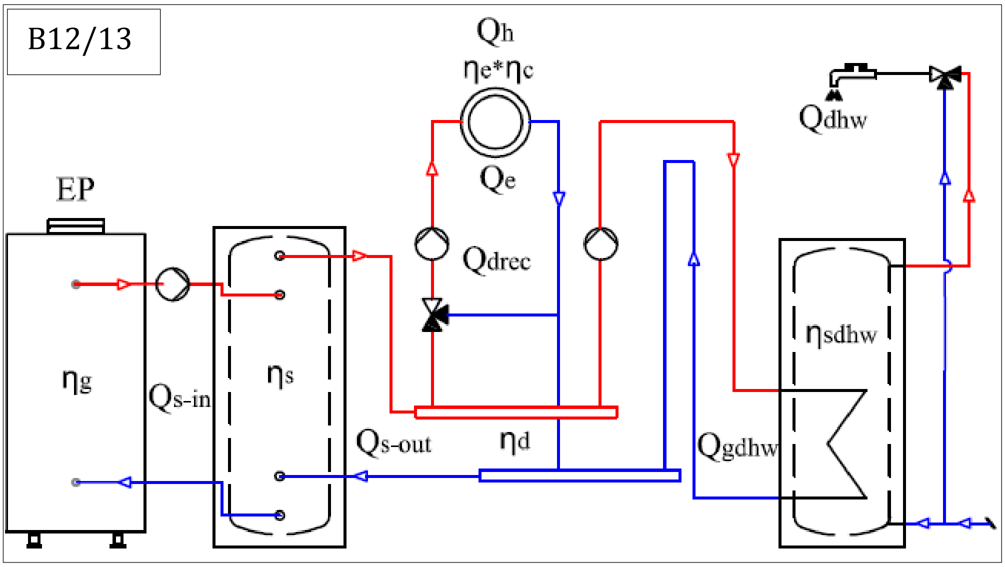

B4/5
Qrad
ηgsol
Qsol
Qh
ηe*ηc
Qe
Qdhw
EP
Qdrec
ηdsol
ηg
Qgdhw
ηsdhw
Qg
ηd
Qssol-in


B6
Qh
ηe*ηc
EP
Qe
ηg
Qdrec
Qg
ηd

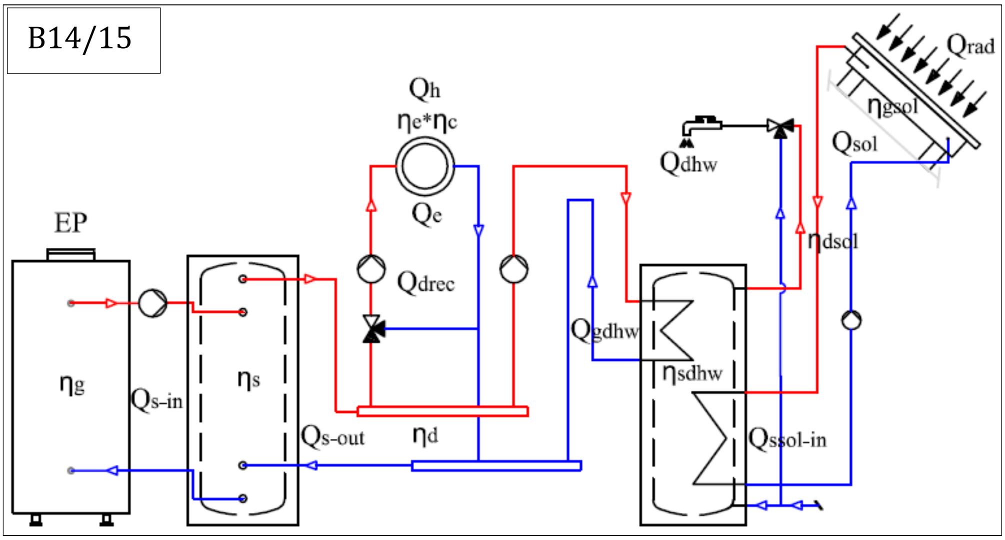

B7/8
Qh
ηe*ηc
Qdhw
Qe
EP
Qdrec
ηg
ηsdhw
Qg
ηd
Qgdhw


B9/10
Qrad
ηgsol
Qsol
Qh
ηe*ηc
Qe
Qdhw
EP
ηdsol
Qdrec
ηg
Qgdhw
Qg
ηsdhw
ηd
Qssol-in

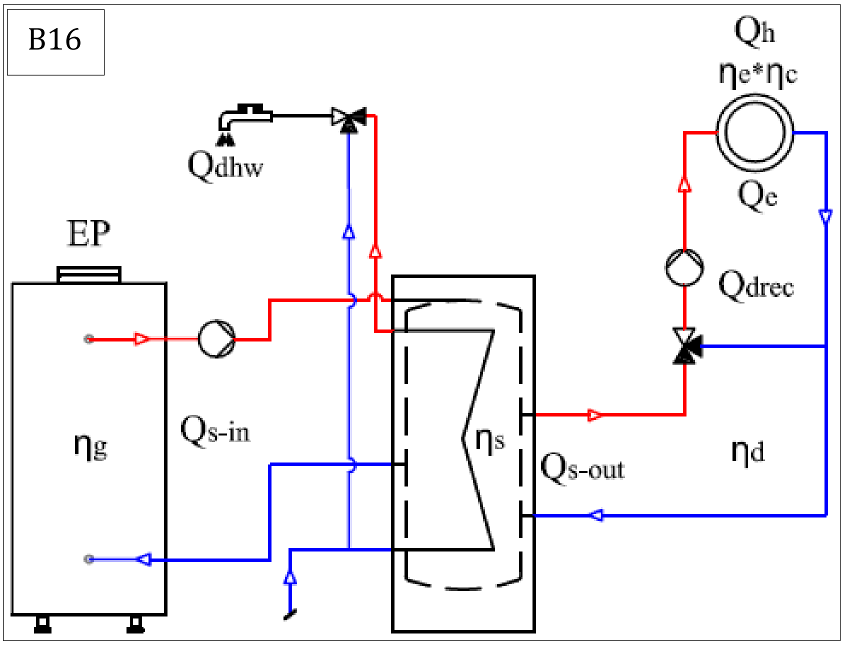

B11
Qh
ηe*ηc
EP
Qe
Qdrec
ηg
Qs-in
ηs
ηd
Qs-out

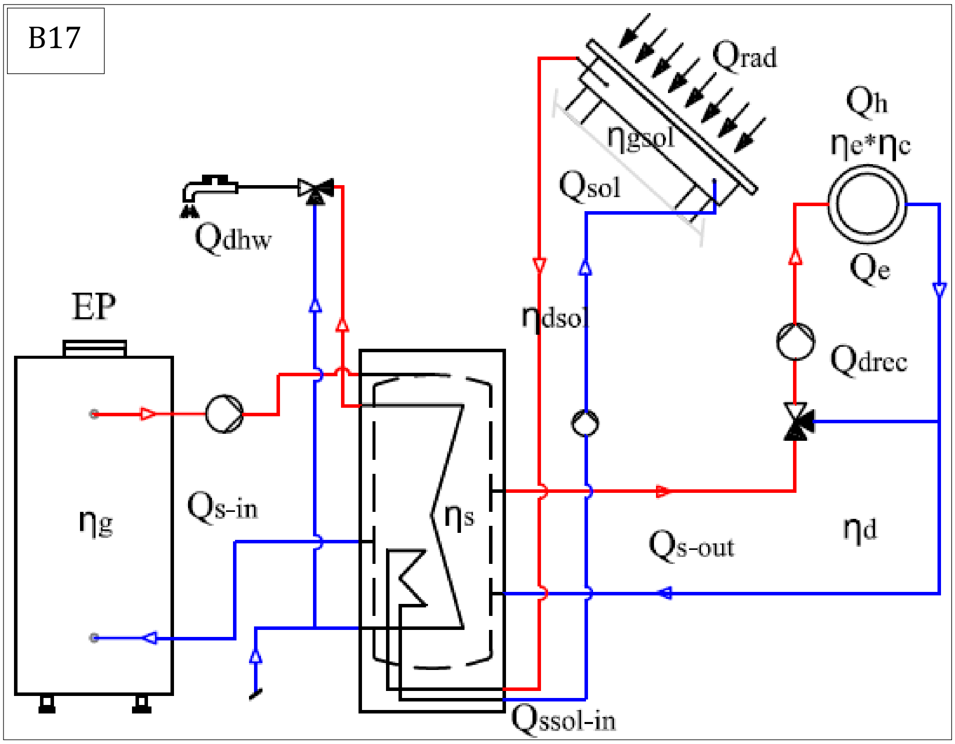


B12/13
Qh
ηe*ηc
Qdhw
Qe
EP
Qdrec
ηsdhw
ηg
Qs-in
ηs
Qs-out
ηd
Qgdhw



B14/15
Qrad
ηgsol
Qh
ηe*ηc
Qsol
Qdhw
Qe
ηdsol
EP
Qdrec
Qgdhw
ηsdhw
ηg
Qs-in
ηs
Qs-out
ηd
Qssol-in


B16
Qh
ηe*ηc
Qdhw
Qe
EP
Qdrec
ηg
Qs-in
ηs
Qs-out
ηd


B17
Qrad
Qh
ηgsol
ηe*ηc
Qsol
Qdhw
Qe
EP
ηdsol
Qdrec
ηg
Qs-in
ηs
Qs-out
ηd
Qssol-in

PERFORMANCE INDICATORS AND THEIR RELATIONSHIPS/RATIOS IN THE HYDRAULIC SCHEMES A1-A2-A5-A6-A7-A10-A11-A12[10]:

For the part of the plant only related to the production of the DHW:

- Q_{dhw} (kWh)= annual DHW energy demand;
- Q_{gdhw} (kWh)= annual DHW energy demand covered by the generation;
- $Q_{sdhw\text{-}out}$ (kWh)= Q_{dhw}-Q_{gdhw}= annual solar energy removed from the DHW storage, i.e. annual DHW energy demand covered by the solar collectors;
- η_{sdhw}= annual DHW storage efficiency;
- $Q_{ssol\text{-}in}$ (kWh)= $Q_{sdhw\text{-}out}/\eta_{sdhw}$= annual solar energy introduced in the DHW storage;
- η_{dsol}= annual solar distribution efficiency;
- Q_{sol} (kWh)= $Q_{ssol\text{-}in}/\eta_{dsol}$= annual energy provided by the solar collectors;
- η_{gsol}= annual solar generation efficiency;
- Q_{rad} (kWh)= Q_{sol}/η_{gsol}= annual incident radiation on the solar collectors;

For the part of the plant only related to the heating service:

- Q_h (kWh)= annual heating energy demand;
- η_e*η_c= annual heating emission efficiency * annual heating control efficiency;

[10] The parameters and their relationships/ratios indicated can be applied to all the mentioned schemes. Where in each single scheme does not appear one of the parameters, it has to be taken in the relationships/ratios equal to 0 if an energy, equal to 1 if an efficiency.

- Q_e (kWh)= $Q_h/(\eta_e*\eta_c)$= annual heating energy introduced in the building from the emission subsystem;
- Q_{drec} (kWh)= annual recovered distribution losses;

For the common part of the plant:

- η_d= annual overall efficiency of the distribution subsystem;
- Q_g (kWh)= $(Q_e+Q_{drec}+Q_{gdhw})/\eta_d$= annual energy provided by the generation;
- η_g= annual overall efficiency of the generation subsystem;
- EP (kWh)= Q_g/η_g= annual primary energy introduced in the generation;

PERFORMANCE INDICATORS AND THEIR RELATIONSHIPS/RATIOS IN THE HYDRAULIC SCHEMES A15-A16-A17[11]:

For the part of the plant only related to the production of the DHW:

- Q_{dhw} (kWh)= annual DHW energy demand;
- Q_{gdhw} (kWh)= annual DHW energy demand covered by the generation;
- $Q_{sdhw\text{-}out}$ (kWh)= Q_{dhw}-Q_{gdhw}= annual solar energy removed from the DHW storage, i.e. annual DHW energy demand covered by the solar collectors;
- η_{sdhw}= annual DHW storage efficiency;
- $Q_{ssol\text{-}in}$ (kWh)= $Q_{sdhw\text{-}out}/\eta_{sdhw}$= annual solar energy introduced in the DHW storage;
- η_{dsol}= annual solar distribution efficiency;

[11] See note 10

- Q_{sol} (kWh)= $Q_{ssol-in}/\eta_{dsol}$= annual energy provided by the solar collectors;
- η_{gsol}= annual solar generation efficiency;
- Q_{rad} (kWh)= Q_{sol}/η_{gsol}= annual incident radiation on the solar collectors;

For the part of the plant only related to the heating service:

- Q_h (kWh)= annual heating energy demand;
- $\eta_e*\eta_c$= annual heating emission efficiency * annual heating control efficiency;
- Q_e (kWh)= $Q_h/(\eta_e*\eta_c)$= annual heating energy introduced in the building from the emission subsystem;
- Q_{drec} (kWh)= annual recovered distribution losses;
- η_d= annual heating distribution efficiency;
- Q_{s-out} (kWh)= $(Q_e+Q_{drec})/\eta_d$= annual heating energy provided by the storage;
- η_s= annual heating storage efficiency;
- Q_{s-in} (kWh)= $(Q_{s-out})/\eta_d$= annual heating energy introduced in the storage;

For the common part of the plant:

- η_g= annual overall efficiency of the generation subsystem;
- EP (kWh)= $(Q_{s-out}+Q_{gdhw})/\eta_g$= annual primary energy introduced in the generation;

PERFORMANCE INDICATORS AND THEIR RELATIONSHIPS/RATIOS IN THE HYDRAULIC SCHEMES A18- A19[12]

For the part of the plant only related to the production of the DHW:

- Q_{dhw} (kWh)= annual DHW energy demand;
- η_{sdhw}= annual DHW storage efficiency;
- Q_{gdhw} (kWh)= annual energy introduced in the DHW storage from the generation, i.e. annual DHW energy demand covered by the generation (with η_{sdhw}=1);
- $Q_{ssol\text{-}in}$ (kWh)= Q_{dhw}/η_{sdhw}-Q_{gdhw} = annual solar energy introduced in the DHW storage, i.e. annual DHW energy demand covered by the solar collectors (with η_{sdhw} =1);
- η_{dsol}= annual solar distribution efficiency;
- Q_{sol} (kWh)= $Q_{ssol\text{-}in}/\eta_{dsol}$= annual energy provided by the solar collectors;
- η_{gsol}= annual solar generation efficiency;
- Q_{rad} (kWh)= Q_{sol}/η_{gsol}= annual incident radiation on the solar collectors;

For the part of the plant only related to the heating service:

- Q_h (kWh)= annual heating energy demand;
- η_e*η_c= annual heating emission efficiency * annual heating control efficiency;
- Q_e (kWh)= $Q_h/(\eta_e*\eta_c)$= annual heating energy introduced in the building from the emission subsystem;
- Q_{drec} (kWh)= annual recovered distribution losses;

[12] See note 10

- η_d= annual heating distribution efficiency;
- Q_{s-out} (kWh)= $(Q_e+Q_{drec})/\eta_d$= annual heating energy provided by the storage;
- η_s= annual heating storage efficiency;
- Q_{s-in} (kWh)= $(Q_{s-out})/\eta_d$= annual heating energy introduced in the storage;

For the common part of the plant:

- η_g= annual overall efficiency of the generation subsystem;
- EP (kWh)= $(Q_{s-out}+Q_{gdhw})/\eta_g$= annual primary energy introduced in the generation;

PERFORMANCE INDICATORS AND THEIR RELATIONSHIPS/RATIOS IN THE HYDRAULIC SCHEMES A3-A4-A8-A9-A13-A14-B1-B2-B3-B4-B5-B6-B7-B8-B9-B10-B11-B12-B13-B14-B15[13]

For the part of the plant only related to the production of the DHW:

- Q_{dhw} (kWh)= annual DHW energy demand;
- η_{sdhw}= annual DHW storage efficiency;
- Q_{gdhw} (kWh)= annual energy introduced in the DHW storage from the generation, i.e. annual DHW energy demand covered by the generation (with η_{sdhw}=1);
- $Q_{ssol-in}$ (kWh)= $Q_{dhw}/\eta_{sdhw}-Q_{gdhw}$ = annual solar energy introduced in the DHW storage, i.e. annual DHW energy demand covered by the solar collectors (with η_{sdhw} =1);
- η_{dsol}= annual solar distribution efficiency;

[13] See note 10

- Q_{sol} (kWh)= $Q_{ssol\text{-}in}/\eta_{dsol}$= annual energy provided by the solar collectors;
- η_{gsol}= annual solar generation efficiency;
- Q_{rad} (kWh)= Q_{sol}/η_{gsol}= annual incident radiation on the solar collectors;

For the part of the plant only related to the heating service:

- Q_h (kWh)= annual heating energy demand;
- $\eta_e*\eta_c$= annual heating emission efficiency * annual heating control efficiency;
- Q_e (kWh)= $Q_h/(\eta_e*\eta_c)$= annual heating energy introduced in the building from the emission subsystem;
- Q_{drec} (kWh)= annual recovered distribution losses;

For the common part of the plant:

- η_d= annual overall efficiency of the distribution subsystem;
- $Q_{s\text{-}out}$ (kWh)= $(Q_e+Q_{drec}+Q_{gdhw})/\eta_d$= annual energy provided by the storage;
- η_s= annual storage efficiency;
- $Q_{s\text{-}in}$ (kWh)= $(Q_{s\text{-}out})/\eta_d$= annual energy introduced in the storage;
- η_g= annual overall efficiency of the generation subsystem;
- EP (kWh)= Q_g/η_g= annual primary energy introduced in the generation;

PERFORMANCE INDICATORS AND THEIR RELATIONSHIPS/RATIOS IN THE HYDRAULIC SCHEMES B16-B17[14]

For the part of the plant only related to the production of the DHW:

- Q_{dhw} (kWh)= annual DHW energy demand;

For the part of the plant only related to the heating service:

- Q_h (kWh)= annual heating energy demand;
- $\eta_e*\eta_c$= annual heating emission efficiency * annual heating control efficiency;
- Q_e (kWh)= $Q_h/(\eta_e*\eta_c)$= annual heating energy introduced in the building from the emission subsystem;
- Q_{drec} (kWh)= annual recovered distribution losses;
- η_d= annual heating distribution efficiency;
- $Q_{s\text{-}out}$ (kWh)= $(Q_e+Q_{drec})/\eta_d$= annual heating energy provided by the storage;

For the common part of the plant:

- η_s= annual storage efficiency;
- $Q_{ssol\text{-}in}$ (kWh)= $(Q_{s\text{-}out}+Q_{dhw})/\eta_s-Q_{s\text{-}in}$= annual solar energy introduced in the DHW storage, i.e. annual DHW+ heating energy demand covered by the solar collectors (with η_s =1);
- η_{dsol}= annual solar distribution efficiency;
- Q_{sol} (kWh)= $Q_{ssol\text{-}in}/\eta_{dsol}$= annual energy provided by the solar collectors;
- η_{gsol}= annual solar generation efficiency;

[14] See note 10

- Q_{rad} (kWh)= Q_{sol}/η_{gsol}= annual incident radiation on the solar collectors;
- $Q_{s\text{-}in}$ (kWh)= $(Q_{s\text{-}out})/\eta_d$= annual energy introduced in the storage from the generation, i.e. annual DHW+ heating energy demand covered by the generation (with η_s =1);
- η_g= annual overall efficiency of the generation subsystem;
- EP (kWh)= Q_g/η_g= annual primary energy introduced in the generation;

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