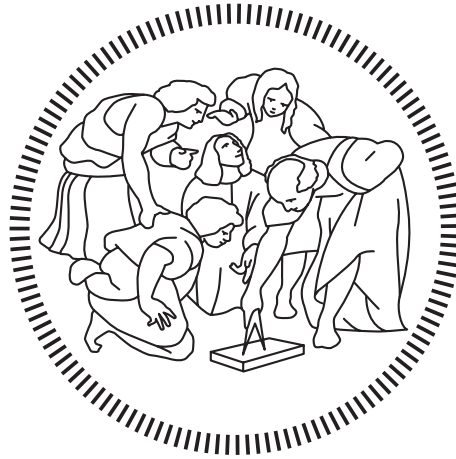


Politecnico di Milano

SCUOLA DI INGEGNERIA INDUSTRIALE E DELL'INFORMAZIONE

Master of Science – Automation and Control Engineering



**Implementation of Moist Air in Large Air Volumes
Simulations for Energy-Related Efficiency in
Buildings**

Supervisor:

Prof. Alberto Leva

Co-Supervisor

Eng. Ettore Zanetti

Candidate:

Edoardo Sozzi 926480

Academic Year 2019/2020

Ringraziamenti

In primis desidero ringraziare il Prof. Leva per l'opportunità e il supporto datomi in questi mesi, ringrazio Ettore per la sua pazienza e per gli spunti frequenti che mi hanno permesso di superare gli ostacoli affrontati.

Ringrazio la mia famiglia che mi ha sempre sostenuto in questi anni: in particolare i miei genitori, onnipresenti (non servono altre parole) Matilde 'sorella' di una vita, Viola e tutti gli zii, la nonna Rosa, fonte inesauribile di saggezza e.... cibo.

Ringrazio i miei più cari amici di Bettola: Nicolò, Andrea e Carlotta che non mi hanno mai lasciato solo e sono sempre pronti a sorreggermi nei momenti di difficoltà.

Un grazie al mio compagno di 'avventure' Lorenzo e a tutti gli amici del gruppo di studio 'Flaming Dragons', nato in questi anni di vita universitaria, con i quali ho un rapporto speciale.

Un ultimo pensiero va anche alle persone che non ci sono più e che hanno contribuito nel farmi diventare la persona che sono ora. Sicuramente mi stanno guardando e sono orgogliose di me.

Edo

Sommario

Negli ultimi anni è stato in gran parte dimostrato che il consumo globale energetico è largamente dovuto all'utilizzo di energia degli edifici e degli agglomerati urbani. È stato osservato più precisamente che il dispendio energetico maggiore è causato dagli impianti di condizionamento e riscaldamento degli edifici (HVAC). I due principali modi per ridurre al minimo i suddetti consumi sono l'utilizzo di tecniche di costruzione sempre più all'avanguardia, impiegando materiali sempre più efficienti dal punto di vista energetico, e l'adozione di sistemi di controllo innovativi per la gestione energetica.

In questo lavoro mi sono occupato di esporre una completa revisione dei principali software e paradigmi modellistici che siano in grado di supportare il difficile problema della progettazione di edifici (o raggruppamenti di essi) ad alta efficienza energetica. La progettazione di questi ultimi è ampiamente limitata dalla complessità degli stessi, intesi come sistemi, le cui performance sono determinate dall'interazione dei vari sottosistemi di cui sono composti. Negli ultimi 50 anni sono stati prodotti innumerevoli software in aiuto della simulazione delle performance energetiche degli edifici. Negli ultimi anni in particolare sono state implementate tecniche molto utili in questo ambito, note come Object-Oriented Modeling and Simulation (OOMS), sono basate sul concetto di equazioni anziché di algoritmi. Tale approccio risulta agevole e riesce a risolvere molte difficoltà di modellazione.

In questa tesi, tramite l'approccio modellistico Object Oriented del linguaggio **Mod-**

elica si è attuato un processo di 'restauro' e di ampliamento di una precedente libreria atta alla modellazione di ampi volumi d'aria all'interno di edifici. L'obiettivo è quello di ricreare una situazione di modello il più vicina possibile alla realtà al fine di arrivare a simulazioni sempre più veritiere e introdurre maggiori gradi di complessità. Successivamente le idee presentate sono state supportate da alcune applicazioni e simulazioni che mettono in pratica le tecniche proposte.

Parole chiave: Modelica, Comportamento termico degli edifici, Heating, Ventilation, and Air Conditioning (HVAC), Object Oriented Modeling (OOM), Efficienza energetica, Modellazione di ampi volumi d'aria

Abstract

In recent years it has been largely demonstrated that global energy consumption is largely due to the energy use of buildings and urban agglomerations. More precisely, it has been observed that the greatest energy expenditure is caused by the Heating, Ventilation and Air Conditioning of buildings (HVAC). The two main ways to minimize the mentioned consumption are the use of advanced construction techniques, using increasingly energy-efficient materials, and the adoption of innovative control systems for energy management.

In this work one has dealt with a complete review of the main software and modeling paradigms that are able to support the difficult problem of designing buildings (or groups of them) with high energy efficiency. The design of the latter is largely limited by the complexity of the same, viewed as systems, whose performances are determined by the interaction of the various subsystems of which they are composed. In the last 50 years, countless software programs have been produced to help simulate the energy performance of buildings. In the last few years in particular, very useful techniques have been implemented in this area, known as Object-Oriented Modeling and Simulation (OOMS), based on the concept of equations rather than algorithms. This approach is easy and manages to solve many modeling difficulties.

In this thesis, through the Object Oriented modeling approach of the **Modelica** language, a process of 'restoration' and expansion of a previous library for the modeling of large volumes of air inside buildings is carried out. The goal is to recreate

a model situation as close as possible to reality in order to reach increasingly truthful simulations and introduce greater degrees of complexity. Subsequently the ideas presented were supported by some applications and simulations that put the proposed techniques into practice.

Keywords: Modelica, Thermal behavior of buildings, HVAC, OOMS, Energy efficiency, Modeling of large volumes of air

Contents

Acknowledgements	iii
Sommario	v
Abstract	vii
Contents	xi
List of Figures	xiv
List of Tables	xv
1 Introduction	1
1.1 The European situation	2
1.2 New technologies for efficient energy use	5
1.3 Modeling & simulation	6
1.3.1 CFD Modelica	7
2 Building energy simulation software overview	9
2.1 State of the art	10
2.1.1 Overview of the present tools	12
2.1.2 Early design stage software	22
2.1.3 Summary	22
3 Modelling Approach	25

3.1	Object-Oriented modeling	27
3.1.1	Classes and Models	28
3.1.2	Inheritance	29
3.1.3	Connectors	29
3.1.4	Continuous time system simulation	29
3.1.5	Discrete time system simulation	30
3.2	Supporting the design process	30
3.3	Modeling principles	32
3.4	Multi-domain heterogeneous models	33
3.4.1	Multi domain capabilities	33
3.4.2	Lumped or zero-dimensional models	33
3.4.3	Discrete time systems	34
3.4.4	Scalable level of detail	34
4	CFD Modelica library	37
4.1	State of the art	38
4.2	Description of the model	41
4.2.1	Generic form of the governing equations	43
4.2.2	Turbulence model	44
4.2.3	Near-wall treatment	46
4.3	Implementation in Modelica	48
4.3.1	The grid	48
4.3.2	Domain Boundaries	50
4.3.3	Preservation equations	51
4.3.4	Turbulence Model	58
4.3.5	Interfaces	58
4.3.6	3D implementation	64

4.4 Simulations and results	66
5 Conclusion	71
Acronyms	73
Bibliography	75

List of Figures

Figure 1.1	End use wise energy consumption in (a) residential and (b) commercial, buildings.	2
Figure 1.2	Energy consumption of residential for space heating per m ² (normal climate)	4
Figure 2.1	System architecture of a model with Modelica.	12
Figure 2.2	DesignBuilder Example of Internal CFD Analysis Output	14
Figure 2.3	User Interface of IES-VE Software	15
Figure 2.4	UI of a Case Study using eQuest	18
Figure 2.5	Potential energy savings/losses in a typical residential as estimated by GBS	19
Figure 2.6	RIUSKA's simulation results for energy consumption in a typical residential	21
Figure 2.7	Comparison of ten different BPS tools that can account for NZEB in the early design stages.	23
Figure 3.1	The V-cycle design process.	31
Figure 4.1	(Left) non uniform structured grid – (Right) staggered grid for the discretisation of the NS equations	48

Figure 4.3	Grid with dimensions and notations. The grey volume is the CV in which the continuity equation has been integrated. Arrows indicate the positive directions of the mass flows.	53
Figure 4.4	Grid for the discretised of x-momentum. In grey the CV for discretising the x-momentum, with other colors the surrounding P-cells.	56
Figure 4.5	Grid for the discretised of y-momentum. In grey the CV for discretising the y-momentum, with other colors the surrounding P-cells.	57
Figure 4.6	Example of interaction between different models through connectors: a pipe fed with hot water heating the interior of the room.	60
Figure 4.7	The three configurations that boundary connectors can assume: left unconnected (top), the thermal one is connected (centre), and the fluid one is connected (bottom).	61
Figure 4.8	Notation used for the faces of the volumes (left), and their numbering convention (right).	64
Figure 4.9	Different zones and their numbering.	65
Figure 4.10	Analysis of the room considered, the six squares correspond to the walls of the room and the source and sink nodes simulate the air recycling behavior of a fan coil, the 3D white cube is the airflow model.	67
Figure 4.11	Temperature sensor in three different positions of the room with MoistAir as inlet	68
Figure 4.12	Temperature sensor in the center of the room with DryAir as inlet	69

List of Tables

Table 4.1	The terms in the generic form of the Convective-Diffusive unsteady equation	44
Table 4.2	Set of variables on the domain boundaries	50
Table 4.3	Boundary conditions for temperatures	50
Table 4.4	Variables contained within the Modelica interfaces: Heat connectors	59
Table 4.5	Variables contained within the Modelica interfaces: Fluid connectors	59

Chapter 1

Introduction

The overall world's energy consumption is largely due to the consumption of buildings, whether they are single or multi-family residences, commercial units, shops, offices or restaurants, etc. Driven by the rising population, expanding economy and a demand for improved quality of life, this expenditure has increased and the growth rates are expected to continue, fuelling the energy demand further. The expected increase in energy demand, along with the predominance of coal in the energy mix, highlights the significance of promoting energy efficiency. Higher rate of urbanization with increased floor space for both residential and commercial purposes has imposed enormous pressure on the existing sources of energy.

Considering the limited availability of energy resources and the highly transient nature of renewable ones, the importance of energy conservation and of buildings energy efficiency studies is evident. Consumption of electricity has increased in the commercial sector in the past ten years. In commercial buildings, the annual energy consumption per square meter of the floor area is in excess of 200 kW h with air-conditioning and lighting serving as the two most energy consuming end-use applications within a building. A classification by use of the various consumptions within a residential or commercial building is shown in [fig.1.1]. Growth in buildings

sector energy consumption is fueled primarily by the growth in population, households, and commercial floor space, which are expected to increase by 28% within 2035 [1].

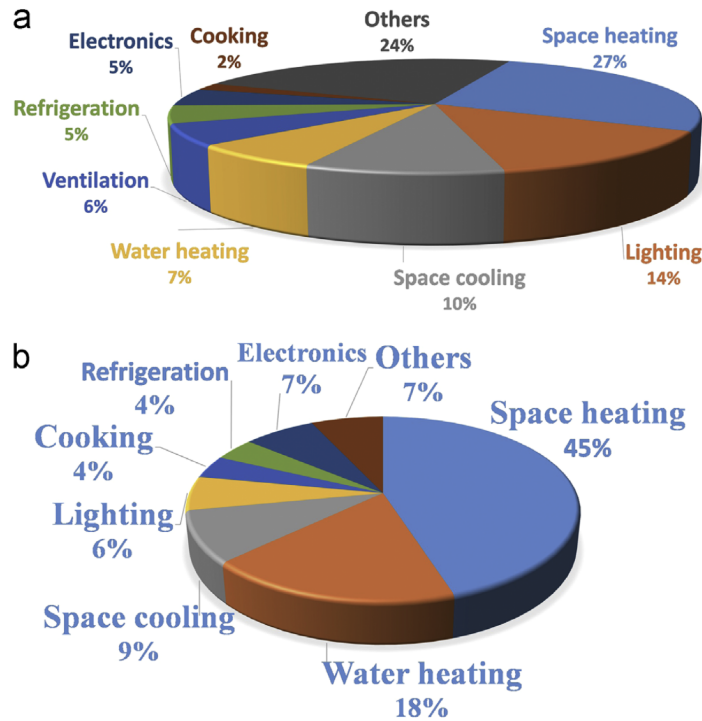


Figure 1.1. End use wise energy consumption in (a) residential and (b) commercial, buildings.

1.1 The European situation

In Europe it can be observed that buildings are responsible for 40% of the total energy consumption and 36% of EU CO₂ emissions. Today around 75% of the EU building stock is energy inefficient. This means that much of the energy used is wasted. This waste of energy can be minimized by upgrading existing buildings and looking for smart solutions and energy efficient materials when building new homes. The refurbishment of existing buildings could reduce the EU's total energy consumption by around 5-6% and carbon dioxide emissions by around 5%. However, on average, less than 1% of the national housing stock is refurbished every year. (Member States'

percentages range from 0.4% to 1.2%.) To achieve our climate and energy targets, restructuring rates should at least double [2].

The EU recently introduced ambitious new policies to help Member States improve energy efficiency in buildings. Knowing that costs are often the main obstacle to renovation, the new rules also facilitate access to finance to upgrade the building stock.

The Energy Performance of Buildings Directive 2010/31 / EU and the Energy Efficiency Directive 2012/27 / EU were revised in 2018, as part of the "Clean Energy for All Europeans" package, with the aim of reflecting better the EU goal of leading the transition to clean energy.

The most important elements of the directives include:

- strengthened long-term restructuring strategies for EU countries
- nearly zero energy buildings
- energy performance certificates
- consideration for health and well-being (air pollution), e-mobility (electric charging points) and smart technologies (smart meters, self-regulating equipment) in new buildings

By 10 March 2020, EU countries must transpose the new and revised provisions of the Energy Performance of Buildings Directive into national legislation. In addition, each EU country must present its own strategy to address the energy consumption problem of buildings for the period 2021-2030 through the integrated national energy and climate plans. The cumulative impact of these efforts at the national level will contribute to the overall goal of achieving an energy efficiency target of 32.5% for the EU by 2030.

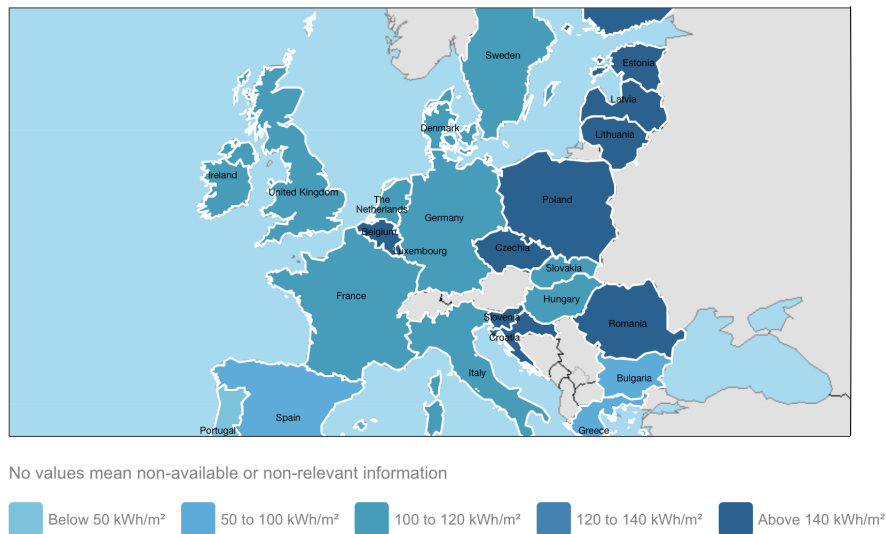


Figure 1.2. Energy consumption of residential for space heating per m² (normal climate)

Since the international climate summit COP21 successfully held in Paris in 2015, extensive commitments have been made regarding energy efficiency and carbon emissions. At the European level, the Energy Efficiency Directive (EED) and the European Performance of Buildings Directive (EPBD) have revised in November 2016 their energy efficiency target in 2030 of 30% of reduction compared to 2007 reference instead of 27%. The main way to reach this goal, according to these directives, is to improve energy efficiency in the building sector, which accounts for 40% of final energy consumption in EU countries [3].

One of the tools made available to track the characteristics and energy performance of buildings in the EU is the Building Stock Observatory. It monitors and evaluates improvements in energy efficiency in buildings. The results are analyzed and entered into a database, a map representing the data [(fig.1.2)] and information sheets.

1.2 New technologies for efficient energy use

Investments in technological research and building development can drastically reduce the problem of energy waste. The main actions that can make a contribution in this regard are described below [4]. First of all, it is immediate to recognize how highly efficient electrical equipment and appliances can lead to a reduction in costs and energy consumption. The most efficient appliances require a factor of two to five less energy than the least efficient appliances available today. The thermal envelope, i.e. the ability of a building to avoid heat or mass exchanges between its external and internal conditions. Its effectiveness depends on various elements, such as the thermal properties of doors and windows, the levels of insulation of the facades and the rate of exchange of internal and external air [5–7]. Cooling energy can be reduced in several ways, such as finding the best building orientation, using high-reflectivity materials or providing fixed or adjustable shading. Without going into details, it is evident that lighting and water heating also play a fundamental role, and they too can be optimized.

But how is it possible to manage all these electrical subsystems inside buildings? BEMSs (Building energy management systems) are control systems that use microprocessors for monitoring, data storage and communication. They communicate via telephone or internet network with a remote manager who manages consumption and avoids wasting energy.

1.3 Modeling & simulation

At this point it is immediate how a good home energy assessment is the first step to follow to determine how much energy is consumed. An assessment will show problems that may, when corrected, save a significant amounts of money over time. Energy assessments also determine the efficiency of the heating and cooling systems. This type of assessment can be implemented directly on the building itself or through the simulation of models that somehow represent my entire structure and my HVAC systems within it. Obviously, the latter mode is the only one available when the building is not present and is under development. All the aspects and components that are part of the building are important, and thus have to be included in a overall model, in order to have a reasonable idea of the overall energy consumption and the possible solution to be taken in order to reduce it. The building design process can be complicated in many ways. Every small limit imposed can cause small defects and their sum can result in a big impact on the final product. In this regard that the use of modeling and simulation techniques can help us.

Simulation and modeling softwares thus play a fundamental role in the energy efficiency of buildings. Unfortunately most softwares have lacks in modularity, since they have been designed before this requirement becomes one of the main issue. The introduction of Object Oriented (OO) modeling languages provides numerous advantages in simulation. These techniques (Object-Oriented modeling, using a language named Modelica [8,9]) have already been adopted in some building efficiency applications [10].

1.3.1 CFD Modelica

One of these applications is the development of a library (**CFD Modelica** [11]) which aims to try to cover the main lacks of the actual energy building performance simulation tools. In this library the models have been developed following a structural approach, in this way each model has been assigned to a particular physical element, and so connections between models are similar to physical interactions that occur in the reality. Through this type of approach, the library consists of the definition of the various physical elements and their possible interactions, the determination of the various scalable levels of precision with which the elements themselves are to be described and, above all, the sets of equations which aims at describing the behavior of the physical component, starting from first principle (e.g. mass, energy and momentum balance equations), reducing the number of empirical correlation as well non physical parameters. The objective of this thesis work is to implement an expansion of the library, in particular, the package of models of the various substances already present in the CFD modelica has been expanded by adding moist air. In this way the simulations can reach ever higher levels of accuracy and complexity. Indeed, it is well known that relative humidity inside buildings is of particular importance as regards the comfort of the occupants. Poor comfort conditions can result in a loss of productivity for the occupants [12, 13]. If the surroundings are very humid (high RH), little moisture is able to evaporate to the surrounding air, resulting in less cooling of the body. In high humidity conditions people often feel hotter than the actual temperature would suggest, due to this lack of cooling. Also, the presence of excess moisture on the skin can result in the skin feeling wet and increased friction between skin and clothing, all things that add to the occupant's discomfort. The opposite happens in a space with low humidity levels, where too much moisture is

removed from the body. This leaves the occupant with dry skin and mucous surfaces (inside the nose, mouth and eyes). CEN EN 15251 [14] recommends that the relative humidity be kept between 25% RH and 60% RH for new buildings. ISO Standard 7730 [15] suggests the indoor RH should be between 30% RH and 70% RH

In the next chapter an overview of the main energy simulation software currently used in the development of high efficiency buildings will be shown, describing their main features characteristics.

Chapter 2

Building energy simulation software overview

In the early stages of a building design, carrying out real tests can be unlikely and difficult for various reasons (the building is not yet present or the test costs are too high). For such reasons, computer based simulation are more than an opportunity, replacing physical measurements for many problems. Over the past 50 years, the building energy community has developed numerous software for energy simulation. This chapter first of all reserves the right to propose a state of the art in the field of the aforementioned software, then the main tools currently used are listed and finally it will be briefly exposed how an Object Oriented language such as Modelica can be an excellent alternative.

2.1 State of the art

Energy simulation software tools are an important support used for building designers to reduce the cost of energy in buildings. The energy simulation software allow to determinate with accuracy some variables that can support designers to take decisions about the best measures to apply for any building in development or already existent. There are several energy simulation software tools in the market.

About one third of the energy consumption in buildings is used to increase thermal conditions of the dwellings and for lighting. Thermal simulation software tools for buildings allow to:

- Determine the appropriate size of HVAC systems;
- Analyze the energy consumption;
- Calculate the cost of the energy used.

The development of ES software started in the late 60s. At present specialists guess if the tools available today will be able to face in an appropriate way the challenges rising in the ES of buildings.

An excellent work that allowed to show the scenario of the ES software is reported in [16]. The ideas explained in this work, and based on two important workshops organized respectively the 1995 and 1996 by the US Departments of Energy and Defense, allowed the development of one of the major projects, EnergyPlus [17].

In the following years, an excellent summary of the scenario was represented by these sentences that have had a wide consensus in the community of this field [18]: “The existing simulators were too rigid in their structure to be able to accommodate the improvements and exibility that would be called for in the future. Each added feature required a larger implementation effort than the previous one.” and “A promising technology for the future were the general simulation methods offered by equation-

based methods using program-neutral model descriptions and domain-independent solution methods". The author of these sentences himself fed in [19] the idea that these software could be replaced by equation-based tools, leading to a true whole building simulation tool. Equation-based approaches originate from the OO modeling languages, their first generation (ObjectMath [20, 21], Dymola [22], Omola [23], NMF [24], gPROMS [25], Allan [26], Smile [27], MOSES [28] etc.) were developed in the 90's in the fields of robotics, vehicles, thermal power plants, nuclear power plants, airplane simulation, real-time simulation of gear boxes, etc. Although they proved to be very useful tools, the great variety of languages was not totally satisfying for the community, so in the fall of 1996 a group of researchers from universities and industry started work towards standardization and making this object-oriented modeling technology widely available. Thus was born the Modelica language, designed for modeling dynamic behavior of engineering systems, intended to become a de facto standard [68]. To date Modelica is not yet a standard, but it is being developed by numerous scientific communities. Just think, for example, of three European projects that invested 54 million Euros for 370 person years to further develop the Modelica language, Modelica tools, Modelica libraries and related technologies [29].

The main difference between Modelica and the rest of the other building simulation programs (DOE-2, TRNSYS, EnergyPlus, ESP-r) is that modelica is an open language, and not a specific computer software: Modelica is a high-level declarative language that specifies the physical laws or the control logic. Equations in this language are typically encapsulated into models that are then used to schematically define the system architecture [fig.2.1].

Another key aspect of the Modelica is that it can be used in different engineering fields, as well as the analysis of the interaction of such fields and different natures systems. This is a demonstration of how several of the major car manufacturers have

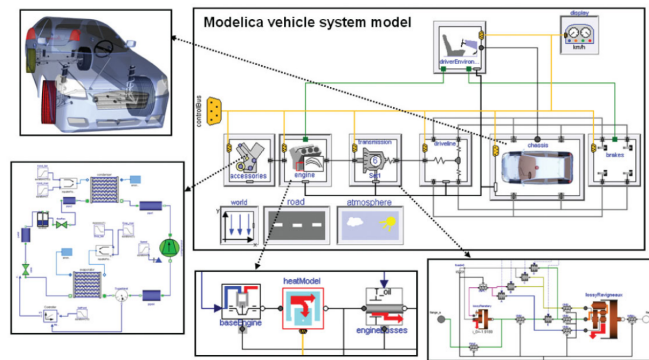


Figure 2.1. System architecture of a model with Modelica.

decided to invest in this language after encountering many limitations with other software [30].

In order to compare present industry-standard tools with an equation based one, M. Wetter in performed a comparison between TRNSYS [31] and the preliminary version of the Modelica Buildings library [32]. The work evidences that the time spent in the model development phase using Modelica is five to tenfold less with respect to TRNSYS.

The challenges of the future Energy Simulation (ES) tools as well any simulation development project include: tool interoperability (especially regarding CAD and product modeling tools), Internet, object-oriented programming, modularity and graphical user interface (GUI) technology.

2.1.1 Overview of the present tools

In order to achieve these energy goals, building information molding (Building Information Molding (BIM)) can be used in planning, designing, implementing, and managing green building projects. BIM is totally different from Computer Aided Manufacturing (Computer Aided Manufacturing (CAD)) programs which refer to how a building looks while the first deals with how a building works. Moreover, BIM

provides detailed information on the building infrastructure and on its individual components (e.g., floors, doors, windows, walls, and internal energy systems). This intelligent model produced by BIM gives full flexibility to building designers and architects to make the necessary adjustments to their designs, in order to achieve the most efficient models for the building [33,34]. As part of BIM, numerous building energy modeling software helps in designing efficient energy systems.

In this section an overview of the main software will be made underlining the features and capabilities of some major building energy simulation programs.

DesignBuilder

DesignBuilder is a simulation software used for modeling energy consumption in virtual buildings. The main features of DesignBuilder lie in its user-friendly interface and the wide range of performance data it can provide such as annual energy consumption, properties of “heating, ventilation, and air-conditioning (HVAC)” components, besides the variations of temperatures throughout the year [35]. DesignBuilder focuses on four types of energy simulations: (1) simulation of cooling systems, (2) simulation of heating systems, (3) simulation of real weather data, and (4) Simulation of energy performance indicator. The purpose of cooling and heating simulations is to determine the properties/sizes of the cooling/heating components appropriate for the building spaces. The application calculates heating capacities required to maintain the desirable temperatures in each area of the building and displays the heat loss in various parts of the building such as walls, floors, partitions, roofs glazing, external infiltration, and internal ventilation. In the building zones, where mechanical cooling systems are not planned to be installed, the natural effects can be selected on the zone HVAC tab in the application. In fig.2.2 is depicted an example for internal Fluid Dynamics Analysis in order to set a determined comfort for a specific room occupants.

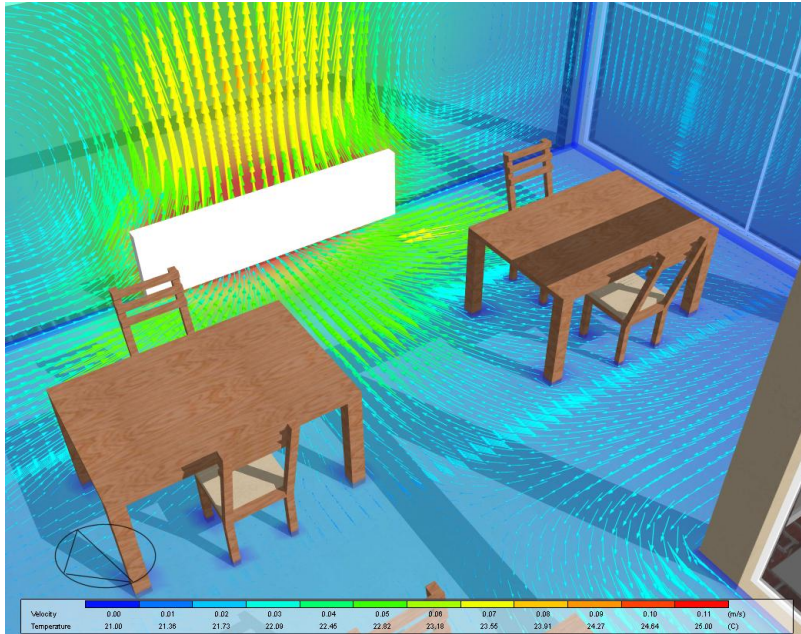


Figure 2.2. DesignBuilder Example of Internal CFD Analysis Output

IDA-ICE

IDA-ICE (Indoor Climate and Energy) is a multi-zone energy modeling application specialized in accurate calculations of indoor climate of individual zones, besides calculating the total energy in the whole building. Physical systems from several domains are in IDA described using symbolic equations, stated in either or both of the simulation languages Neutral Model Format (NMF) or Modelica. There are three user levels in IDA-ICE: standard, wizard, and advanced. The main features of this modeling application include fast processing of energy simulations and reporting in all types of building designs, besides providing simplified design algorithms for less experienced users. IDA-ICE includes 3D design environment, where 3D animated objects can be displayed, including 3D solar and shading graphics. Also, it is possible to display the 3D overview of the building during all steps of project design via providing high-quality animated views [36].

IES-VE

IES-VE (Integrated Environmental Solutions-Virtual Environment) is a modeling software used for simulating energy consumption in a virtual environment. It contains a set of integrated applications under a Common User Interface (CUI), with a centralized Integrated Data Model (IDM), and hence, the data input for one application can be automatically used by the other applications.

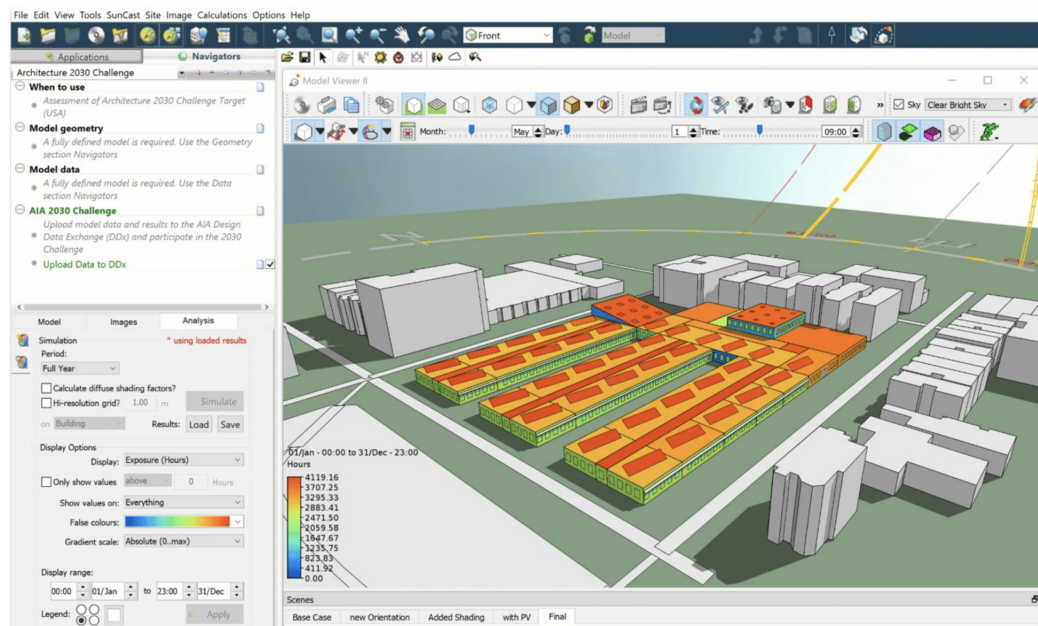


Figure 2.3. User Interface of IES-VE Software

IES-VE contains various modules that cover various aspects of energy consumption in the building, such as “SunCast” for solar shading designs and analysis, “Radiance” for lighting simulation, “ApacheSim” for thermal simulation, and “ModelIT” used to import the 3D geometry of the building from other CAD programs. The main key features of IES-VE application include (1) schematic geometry wizard which provides simplified approach to building geometry and its design parameters, (2) solar algorithm, which enables tracking the sun path through contiguous and noncontiguous zones of the building, and (3) HVAC systems wizard, which enables streamlining HVAC systems in five easy steps, or less.

EnergyPlus

EnergyPlus is a modular, structured code based on the most popular features and capabilities of BLAST and DOE-2.1E. It is a simulation engine with input and output of text files. By adopting integrated and modular algorithms, EnergyPlus provides accurate estimations of temperatures in various zones of the building, which results in better calculations of assorted design parameters of the energy models, such as its optimized thermal settings [37, 38]. The main noticeable features of EnergyPlus include (1) concurrent and integrated solutions of thermal zone characteristics; (2) solutions for heat balance conditions, such as convective and radiant objects that produce settings for surface temperatures, humidity, and condensation; (3) solutions for glare and illuminance to be used in providing visual comfort; (4) models for heat balances that calculate solar energy absorbed by window panes and models for controllable window blinds and electrochromic glazing; (5) wide range of built-in lighting and HVAC control strategies; (6) summarized and comprehensive simulation reports, as well as user- customized reports with wide range of options including time resolution from sub-hourly to annual energy calculations; (7) Functional Mockup Interface for co-simulation with other energy modeling applications, such as SPARK, TRNSYS, and COMIS.

TRNSYS

TRNSYS (TRaNsient SYstems Simulation) is a transient system simulation program with a modular structure that implements a component-based approach. TRNSYS components may be as simple as a pump or pipe, or as complex as a multi-zone building model. The components are configured and assembled using a fully integrated visual interface known as the TRNSYS Simulation Studio, while building input data is entered through a dedicated visual interface (TRN-Build). For example, the solar

collector is represented by certain configuration data such as collector array area, number of collectors connected in series, total energy gain, and maximum outlet temperature. TRNSYS contains a wide range of standard component models, which give users full flexibility in selecting the most appropriate design models, especially at the early planning stages of the project, when full building details are unknown. These presumed models can be easily replaced with more realistic models, as soon as extra details are available. For instance, in the early stage of planning process, the total heating energy could be known, but the heating components may not be selected yet. Therefore, simple heating components can be used at this stage, and then they can be replaced later with more detailed heating components, once all the details are known. Moreover, TRNSYS is capable of providing detailed models and simulations for all time-dependent energy systems, such as solar energy systems, photovoltaic systems, low energy-consuming systems, HVAC systems, and renewable energy systems [39].

eQUEST

eQUEST is a easy to use building energy use analysis tool which provides high quality results by combining a building creation wizard, an energy efficiency measure (EEM) wizard and a graphical results display module with an enhanced DOE-2.2-derived building energy use simulation program. eQUEST energy simulations are performed on an hourly basis, taking into consideration all the physical characteristics of the building including walls, floors, ceilings, glass, ventilation, electrical loads, and the number of residents in the building. The main features of eQUEST include (1) enabling the users to create individual energy simulation models for energy-consuming devices, such as air conditioners, fans, boilers, and pumps, (2) creating multiple and simultaneous energy simulations for different zones of the building, (3) monitoring the various simulation results in side-by-side graphs, (4) offering estimations for the

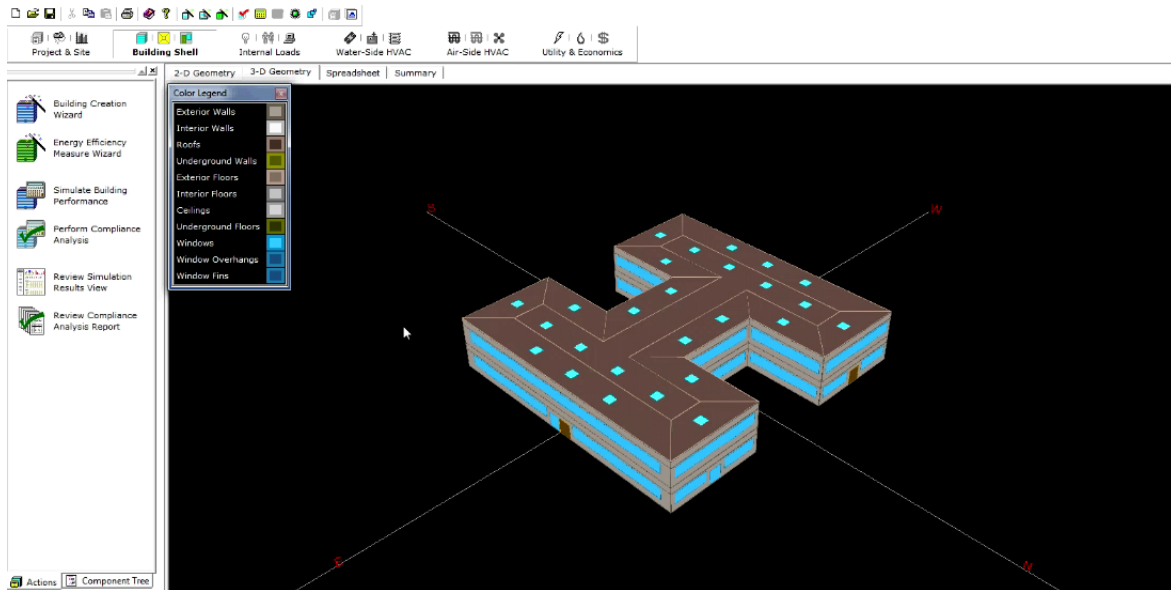


Figure 2.4. UI of a Case Study using eQuest

energy consumption and automatic implementation of energy efficiency measures, and (5) containing daylighting control system and dynamic model for estimating the effect of sunlight on the energy consumption [40,41].

Autodesk Green Building Studio

Autodesk Green Building Studio® is an energy modeling cloud-based application that optimizes the energy consumption efficiency by creating adaptable energy models for the building. Autodesk GBS can also be used as a standalone web service that focuses on reducing the dependency on fossil fuel at the early stages of the building design, and on creating high-quality energy models in shorter time and lower costs, compared with other applications.

The main features of Autodesk GBS include (1) detailed “analytical energy models” created from architectural models and thermal characteristics of the building elements, (2) whole building energy analysis, which takes into account all of a building’s energy-consuming elements, (3) at the early stage of design process, Autodesk GBS adds default values and assumptions for the design parameters, based on the type

and location of the building, in order to complete the energy analytical model, (4) predictive analytical simulation and reporting, created by automatic testing of a variety of building characteristics, and providing straightforward guidance on the variations that will have the greatest impact on energy consumption, (5) weather data applicable to new and existing buildings, by providing access to a large number of virtual weather stations [42, 43].

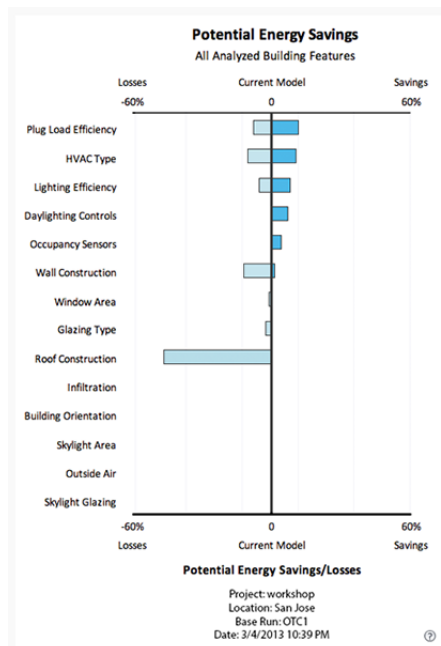


Figure 2.5. Potential energy savings/losses in a typical residential as estimated by GBS

Ecotect

Autodesk Ecotect is an environmental energy BIM modeling application, which is mainly used for designing lighting systems and analyzing thermal loads, while taking into account the effect of shadows, reflections, and solar radiation [44, 45]. This includes visualization of volumetric and spatial analysis results, including imported 3D CFD data. Real-time animation features are provided along with interactive acoustic and solar ray tracing that updates in real time with changes to building geometry and material properties. The main features of Ecotect include (1) solar energy modeling

and analysis by quantifying the distribution of solar radiation throughout the day, and displaying the results in 3D graphs, as shown in Fig. 18; (2) calculation of the whole building energy consumption and cost on annual, monthly, daily, and hourly basis, using a global database of weather information, besides its ability to customize the graphical representation of the results; (3) calculation of thermal loads of the building, taking into account the internal loads, solar radiation, and infiltration, besides the effect of occupancy and building surroundings; (4) visualization of weather data that comes from Autodesk Climate Server, which contains over a million virtual weather stations; (5) daylighting and electric lighting analysis, which allows users to input the location of the building, time zone, and the preferred sky model. Hence, the simulation results are visualized through comprehensive 3D graphs [44, 46, 47].

RIUSKA

RIUSKA is an energy modeling application, based on importing geometrical data of the building through “Industry Foundation Classes (IFC)” file format. Additional information is required to run the simulation process such as construction types, geographical location, properties of HVAC components, and allocation of building spaces into thermal zones. The core of RIUSKA is based on DOE 2.1E simulation program, and it can be used to perform the following tasks: (1) calculation of temperatures in all zones of the building throughout the whole year; (2) comparisons of various architectural designs of the individual parts of the building such as windows, window shadings, and façade design solutions; (3) comparisons of indoor climate quality levels [48–50]. In order to provide a model for energy consumption in a building, RIUSKA takes into consideration all the building characteristics such as the building geometry, structures, massiveness, weather conditions, thermal loads, and usage hours of components. It can perform hourly, daily, monthly, and annual

calculations for energy consumption in various spaces of the building. The “Heat Loss” module in RIUSKA is used to estimate the expected heat losses for each zone in the building for a given outdoor temperature. Therefore, the application can be used for calculating the heat distribution throughout the individual parts of the building (e.g., doors, walls, and windows).

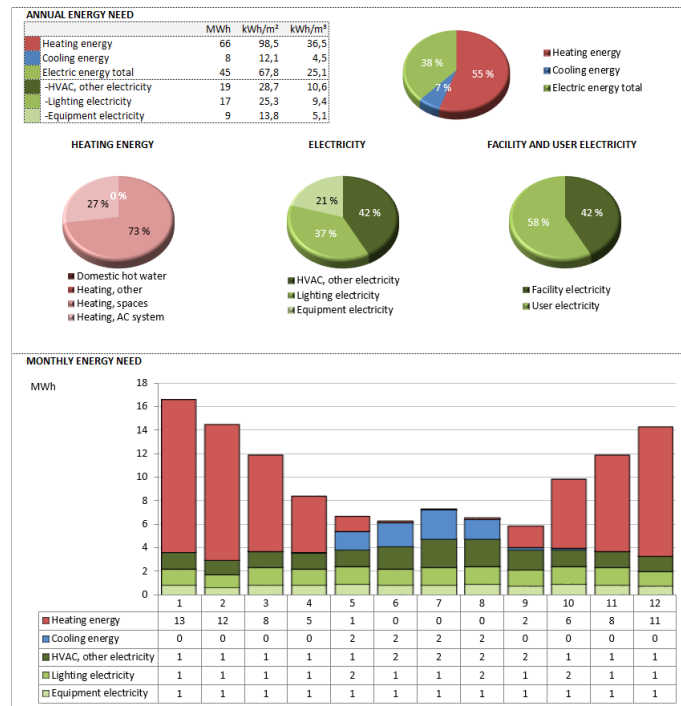


Figure 2.6. RIUSKA’s simulation results for energy consumption in a typical residential

VIP Energy

VIP-Energy is a simulation application used for modeling the energy performance of buildings on hourly basis, for the whole year. Moreover, the “Dynamic Calculation” module in the application enables the repetition of energy calculations every hour. The energy calculations carried out by VIP-Energy take into account various factors, such as solar radiation, humidity, and varying demands of room temperatures. On the other hand, the program is not designed for modeling heating or cooling systems [51]. The internal components of the building affect the calculations in different ways. For

example, internal construction parts (e.g., floors, walls, and ceilings) store/ release thermal energy according to temperature fluctuations, while direct solar energy is stored even if the air temperature is not changing. VIP-Energy creates a model with energy exchange between the interior walls and sidings. The difference in temperature between internal sur- faces results in radiant exchange, proportional to the surface areas of the indoor and exterior walls [52].

2.1.2 Early design stage software

Building Performance Simulation tools are essential instrument in designing Net Zero Energy Buildings (NZEBs). Like some of the software described in the previous section, BPS tools are particularly important during the early design stages, when most of the decision that concern the shape, orientation and location have to be taken in order to provide useful information to designers. In [53] a comparison was made between 10 different tools that are able to support the NZEB during early design stages.

2.1.3 Summary

Nowadays, there are several energy modeling and simulation applications with various levels of complexity and responses to varying operating conditions, and input parameters.

In this paper, we analyzed the performance of ten of the most common energy modeling and simulation applications: DesignBuilder, IDA-ICE, IES-VE, Energy-Plus, TRNSYS, eQUEST, Autodesk Green Building Studio, Ecotect, RIUSKA, and VIP-Energy. Based on thorough analytical comparisons of these applications, we concluded that TRNSYS is the most complete application, but depending on the user's perspectives and expectations, the other applications could be more appropriate.

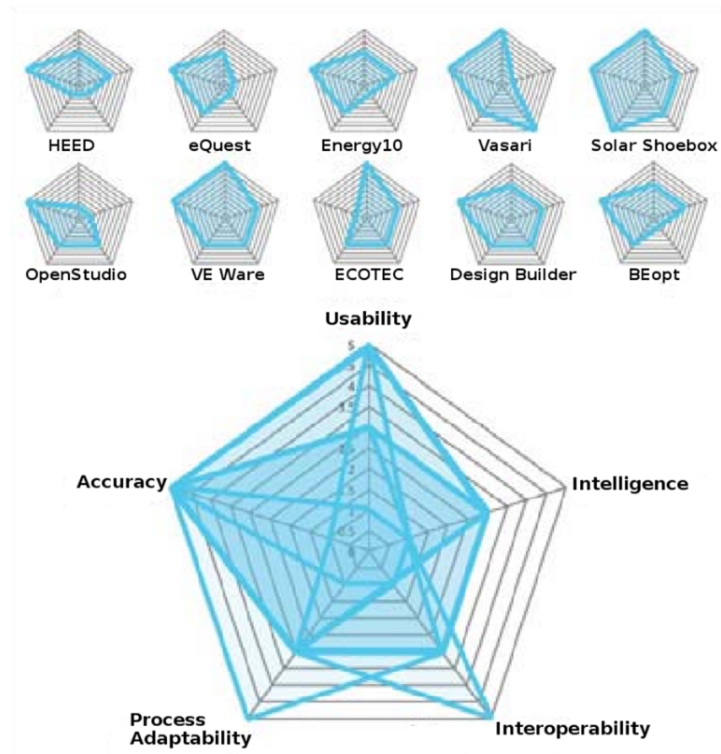


Figure 2.7. Comparison of ten different BPS tools that can account for NZEB in the early design stages.

The next chapter will show how equation based modeling techniques can fill the gap, going in the direction of a unified multi-domain simulation tool suited for the assessment of energy performances of buildings.

Chapter 3

Modelling Approach

In recent years, modeling and simulation have increasingly taken hold in the scientific community and have proved to be of fundamental importance in industrial product design and development. Design of mathematical models representing a system in the computer is a method utilized for reducing costs, determining and optimizing the system properties before it will effectively built. In practice, these methods greatly simplify costs, development times and improve the quality of the final product. “An experiment is the process of extracting information from a system by exercising its inputs” (Fritzson, 2004). With the aid of computers, it is possible to build models of the system, interrogate them, and produce experiments using them, this is called simulation. If the model is representative, results can be produced from it as many times as required. Using validated models, the need for a large number of physical experiments on test equipment can be avoided; instead experimentation through models can be used.

The major advantage of modeling is to have a representation that is as faithful as possible to the system you want to represent. In this way, for example, it is possible to investigate its behavior in situations that cannot be tested in reality due to the high quantity of tests to be carried out or even just the time required to carry them

out in reality compared to the help of a computer.

In recent years, the consolidation of an increasingly high computational capacity has led to greater accessibility to model-based design. If some years ago engineers were able to design their systems without massively using softwares (e.g. simply components, data sheets, or sizing formulas usually valid for steady-state operations) today every engineering process is supported by computer-aided-design tools. This has led to a greater demand for these tools and above all has led customers to seek an increasingly high quality of products, with certain characteristics, such as the ability of representing the dynamic behavior of the overall system, reliability, extensibility and ease to maintain. These are the three main issues which model developer has to deal with.

To address all the presented issues a mix of engineering and software skills are necessary. First of all the developer has to know the system to be modeled, the physical assumptions behind it and all the relevant phenomena that occur. Second, if the system is not just a “toy example” the dimension of the model as well the number of components to be considered grows rapidly. The resulting product should be able to adequately represent the overall system without being too complex, easy to test, validate, maintain and if possible re-usable.

What is needed is therefore a conceptual framework, in which the modelling activity concerning the system level can easily integrate the different model types (giving them standard format), while at the same time minimising the effort required to structure the system description and to interface new or existing models of existing objects. The object-oriented approach to modelling is a credible methodology to deal with complex and heterogeneous systems, while computer simulation is the means to use such models in practice for assessing the global system performance.

To conclude, a modern modeling approach requires as many modern paradigms,

where the models are modularly assembled from aggregations of simpler models. Each having a direct correspondence with a physical component or sub-system. In order to describe each component in a natural and physically based way, it is necessary to follow an a-casual approach, where causality is only defined at the global model level, and the burden of doing this is left to simulation tool. Therefore modern modeling languages and simulation tools should be based on object oriented concepts, taking into consideration the reuse of pre-existing models and libraries.

In this chapter we will present the principles of the object oriented language, in particular we will focus on the language used in this work, Modelica, and how to develop models that can support the design of a complex system (in this particular case a building) through the various phases of a project, from early stages to deployment.

3.1 Object-Oriented modeling

Modelica's view is different from that of other OO programming languages such as C++ or Java, since the Modelica language emphasizes structured mathematical modeling. In this context, object-orientation aims at handling the complexity of large system descriptions, through structuring. A Modelica model is simply a mathematical description that simplifies the analysis of a physical system. The declarative concept with which Modelica describes the properties of dynamic systems is inspired by mathematics where it is common to state or declare what holds, rather than giving a detailed stepwise algorithm on how to achieve the desired goal as is required when using procedural languages (eg C or Fortran). There is a clear separation from the definition of the problem (described by a set of equations) and its solution, provided by a suitable algorithm. Object-oriented mathematical modeling, can be summarized as follows:

- Object-orientation is primarily used as a structuring concept, emphasizing the declarative structure and reuse of mathematical models.
- Dynamic model properties are expressed in a declarative way through equations.
- An object is a collection of instance variables and equations that share a set of stored data.
- Object orientation is not viewed as dynamic message passing.

As mentioned earlier, a-causal modeling is a type of declarative modeling, which means that the models are based on equations instead of assignment statements. The major advantage of this method is that the solution of the equations follows the data flow context in which the solution is computed. So the context can be known by assigning the output variables and the external input variables to the simulated system. The a-causality of Modelica models makes these more reusable than traditional classes containing assignment statements where the input-output causality is fixed. Beyond the above mentioned advantages, here follow the main features of Modelica that make easier modeling complex multi-physical systems with it (for more detailed explanations please refers to [54]).

3.1.1 Classes and Models

Modelica, provides the notions of classes and objects, also called instances, as a tool for solving modeling and programming problems. Every object in Modelica has a class that defines its data and behavior. There is a special type of Class that is called Model. The Model contains the definition of variables, parameters and the corresponding equations. Equations are more flexible than assignments since they do not prescribe a certain data flow direction. This is the key to the physical modeling capabilities and increased reuse potential of Modelica models.

3.1.2 Inheritance

One of the major benefits of object-orientation is the ability to extend the behavior and properties of an existing class. The original class, known as the superclass or base class, is extended to create a more specialized version of that class, known as the subclass or derived class. In this process, the behavior and properties of the original class in the form of field declarations, equations, and other contents is reused, or inherited, by the subclass.

3.1.3 Connectors

A Connector is a particular kind of Class that declares variables that are part of the interface of a component (i.e. a model) defined by the connectors of that component. Thus, connectors specify the interface for interaction between a component and its surroundings. Heterogeneous models that represent different physical systems can be connected together if they share the same connector (i.e. they have the same interface). In such a way it is possible to couple electrical models with mechanical ones and so forth. Interfaces are one of the key features of OO modeling.

3.1.4 Continuous time system simulation

Equations contained in the models can be either Ordinary Differential Equations (ODE), Differential Algebraic Equations (DAE) or Algebraic Equations, depending on the modeled system. The analyst does not have to cope with the time discretisation of such equations because all the symbolic manipulations as well as the numerical solution are left to the Modelica tool. Such an approach is a big advantage because the solution of the problem is divided by the problem itself, to the advantage of code re-usability and maintenance.

3.1.5 Discrete time system simulation

As we have mentioned previously physical systems evolve continuously over time, whereas certain man-made systems evolve by discrete steps between states. Modelica supports the simulation of discrete time systems, which time evolution is based on events. These models are useful when modeling control oriented systems or algorithm. When these models (continuous and discrete) are coupled together they result in a so called hybrid system. A typical example is a digital computer interacting with the external physical world. Using Modelica such systems can be modeled straightforwardly.

3.2 Supporting the design process

Formulating a plan that can assist an engineer in creating a product with a specific performance is called engineering design process. This process includes several steps and some parts must be repeated before the start of the production of a certain product. In the figure ?? are evidenced the various phases, starting from the system requirements down to the realization of the product and further stages as the verification and maintenance.

As mentioned above, models are fundamental in the early stages of a design process, in order to design properly the system without wasting time and reducing as much as possible the problems. There are many reasons that make models better than real experiment:

- experiments are too expensive, too dangerous, or the system to be investigated does not yet exist,
- the time scale is not compatible with experimenter,

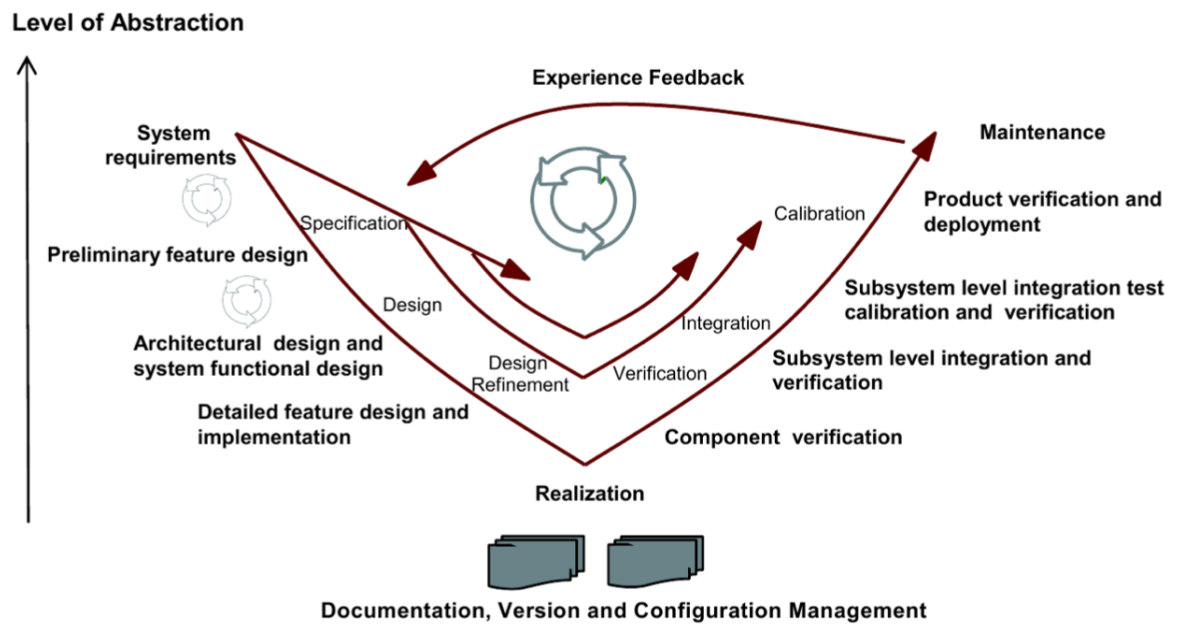


Figure 3.1. The V-cycle design process.

- variables may be inaccessible,
- easy manipulation of the models,
- suppression of disturbances

If the system is very complex and a high level of detail is required, the design process can be lengthy with a duration of the order of years. Each phase of the project must be meticulously completed and if errors are found in the following step, the process must be repeated in order to solve the problems encountered. This means that each step can be performed more than one time, if the requirements are not fulfilled. This strong interaction between the design phases is more proficient if the designers are the same or at least they work with the same methodology.

Unfortunately in the building sector these development methods are not present, in fact in each task different technicians operate and follow through the project: architects sketch up the first guess of the building then engineers design the structure

of the building, the HVAC systems, the lighting and control systems, etc. Many figures work around the design of a building and each one is dedicated to the development of a phase, then passing into the hands of the next figure. Each of these professionals uses their own modeling tool, devoted to model its own part of the system. If a problem occurs and some steps of the design have to be reiterated the specialist has to start almost from scratch.

The OO languages presented and in particular Modelica can be used to overcome these problems, however guidelines have to be defined. These guidelines aim at clarifying how the models belonging to a certain library can be used to follow the entire life of a product. The resulting models should be tunable according to the purpose of the library, the context in which they operate, properly answer to the right questions (and at the right time) and according to the information available at a given time.

3.3 Modeling principles

The basic idea with which this type of modeling is approached is centered on the fact that each model represents a specific physical element, and so connections between models are similar to physical interactions that occur in the reality. Each model has standard connectors and they behave according to the physical quantities specified to the boundaries by the surrounding elements.

The models developed in this way are easily classified and therefore their development is simpler. The result of this are first principle models, i.e. models that involve only basic physical laws (e.g. energy, momentum, and mass conservation). In the library studied in this work there is no need for any model identification and for this each model has a series of parameters that have a strong physical meaning.

3.4 Multi-domain heterogeneous models

As already mentioned, buildings are heterogeneous systems composed of interactions between various elements, therefore energy performance is closely related to these interactions. This means that if a precise forecast of energy values is required, ES softwares have to account for all these phenomena. The characteristics of the modeling language, therefore, are right for us and are described briefly below.

3.4.1 Multi domain capabilities

One of the main advantage of Modelica is the ability to couple together models that belongs to different physical domains. Buildings are typical environments where these types of interactions take place. For example air (a fluid) comes into contact with solid elements and the air conditioning system is fed with a fluid vector (either water or a refrigerant fluid) that is heated / cooled through an HVAC system. The HVAC system operates via pumps or motors that require electrical-mechanical modeling. An other example could be the fuel combustion inside a boiler that feed hot water through the heating system; or the solar radiation that heat the external walls and passes through the windows and is refracted by the interior spaces. All these different phenomena can be modeled separately, and then coupled together with standard connectors. Doing so the model can be maintained, developed and upgraded easily.

3.4.2 Lumped or zero-dimensional models

There are elements that can be described in different ways. The way they are described depends on the application or the impact they have on the overall system. An example are pipes or containment walls. For example, if the temperature gradient through a wall is relevant and it affects the overall performance of the system, it should be

modeled with a 1D multilayer model (describing the material properties of each layer). On the contrary, if it is not the key point of the system (and detailed informations are not available) it can be modeled with a zero dimensional model. Using Modelica these two descriptions can coexist and they can be properly selected, depending on the nature of the system, without complex modification to the structure of the models but just selecting some parameters.

3.4.3 Discrete time systems

As already mentioned, many man-made systems evolve in discrete states, and are supported in Modelica. These systems are essential in the supervision and control of the overall system. A detailed model of the system without a precise representation of its control strategy is useless. Modelica is possible to simulate the system together with its control strategy, thus evaluating the best solution. To mention that in the near future, Modelica models will be straightforwardly converted into algorithms directly deployable on a DCS.

3.4.4 Scalable level of detail

One of the main aspects of Object Oriented modeling thanks to the definition of interfaces is that of being able to adapt the various models to the various stages of development, without having to adopt replacements or start from the sketch. The interfaces remain the same, however the behavior of the model changes. For example in some preliminary analyzes it is enough to sketch out the energy needs using a static model. The dynamics of the model can then be considered. For example, it can be assumed that a boiler supplies hot water based on certain temperatures, without however considering a control system. Using such a simple description the analyst can focus on the other components of the system like the heating elements or the piping

network. Finally, the most suitable control system for the model can be studied and implemented in order to regulate the fuel flow. The a-causal equation based approach is very useful for these kind of studies since one can impose a value for a specific variable (e.g. an output) and see what happen to the other ones (e.g. the inputs), without manually inverting the model.

Chapter 4

CFD Modelica library

In recent years, numerous approaches have been developed - starting from purely empirical up to the CFD ones - to the problem of modeling air flows in order to evaluate the ventilation performance and energy consumption in buildings. Moreover, since the ultimate goal is whole building modeling, airflow simulation needs coupling with Energy Simulation (ES), in order to assess the overall energy performance. Due to the big differences between Airflow modeling and ES software, the only possible way around this problem is co-simulation. For example, in recent years a lot of effort has been spent in to couple ES and CFD tools. This work aims to expand an existing library that offers an alternative, in the form of an innovative approach, for solving the Navier-Stokes (Navier-Stokes (NS)) equations in a general multi-domain modeling framework. This allows to model and simulate the overall building in an unique framework. In particular, an extension of the substance used for modeling was implemented, the simple dry air used previously did not allow specific efficiency from the point of view of relative humidity and moreover, as already mentioned, the behavior of the air mixtures is of fundamental importance in the context of the general comfort of the occupants. Notice that co-simulation is mainly used when fully mixed models are not developed adequately especially in Computational Fluid Dynamics (CFD)

modeling, where there are difficulties in integrating models of different types [55–57].

The library presented below provides a contribution regarding a particular spatial discretization of the Navier-Stokes equations, considering keeping the number of empirical parameters to a minimum and proposing, through an OO approach, modular models with scalable levels of complexity and standard interfaces. These interfaces allow the coupling of the obtained models with others belonging to different physical domains or typologies.

4.1 State of the art

In the context of the building simulation one of the main aspect to be considered is the thermodynamic state behavior of the airflow models. Such models can help create a thermally comfortable environment — e.g., with a desired temperature or humidity distribution. The simulation of models, and in particular the scalable-detail paradigm proposed here, allows to assess the energy performance of buildings in an earlier stage than CAD-based ones, and to adapt the develop , as well as HVAC components and controls, to the required performance goal.

In [58], a review presented by Q. Chen deals with methods and models of ventilation performance prediction. The work highlights the development made in the last decades, starting from analytical and simple models up to the recent steps taken in the development of Computational Fluid Dynamic (CFD) methods, maintaining the focus on building applications. Using a suitable tool (or a suite of it) to represent the entire building, addressing all of its subsystems, is another widespread and well assessed idea [59] as well demonstrated in the past by the merging of particular tools as BLAST and DOE-2, two historical tools developed by the US government [60]. In fact, at that time the simulation of the behavior and movement of air flows within spaces became

of great importance. Allard in [61] was one of the first to try to tackle the problem of the motion of air flows and the prediction of ventilation performance in a simpler and above all computationally light way, introducing the so called “subzonal” models. The idea behind this work was to split the spatial domain in a quite coarse mesh of volumes, and subsequently use simplified relations to calculate the air flow fields. This idea was treated also in other commercial tools like COMIS [62]. In [63] were proposed further improvements of the models behavior in e.g. forced convection. Further improvements, detailed in [63], were proposed to improve the behaviour of the models in some cases (e.g. forced convection) where an attempt was made to improve the most critical aspects of the method just mentioned but, since the improvements were based on empirical assumptions, however, some loss of generality and applicability could not be avoided. In [62] a different approach was treated by Chen and Xun, which led to good results and therefore was adopted in the following years where they present a zero equation turbulence model particularly appropriate in the context of building energy simulation. Later it was noticed that many improvements can be made to CFD codes, in the context of building simulation, through the use of some simplification (e.g., in the turbulence model) and the usage of meshes, together with an increasing computational power [58]. This type of approach is still used by the main Energy Simulation (ES) software that use co-simulation as a way to couple the entire building with the respective CFD model simulating the contained air. Obviously, in recent years, thanks to technological development and an increase in computational power as well as to the introduction of new architectures, new approaches have been studied. A relevant work in this context is the Fast Fluid Dynamics (FFD) proposed by W. Zuo [64]. FFD uses a semi-lagrangian approach, that is natively parallelisable, thus can be significantly accelerated if implemented on parallel architectures such as Graphic Processing Unit (GPU) ones. The same authors also presented an improved version of

their models, in which undesired numerical diffusion was reduced through higher-order discretisation technique [64]. At present, coupling CFD and ES is commonly used, however it is a fairly complex and resource-intensive process, which can sometimes lead to errors without proper management in preventing misbehavior [65]. An interesting work about co-simulation in the context of buildings and HVAC simulation tools is [66,67]. The authors study how to manage the simulations carried out with the tools involved and highlight the fact that as the number of components involved (i.e. the individual simulation tools) increases, the simulation time used increases with the effect of decreasing overall performance of the simulation itself. The presented scenario is correctly summarised by the sentences taken from [18] and marked as fairly broad consensus issues: “The existing simulators were too rigid in their structure to be able to accommodate the improvements and flexibility that would be called for in the future. Each added feature required a larger implementation effort than the previous one.” and “A promising technology for the future were the general simulation methods offered by equation-based methods using program-neutral model descriptions and domain-independent solution methods”. The same author in [19] stresses the idea of replacing the present tools with equation based ones, leading to a true whole building simulation tool. M. Wetter in [31] presented a comparison between TRNSYS and the beta version of the Modelica Standard Library in order to compare these industry standard tools with equation based ones such as Modelica [31]. The work evidences that the time spent in the model development phase using Modelica is five to tenfold less with respect to TRNSYS. The work evidences that the time spent in the model development phase using Modelica is five to tenfold less with respect to TRNSYS. The main disadvantage of Modelica was the limited number of models representing the various HVAC components and its computing time, especially in the first developed versions. Over the years, however, these shortcomings have been increasingly limited

thanks to an increasing interest in this research field and the preliminary version of the Buildings library has been regularly updated and supported [68]. As already said, the modularity of the language allows the addition of new models in Modelica thanks to less effort than any other traditional tool, benefiting the reuse and diffusion of integrated models. Also, the computational aspects are made transparent by the equation based approach, as stated e.g. in [18]. On the other hand, numerous fields of research in favor of equation-based approaches are increasingly being developed and updated [69]. At present the Modelica Standard Library such as the Modelica Building Library contain numerous models of fluid flows but are not directed towards large volumes or spaces, or more in general, at any case where CFD like models would be the choice of election if "accurate enough" Results are needed (see eg [70]). Based on the panorama just sketched, and on previous results such as [71], this work provides the improvements described in the introduction, and discussed more in detail in the following sections.

4.2 Description of the model

Newtonian fluids can be described through the conservation equations of mass, energy and momentum. These equations, also called Navier-Stokes equations can be written as:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0 \quad (\text{mass}) \quad (4.1a)$$

$$\frac{\partial(\rho e)}{\partial t} + \nabla \cdot (\rho \mathbf{v} h) = \nabla \cdot (k \nabla T) \quad (\text{energy}) \quad (4.1b)$$

$$\frac{\partial(\rho \mathbf{v})}{\partial t} + \nabla \cdot (\rho \mathbf{v} \mathbf{v}^T) + \nabla p = \nabla \cdot (\mu \nabla \mathbf{v}) + \mathbf{f} \quad (\text{momentum}) \quad (4.1c)$$

where the quantities p , T , e , h are respectively the absolute pressure, absolute temperature, specific energy and specific enthalpy of the fluid, together with the

fluid properties , k and μ representing the density, thermal conductivity and dynamic viscosity respectively, while \mathbf{v} and \mathbf{f} represent the fluid velocity and the external forces (e.g. gravity). Bold letters are vector quantities in order to separate them from the scalar ones. For the temperature and pressure ranges considered here, the difference between the ideal gas and the linearized model is very limited, so for the fluid density ρ a linearized model can be used to approximate the ideal gas relationship itself. This leads to

$$\rho = \frac{p}{R^*T} \quad (\text{ideal gas relationship}) \quad (4.2a)$$

$$\rho = \rho_0 + \frac{1}{R^*T_0} - \frac{p_0}{R^*T_0^2}(T - T_0) \quad (\text{linearised model}) \quad (4.2b)$$

with R^* being the specific ideal gas constant, and ρ_0 , p_0 and T_0 representing respectively the fluid density, absolute pressure and absolute temperature at the linearisation point, and $P = p - p_0$ being the relative pressure, used in the rest of the paper instead of the absolute one, to better exploit the available numeric precision. The adoption of a linearised version is absolutely acceptable in the operating ranges considered by us, since, as already mentioned, the discrepancy between the two relations is limited. Besides the state equation, the specific energy and enthalpy ones are clearly needed. Starting from the definition

$$de = \frac{\partial e}{\partial T}dT + \frac{\partial e}{\partial v}dv \quad (4.3)$$

and neglecting the second term, the specific internal energy variation can be written as

$$de = c_v dT \quad (4.4)$$

where c_v , in general, is a function of temperature T . Assuming however that c_v does not depend on T , which is acceptable in our context, one obtains

$$e - e_0 = c_v(T - T_0) \quad (4.5)$$

of course assuming that e_0 and T_0 fulfil $e = c_v T$. Thus, the equations needed in the models are

$$e = c_v T \quad (\text{specific energy}) \quad (4.6a)$$

$$h = e + p \quad (\text{specific enthalpy}) \quad (4.6b)$$

4.2.1 Generic form of the governing equations

Before presenting the implementation of flow equations in Modelica it is important to remember the set of governing equations into the generic Convection-Diffusion (CD) form, i.e.:

$$\underbrace{\frac{\partial \rho \Phi}{\partial t}}_{\text{unsteady}} + \underbrace{\frac{\partial \rho v_i \Phi}{\partial x_j}}_{\text{convective}} = \underbrace{\frac{\partial}{\partial x_i} \left(\Gamma_\Phi \frac{\partial \Phi}{\partial x_i} \right)}_{\text{diffusive}} + \underbrace{S_\Phi}_{\text{source}} \quad (4.7)$$

where the transported quantity is represented by the generic scalar Φ , with its diffusivity coefficient Γ_Φ , and its generation rate per unit volume S_Φ . The idea is to approach the set of governing equations in a unified manner (see [72, 73]). Table 4.1 shows how the equations (4.1a), (4.1b) and (4.1c) are represented through the Convective diffusion equation (4.7), obviously by adopting an appropriate choice of variables. For the sake of simplicity and to lighten the notation the table shown (as well as the rest of the text) is composed of equations in a 2D Cartesian coordinate system (ie, the velocity $v = (v_x, v_y)$, and the coordinates $x = (x, y)$), but each approach can be extended in 3D without loss of generality and in a straightforward manner.

4.2.2 Turbulence model

In simulating turbulent flows (which is the most common flow type of engineering importance), it is necessary to take into account all the small interactions that occur between the various structures of the fluid flow. For engineering applications this is typically done by enhancing the diffusion (which resembles extensive mixing caused by these interactions) through increased diffusivity coefficient. As for the equations of the momentum, this implies the introduction of the turbulent viscosity μ_T , in addition to the molecular viscosity of the fluid μ . By analogy to the molecular viscosity, the turbulent viscosity is defined through “characteristic length” and “velocity scales” (although these are the characteristics of the flow, and not the characteristics of the fluid), as described by given turbulence model.

Table 4.1. The terms in the generic form of the Convective-Diffusive unsteady equation

Generic form			
	Φ	Γ_Φ	S_Φ
Mass	1	0	0
Partial Mass	1	0	0
Energy	$c_v T$	γ_{eff}	Q_{source}
X-Momentum	w_x	μ_{eff}	$\partial P / \partial x$
Y-Momentum	w_Y	μ_{eff}	$\partial P / \partial y - \rho g$

Different turbulence models yield the characteristic length and velocity scales by solving additional (algebraic or differential) model equations. To keep the level of complexity as low as possible here we use a zero-equation turbulence model: no additional equations are solved, but algebraic equations have been used to define the characteristic scales. Following Prandtl’s mixing length idea, it is assumed that the

turbulent viscosity varies linearly with the minimal distance from the wall y_w , as

$$\mu_T^+ = ky^+ \quad (4.8)$$

where $\mu_T^+ = \mu_T/\mu$ is the normalised eddy viscosity, $y^+ = \rho u_\tau y_w/\mu$ is the normalised minimal distance from the wall, and the normalisation is performed using the friction velocity u_τ , while $k = 0.41$ is the Von Karman constant. In this model, the minimum distance from the wall y_w represents the characteristic length scale, while the friction velocity u_τ is taken as the corresponding velocity scale. Through the momentum boundary layer theory, the friction velocity is defined here with the velocity magnitude U calculated in the immediate wall vicinity $u_\tau = c_U U$, with the proportionality constant $c_U = 0.0945$ proposed by Chen and Xu [74] for the HVAC simulations. It should be emphasized that this simple model is calculated for equilibrium flow conditions, so for non-equilibrium ones (e.g. with stagnation point or strong recirculation) it can generate modeling errors. For the calculation of the temperature distributions in the flows delimited by walls the same idea was used to describe the turbulent effects with the introduction of the turbulent thermal conductivity k_T . The analogies between the momentum and thermal boundary layer lie in the fact that the Prandtl number defines the ratio between the momentum and thermal diffusivity $Pr = c_p \mu/k$ (assumed to be constant for a specific fluid). In the same way is the turbulent conductivity k_T expressed through the turbulent viscosity μ_T , and turbulent Prandtl number Pr_T , hence the modeling of turbulence in the energy equation is directly coupled to the turbulence modeling in the momentum equation. Finally, as shown in Table ??, we can implement the turbulence model introducing into the Convective-Diffusive (CD) equation (4.7) the effective viscosity μ_{eff} instead of the dynamic viscosity μ regarding the momentum equation (4.1c), and introducing the effective thermal conductivity γ_{eff} instead of the thermal conductivity

γ regarding the equation (4.1b), ie,

$$\mu_{eff} = \mu + \mu_T = \mu + \rho k u_T y_w \quad (4.9a)$$

$$\gamma_{eff} = \gamma + \gamma_T = \gamma + \frac{\rho k c_p u_T y_w}{Pr_T} \quad (4.9b)$$

4.2.3 Near-wall treatment

In wall-bounded turbulent flows, the greatest variations in the distribution of the flow variables (e.g. velocity, temperature, etc.) occur in the immediate vicinity of the walls. The numerical predictions depend on the accuracy with which these variations are represented (the fluxes of the walls in particular). A straightforward way to accurately represent this steep variation is to increase the spatial resolution in the wall normal direction, however this can be computationally very demanding.

However, a rigorous and precise representation of these steep variations is not necessary in order to capture the energy facts at the system level, so a predefined log-law profile can be used which has proved valid for an attached plane flow with high Reynolds number. This yields

$$U^+ = \frac{1}{k} \ln(Ey^+) \quad (4.10)$$

where $U^+ = U/u_\tau$ is the normalised velocity, and $E = 8.9$ is the log-law constant.

The idea behind this near-wall treatment is to satisfy the log-law behaviour even in the situation when the wall-normal resolution is not sufficient to fully resolve the spatial variation of the flow characteristics in the near-wall region. To this purpose, the effective viscosity – derived using equation (4.10) – is imposed at the walls (whence the name wall viscosity μ_w) in order to provide for a suitable boundary condition in the momentum equation regardless of the spatial resolution in the near-wall region,

obtaining

$$\mu_w = \begin{cases} \mu & \text{if } y^+ < 5 \\ \frac{\rho k u_\tau y_w}{\ln(Ey^+)} & \text{if } y^+ > 30 \end{cases} \quad (4.11a)$$

$$k_w = \begin{cases} k & \text{if } y^+ < 5 \\ \frac{c_p \mu_w}{Pr_t} & \text{if } y^+ > 30 \end{cases} \quad (4.11b)$$

with the linear interpolation used in the y^+ range between 5 and 30. Clearly, using a boundary layer analogy, the same approach can be applied for the thermal equation as well, thus introducing the wall conductivity k_w .

4.3 Implementation in Modelica

4.3.1 The grid

The governing equations (4.1a),(4.1b), (4.1c) need to be discretised over a spatial domain. The grid adopted here for that purpose is a structured and non uniform one, as shown in figure 4.1 (left).

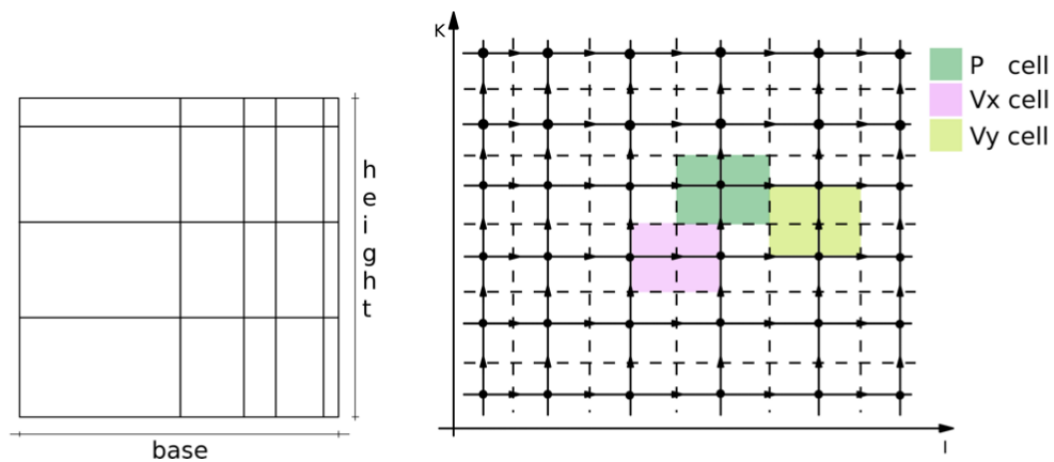


Figure 4.1. (Left) non uniform structured grid – (Right) staggered grid for the discretisation of the NS equations

These equations have been spatially discretised over a staggered grid, an example of such a grid is shown in figure 4.1. The basic idea behind the staggered grid is to integrate the balance equations over CVs that differs (the CVs for momentum equations are shifted from the ones in which energy and mass preservation equations are solved), in order to avoid numerical problems as unrealistic pressure/velocity distribution [72, 73].

Second, this approach makes easier the numerical implementation because the CV located in the P cells (see figure 4.1) provide boundary conditions for the Vx and Vy CV cells and vice versa. Without this staggered approach interpolation between adjacent cells is needed. The result of such a representation (in the 2D case) is a grid

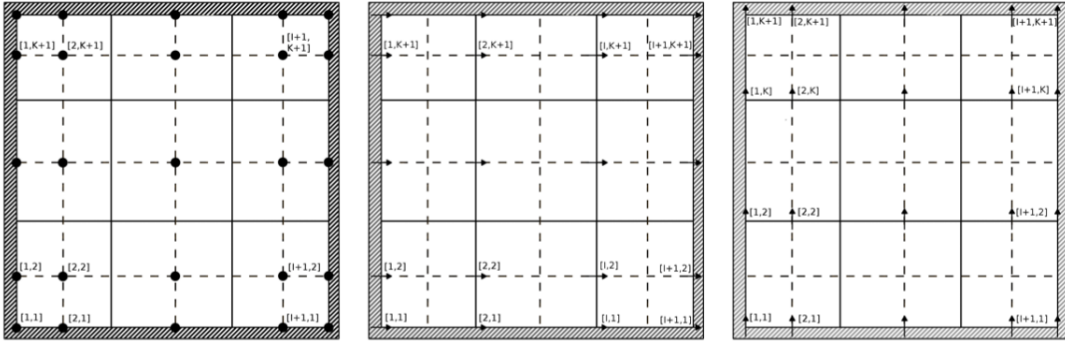


Figure 4.2. Grid for the discretised version of the equations in Modelica: energy and mass (left), x-momentum (center) and y-momentum (right)

of rectangular shaped boxes or Control Volumes (CV); as already said, extension to 3D is straightforward. A spatial domain is thus described by its dimensions (respectively base and height), the number of CVs along the x and y axes (I and K) and the percentage of space associated to each CV. The notion of “staggered grid” recalls that the CVs where the energy and mass preservation are discretised (usually called Pressure or P – cells) differ from the ones where x and y momentum are, as shown in figure 4.1 (right). The staggered grid has been introduced in order to avoid numerical problems as unrealistic pressure/velocity distribution [72, 73]. Second, this approach makes easier the numerical implementation because the CV located in the P cells (see figure 4.1) provide boundary conditions for the V_x and V_y CV cells and vice versa. Without this staggered approach interpolation between adjacent cells is needed. For such a reason three different coordinate systems for univocally numbering the CVs have been adopted. The three systems are respectively for identifying scalar quantities inside P cells, and the V_x , V_y air velocities, as shown in figure 4.3.1.

4.3.2 Domain Boundaries

Boundary conditions, needed to solve the governing equations, are provided in terms of temperatures, partial masses and air velocities on the domain boundaries (e.g., a wall surrounding the room).

Table 4.2. Set of variables on the domain boundaries

	Left	Right	Bottom	Top
T	$T[1,2 \dots K+1]$	$T[I+2,2 \dots K+1]$	$T[2 \dots I+1,1]$	$T[2 \dots I+1,K+2]$
X	$X[1,2 \dots K+1]$	$X[I+2,2 \dots K+1]$	$X[2 \dots I+1,1]$	$X[2 \dots I+1,K+2]$
V_x	$V_x[1,1 \dots K+2]$	$V_x[I+1,1 \dots K+2]$	$V_x[1 \dots I+1, 1]$	$V_x[1 \dots I+1, K+2]$
V_y	$V_y[1 \dots K+1]$	$V_y[I+2,1 \dots K+1]$	$V_y[1 \dots I+2, 1]$	$V_y[1 \dots I+2, K+1]$

Table 4.3. Boundary conditions for temperatures

Left wall boundary	
Fixed temperature	$T[1,2 \dots K+1] = T_{\text{wall}}$
Adiabatic wall	$T[1,2 \dots K+1] = T[2,2 \dots K+1]$

Such values can be assigned to a subset of variables located on the domain border, as shown in figure 4.3.1. Table 4.2 contains the subsets of variables that represent the boundaries. Usually, the velocities on the boundaries are defined as null, except when describing inlets or outlets (the same goes for the mass fractions), e.g. for HVAC. Concerning the temperatures, in order to describe a room with a wall kept at a given temperature, it suffices to assign the desired temperature to each node in the boundary set (as defined in table 4.3).

On the contrary, an adiabatic wall should be described by imposing a null temperature gradient between adjacent cells (see table 4.3).

4.3.3 Preservation equations

This section shows how mass, partial mass (our case in particular), energy and momentum preservation equations have been discretised and implemented in Modelica. The starting point is the numerical integration with the finite volume approach of the CD equation (4.7), a well known subject in the context of fluid dynamics (see [72, 73] for more information). The CD equation in discretized form brings us to this compact expression

$$V\rho\frac{d\Phi_P}{dt} + a_P\Phi_P = a_E\Phi_E + a_W\Phi_W + a_N\Phi_N + A_S\Phi_S + S \quad (4.12)$$

where all the terms accounting for convective and diffusive exchanges are collected into the $a_{P,N,S,W,E}$ coefficients, while the sources are merged into S. If we consider the 2D case such coefficients are defined as

$$a_E = D_e A(|P_e|) + || - F_e, 0 || \quad (4.13a)$$

$$a_W = D_w A(|P_w|) + || F_w, 0 || \quad (4.13b)$$

$$a_N = D_n A(|P_n|) + || - F_n, 0 || \quad (4.13c)$$

$$a_S = D_s A(|P_s|) + || F_s, 0 || \quad (4.13d)$$

$$a_P = a_W + a_E + a_N + a_S \quad (4.13e)$$

And for the partial mass preservation equation

$$aE_{Xi} = Xi_e * (-F_e) \quad (4.14a)$$

$$aW_{Xi} = Xi_w * F_w \quad (4.14b)$$

$$aN_{Xi} = Xi_n * (-F_n) \quad (4.14c)$$

$$aS_{Xi} = Xi_s * F_s \quad (4.14d)$$

$$aP_{Xi} = 0 \quad (4.14e)$$

where $\|a, b\|$ is the maximum between a and b , while D and F are respectively the diffusion conductances and mass fluxes and $X_{i_{E,W,N,S}}$ are the partial masses of the surrounding CVs. Into the equations (4.13) the Péclet numbers ($P_{n,s,w,e}$) are introduced and defined in (4.15) as the ratio between the flows and the diffusive conductances of a given face of the CV.

$$P_x = \frac{F_x}{D_x} \text{ with } x \in \{n, s, w, e\} \quad (4.15)$$

The Péclet number aims at comparing the effect of the diffusion of the scalar quantity Φ with respect to the transport of the same quantity by fluid motion. It comes into play as an argument for function $A()$. This function, introduced in [72], allows to decouple the numerical discretisation from the employed convective scheme. In this way it is possible to define a unique structure for the constitutive equations, where the convection scheme can be adapted, in order to satisfy the given requirements (e.g., concerning accuracy). A general discretised formulation for the CD equation has been presented. The remaining part of the section shows how such a general form can fit the mass, partial masses, energy and momentum preservation equations.

The continuity equation

The discretised continuity equation is obtained by integrating (4.1a) along a CV located in a P-cell (a grey cell in figure 4.3), leading to

$$V \frac{d\rho_P}{dt} + F_e - F_w + F_n - F_s = 0 \quad (4.16)$$

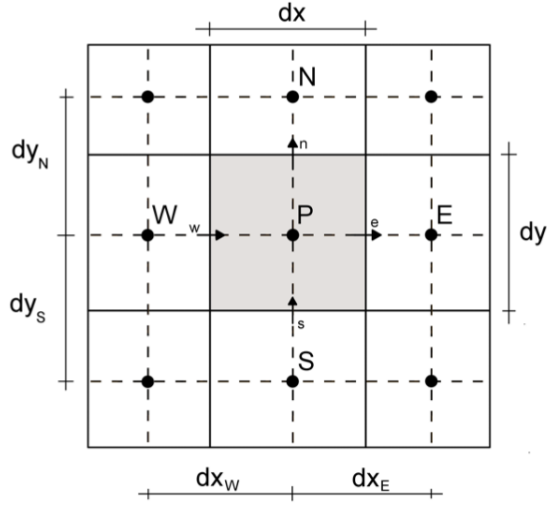


Figure 4.3. Grid with dimensions and notations. The grey volume is the CV in which the continuity equation has been integrated. Arrows indicate the positive directions of the mass flows.

For such a CV, the mass flow on the east face can be computed as

$$F_e = (\rho v_x)_e = v_x^e \cdot \begin{cases} \rho_E & \text{if } v_x^e < 0 \\ \rho_P & \text{if } v_x^e > 0 \end{cases} \quad (4.17)$$

where ρ_P is the density of the CV considered, ρ_E is the density of the CV that surrounds the considered one on its east side, while v_x^e is the x-velocity of the air crossing the eastern surface (other fluxes can be computed in a similar way). Velocities (due to the implementation of the staggered grid approach) are immediately readable from the surrounding x (and y) momentum CVs. Concerning the Modelica representation, taking as reference the numbering convention shown in figures 4.3.1, for the CV $[i, k]$ the density and the velocities are the ones listed in table 4.5. Since the flows defined above are useful for computing other quantities, they are saved into matrices $F_{eM}[*,*]$, $F_{wM}[*,*]$, $F_{nM}[*,*]$ and $F_{sM}[*,*]$ representing the four flows for each volume $[i, k]$.

The energy equation

The discretised energy equation (4.1b), once integrated over a CV located in a P-cell (see grey cell in figure 4.3), can be rewritten as

$$V\rho c_v \frac{dT_P}{dt} + c_v a_P T_P = c_v (a_E T_E + a_W T_W + a_N T_N + a_S T_S) + Q_{source} \quad (4.18)$$

where T_P is the temperature of the CV analysed, and $T_{E,W,N,S}$ are the temperatures of the surrounding CVs. The definition of the coefficients $a_{P,E,W,N,S}$ provided for the general case in (4.13) have to be adapted. In particular, just the diffusive conductance have to be updated, since the CV taken into account is the same used for the continuity equation the flows are the same (as defined in (4.17)). The diffusive conductances are thus computed as

$$D_e = \frac{\Gamma_e A_x}{dx_E} = \frac{\gamma_{eff}^e dy}{dx_E} \quad (4.19a)$$

$$D_w = \frac{\Gamma_w A_x}{dx_W} = \frac{\gamma_{eff}^w dy}{dx_W} \quad (4.19b)$$

$$D_n = \frac{\Gamma_n A_x}{dx_N} = \frac{\gamma_{eff}^n dy}{dx_N} \quad (4.19c)$$

$$D_s = \frac{\Gamma_s A_x}{dx_S} = \frac{\gamma_{eff}^s dy}{dx_S} \quad (4.19d)$$

where γ_{eff} is the effective thermal conductivity of the air. By implementing the general equation (4.18), it is possible to employ different convective schemes by choosing the proper $A(\cdot)$ function. When the CV $[i, k]$ is considered, the distances that appears in equations (4.19) and shown in figure 4.3.1, can be computed with respect to the continuity CV.

Partial mass preservation equation

The discretisation of the partial mass equation can be written as

$$V\rho\frac{dXi_P}{dt} = aE_{Xi} + aW_{Xi} + aN_{Xi} + aS_{Xi} \quad (4.20)$$

where Xi_P is the partial mass of the CV analysed, and the other terms are the transport coefficients for the partial masses previously computed (4.14) as the product of the surrounding mass fractions and the respective mass flows.

x/y momentum equations

The discretised x-momentum equation can be written as

$$V\rho\frac{dv_x^P}{dt} + a_P v_x^P = a_E v_x^E + a_W v_x^W + a_N v_x^N + a_S v_x^S + A_x(P_W - P_E) \quad (4.21)$$

where:

- v_x^P = horizontal velocity of the air in our CV
- $v_x^{E,W,N,S}$ = horizontal velocities of the air in the surrounding ones
- A_x = CV surface normal to the x axes
- $P_{W,E}$ = pressure in the surrounding P-cells

The CV considered for this discretisation is depicted in figure 4.4, shifted along the x axis of half a volume (both left and right).

This has two consequences: first, the velocity located in the centre of the CV (x-cell) is exactly in the middle of the faces of the continuity CV (P-cell). Second, the pressure on the east and west boundaries of the x-momentum CV are exactly the ones computed in the continuity CV.

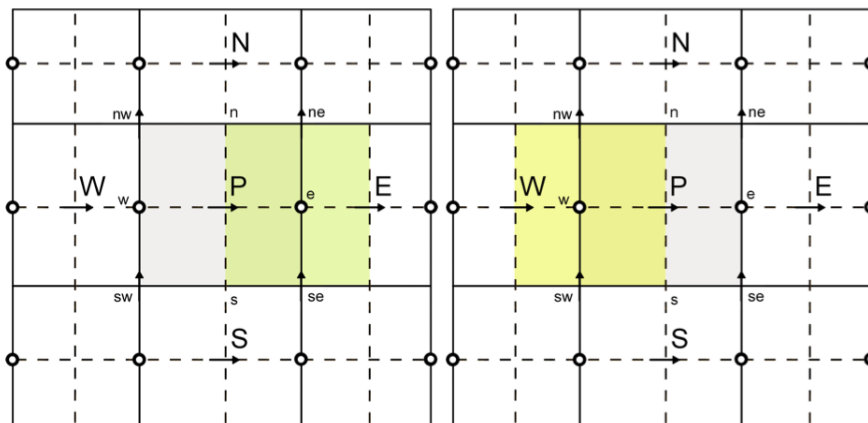


Figure 4.4. Grid for the discretised of x-momentum. In grey the CV for discretising the x-momentum, with other colors the surrounding P-cells.

Also in this case the flow calculation is based on the figure just shown: the flows on the east (e) and west faces (w) can be computed as the mean of the flows of the surrounding continuity CVs

$$F_e = (\rho v_x)_e = \frac{F_e^E + F_w^E}{2} \quad (4.22a)$$

$$F_w = (\rho v_x)_w = \frac{F_e^W + F_w^W}{2} \quad (4.22b)$$

where $F_{e,w}^E$ indicate the fluxes on the east and west faces of the continuity CV located on the right of the x-momentum CV (the same is valid for the opposite face).

For computing the flows over the south (s) and north (n) faces of the x-momentum CV, four vertical velocities on the four corner, respectively $v_y^{NE,NW,SE,SW}$, come into play. For each one of these velocities a fluxes is associated. The two remaining fluxes are calculated through mean values as

$$F_n = (\rho v_y)_n = \frac{F_n^E + F_n^E}{2} \quad (4.23a)$$

$$F_s = (\rho v_y)_s = \frac{F_s^W + F_s^W}{2} \quad (4.23b)$$

Finally, the diffusive conductances can be calculated as in (4.24) without forgetting that the distances of the center of the control volume from the surrounding P-cells are also different.

$$D_e = \frac{\Gamma_e A_x}{dx_E} = \frac{\mu_{eff}^e dy}{dx_E} \quad (4.24a)$$

$$D_w = \frac{\Gamma_w A_x}{dx_W} = \frac{\mu_{eff}^w dy}{dx_W} \quad (4.24b)$$

$$D_n = \frac{\Gamma_n A_y}{dy_N} = \frac{\mu_{eff}^n dx}{dy_N} \quad (4.24c)$$

$$D_s = \frac{\Gamma_s A_y}{dy_S} = \frac{\mu_{eff}^s dx}{dy_S} \quad (4.24d)$$

$$(4.24e)$$

The only difference to consider for the y-momentum preservation equation is the gravity term $\rho_P g V$ where g is the gravity acceleration and the only other notable part of this term ρ_P is calculated as the mean of the north and south density values (respectively the centers of the yellow and the green CVs shown).

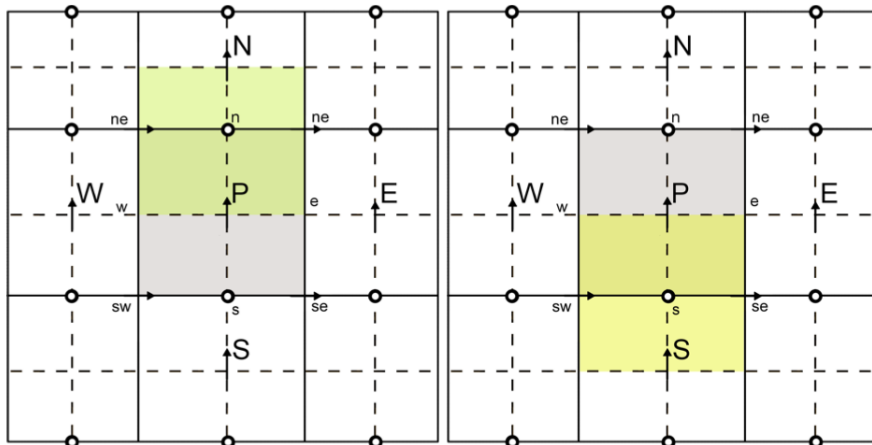


Figure 4.5. Grid for the discretised of y-momentum. In grey the CV for discretising the y-momentum, with other colors the surrounding P-cells.

4.3.4 Turbulence Model

The turbulence model is present in each x and y-momentum CV. It is implemented through the use of some parameters as:

- μ = Air Dynamic Viscosity
- ρ = Air Density (here assumed to be constant)
- C_u = A constant parameter of the turbulence model
- k_{arm} = Von Karman constant
- y_{plus} , y_{wall} = respectively the normalised minimal distance from the wall and the distance between the centre of the CV and the nearest wall

In this model it is also present the possibility to switch the behavior from turbulence to laminar through the boolean flag *laminar*, when the laminar flow assumption is assumed to be valid (e.g. very low velocities or high viscosity). Moreover there are other quantities of viscosity and thermal conductivity in the near-wall region in case of y_{plus} set to 30. These values have been used for a linear interpolation between various cases.

4.3.5 Interfaces

The definition of boundary conditions is facilitated by the presence of standard interfaces contained within the model. The adoption of these aforementioned interfaces (called in Modelica *connectors* [75]) makes it possible to describe particular physical systems. This room library, which describes the interaction between the boundaries and the interior domain, was developed with the intention of making it usable in various scenarios and not for a specific application. The boundaries of the domain, as

defined in subsection 4.3.2, are a specific subset of the domain variables. The room model is intentionally incomplete as it can be completed in the future by connecting it to several surrounding models. The main advantage of Modelica, as already mentioned in the previous chapters, is that the equations belonging to the surrounding models that will connect to our room do not interfere in any way except for the values provided to the connector linked together to the one of the room. The structure of the Modelica connectors (see [9] for more information) linked to the variables and volumes on the boundaries of the room is shown in tables 4.4 and 4.5.

Table 4.4. Variables contained within the Modelica interfaces: Heat connectors

Name	Type	Description
T	Effort	Temperature [K]
Q_flow	Flow	Heat flow rate [W]

Table 4.5. Variables contained within the Modelica interfaces: Fluid connectors

Name	Type	Description
Medium	–	Medium model
P	Effort	Pressure [Pa]
m_flow	Flow	Mass flow rate [kg/s]
h_outflow	Stream	Specific enthalpy [J/(kg·K)]
Xi_outflow [Medium.nXi]	Stream	Independent mixture mass fraction [kg/kg]

In case of internal gains such as the presence of people inside the room, these interfaces can be used to simulate the thermal behavior of these situations by imposing a specific heat flow rate (appearing in the energy equation as a source term) .

An example of the interaction between a pipe and the internal of the room is shown in fig. 4.6 where a pipe. In this case, heat flowing through the connection and coming

into play as a source term in the energy equation, will be defined according to the temperature difference between the pipe surface and the air. The flow motion inside the pipe is out of our interest and is governed by specific equation solved together at the same time with the room simulation without any need for co-simulation.

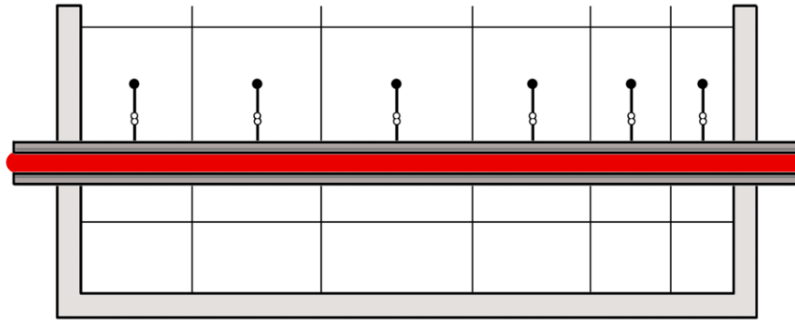


Figure 4.6. Example of interaction between different models through connectors: a pipe fed with hot water heating the interior of the room.

On the domain boundaries the reference variables become temperatures, pressures, partial masses, velocities and densities.

To preserve the maximum degree of abstraction, each boundary node has been created in such a way as to have two connectors of different nature: a heat one and a fluid one. The suitable scenarios are therefore three: both are left unconnected (figure ?? top), the thermal one is connected (figure ?? centre) otherwise the fluid one (figure ?? bottom). There is a constraint, hereinafter explained, that avoids more (heterogeneous) connection at the same time.

Temperature

The temperature of a boundary node T_{mix} (see figures 4.7 can be defined in different ways:

- $T_{mix} = T_{vol}$, where T_{vol} is the temperature of the surrounding volume, if the

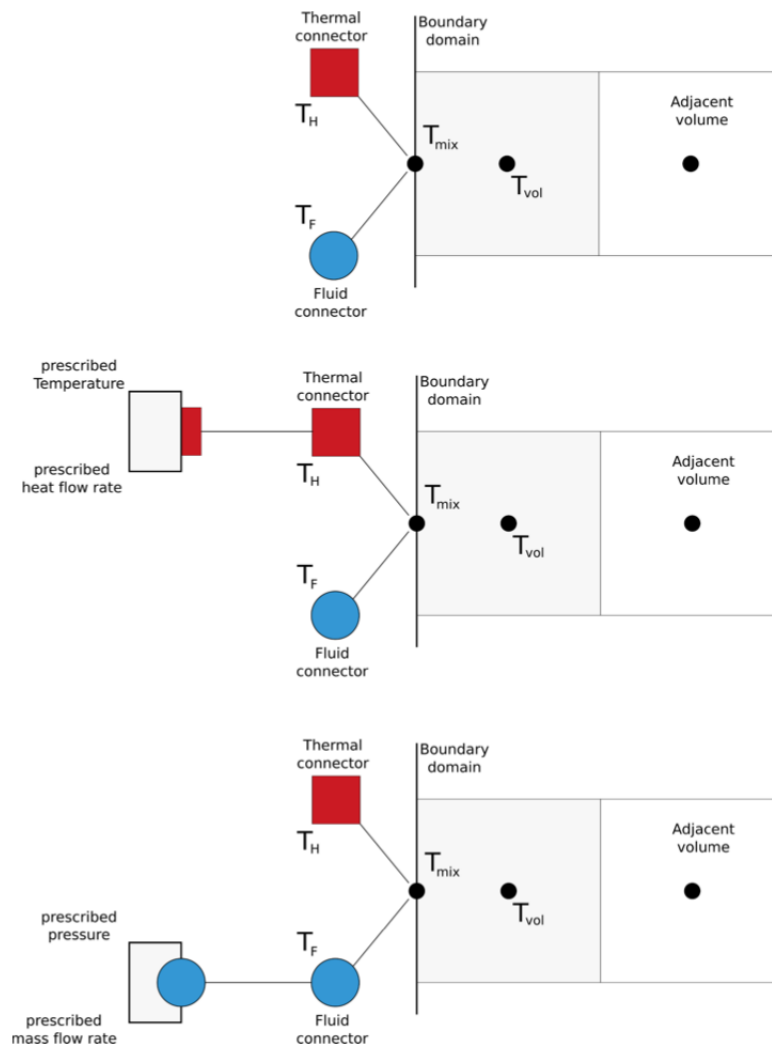


Figure 4.7. The three configurations that boundary connectors can assume: left unconnected (top), the thermal one is connected (centre), and the fluid one is connected (bottom).

connectors are left unconnected.

- $T_{mix} = T_H$, where T_H is the temperature of the heat connector, if connected.
- $T_{mix} = \begin{cases} T_F & \text{if } \dot{m} > 0 \\ T_{vol} & \text{if } \dot{m} < 0 \end{cases}$, where T_F is the fluid temperature, and \dot{m} is the mass flow rate crossing the boundary (positive if entering the volume). This is true if the fluid connector is used.

Without going into too much detail, these conditions have been implemented in a single equation, so they can coexist. With such an approach, each boundary node can have more than one connector linked to it, and the value associated to its node is properly selected in function of the connection established. It is important to emphasize that this temperature equation is valid if and only if no more than one connector (fluid or thermal) is connected to the outside. Such assumption can be verified with an assertion that states that at least one of the two flows has to be zero.

Pressure

The pressure on the boundary is defined by the external fluid connector. If it is connected then the pressure will be imposed or it will assume a value that is consistent with the mass flow rate. If there is not connection, the pressure on the boundary becomes equal to the pressure of the surrounding volume.

Partial masses

The partial masses on the boundaries are imposed through the fluid connector. In the same way with respect to the pressure, if it is connected, the mass fraction value is imposed in a consistent manner with respect to the internal conditions. If there is not connection, the mass fraction on the boundary becomes equal to that of the surrounding volume.

Velocities

The velocities on the domain boundaries depend on the presence or not of fluid connectors. If a fluid connector is linked with an external element that allows a mass flow there will be a velocity associated to that specific boundary point, otherwise not.

Velocity v can be defined according to equation (4.26)

$$v = \frac{\dot{m}}{A\rho} \quad (4.25)$$

where A is the surface of the volume crossed by the fluid flow, and ρ the density of the fluid. Obviously, if there is no fluid interface connection, the mass flow rate is zero and consequently the velocity is zero too.

Densities

The density associated with a point in the boundary domain depends on the fluid connector through the thermodynamic state of the chosen Medium. The Medium is a package containing all those equations and functions that describe the thermodynamic state and the characteristics of the fluid type I want to use. The density associated with a point in the boundary domain depends on the fluid connector through the thermodynamic state of the chosen Medium. The Medium is a package containing all those equations and functions that describe the thermodynamic state and the characteristics of the fluid type I want to use. All properties can be calculated straightforwardly by calling specific functions. In the case of density, the function involved is

$$\rho = f_\rho(P, h^*, X) \quad (4.26)$$

where P and X are the pressure and the mass fraction on the boundary defined by the fluid connector, h^* is the specific enthalpy associated to the fluid flow .

4.3.6 3D implementation

In this chapter the idea of how it is possible to model and simulate a general flow of a two-phase fluid within an multi-physical modeling framework (e.g. Modelica) has been described. The work has been deliberately treated in this paper in a simplified 2D approach to reduce useless and lengthy notations. Obviously a 3D model is needed since the objects usually modeled are large spaces inside buildings (e.g. rooms, atriums ...) and interact in all directions with the other elements of interest. In order to help the reader get familiar with the notation, the following pictures show the convention used to identify the volumes inside the model. Figures 4.8(left) and 4.8(right) show respectively the notation used to identify the faces of the volumes, and how they are numbered (from West to East, from South to North and from Bottom to Top). Figure 4.9 contains a set of images that identify different zones of the considered space. These zones are of interest because when defining boundary conditions or boundary layers have to be treated separately.

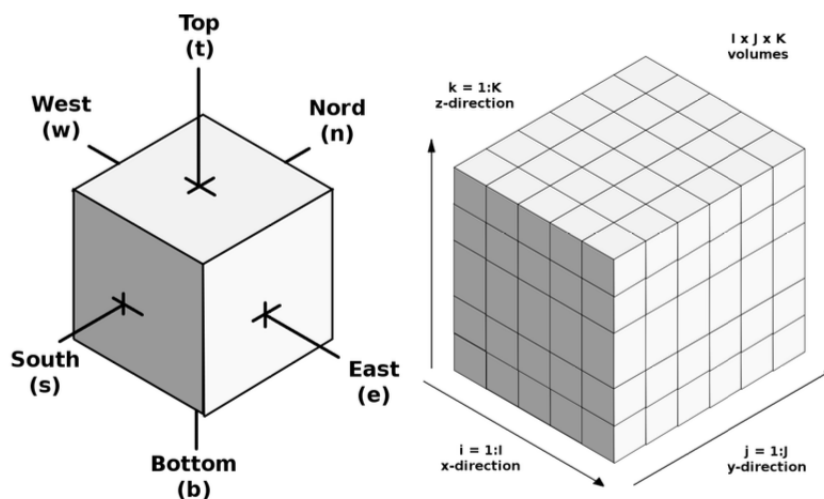


Figure 4.8. Notation used for the faces of the volumes (left), and their numbering convention (right).

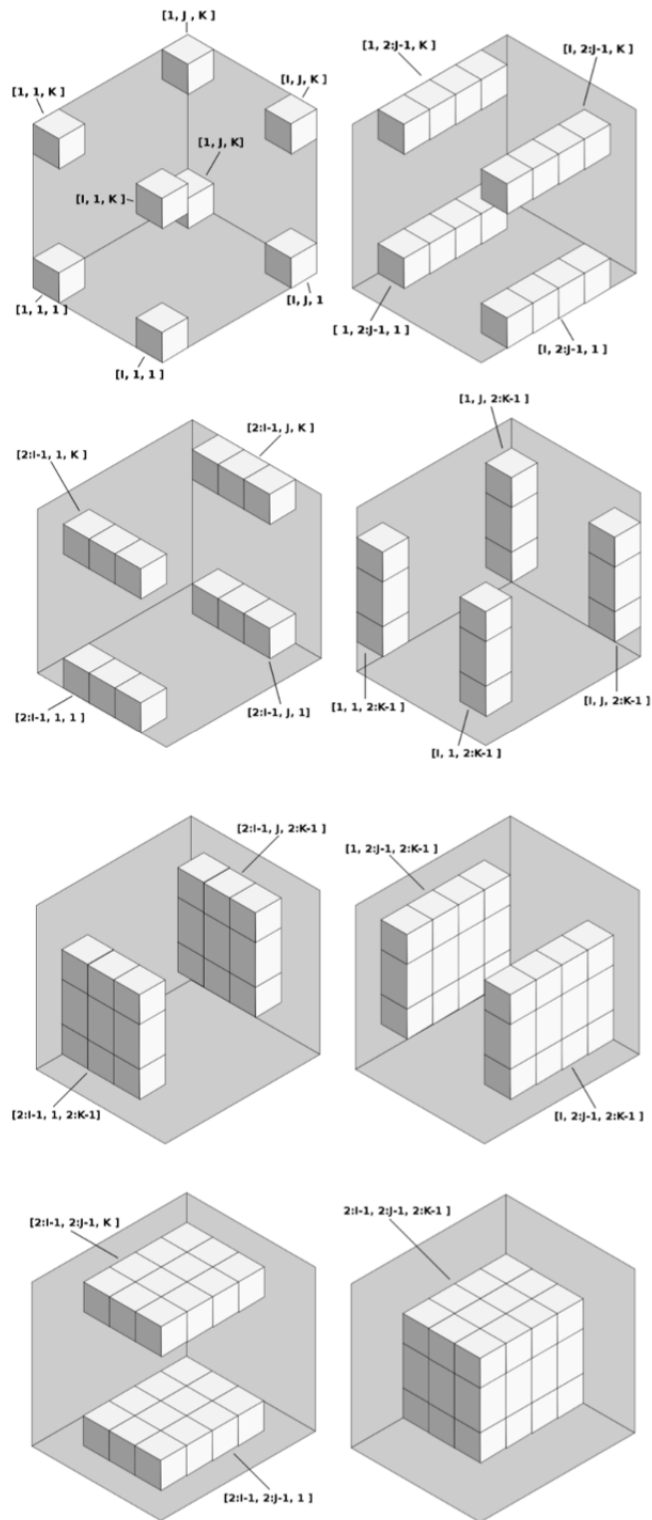


Figure 4.9. Different zones and their numbering.

4.4 Simulations and results

In this phase some dynamic simulations were carried out on the room level model described in the previous paragraphs. We tried to maintain a level of simplification suitable for our simulation parameters and for the operational ranges considered. With such a model it is possible to describe the motion of the air within the room, and more important, the temperature distribution within it. To analyze the behavior of the thermodynamic state and therefore of the humidity rate of the air in the room, it was decided to use a set of components that imitated the use of a fan coil: a source and a sink node, prescribing respectively the fluid pressure, temperature and steam/dry-air mass fractions, and the discharge pressure. Connectors allow for compatibility with lower-detail models, apparently. Furthermore, moving the components of the room (such as the model of fan coil used) can vary the results and can be useful in deciding the placement of the same HVAC component within the room.

The size and number of volumes were chosen based on the time and computational power available, so we opted for a room of $3 \times 3 \times 2.5 \text{ m}^3$ and IxJxK=3x3x3 control volumes.

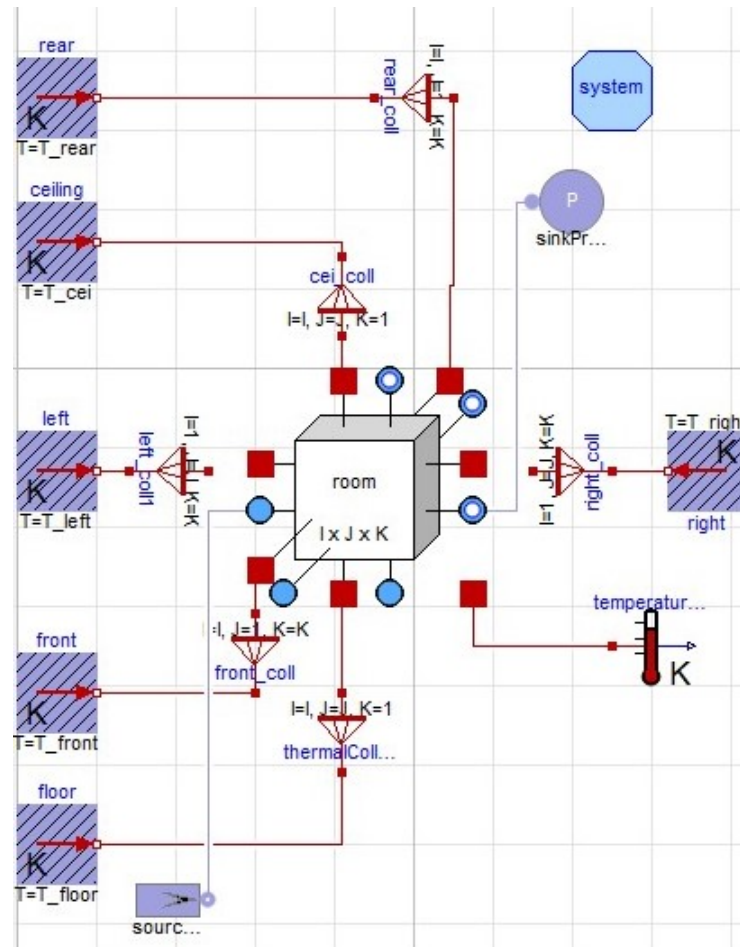


Figure 4.10. Analysis of the room considered, the six squares correspond to the walls of the room and the source and sink nodes simulate the air recycling behavior of a fan coil, the 3D white cube is the airflow model.

The simulations were carried out with the following initial values:

Room side

- $T_{start} = 20^{\circ}C$ start temperature of the room.
- $X_{start} = \{0.01, 0.99\}[Kg/Kg]$ respectively the initial quantity of steam and dry air inside 1Kg of the the mixture.

Source side

- $T_{source} = 15^{\circ}C$ temperature of the inlet fluid.
- $X_{source} = \{0.005, 0.995\}[Kg/Kg]$ respectively the quantity of steam and dry air inside 1Kg of the inlet mixture.

As can be seen from the fig. 4.10, the modeling constraints on the interfaces described in the previous paragraphs were respected, once the flow source was connected to a fluid port, the respective heatport was disconnected. This measure was taken to make the interface outflow temperature equation valid and consistent.

Concerning the walls, their density is $2400 [kg/m^3]$ and to simplify the simulation even more we have decided to make them adiabatic in order to avoid compromising the results.

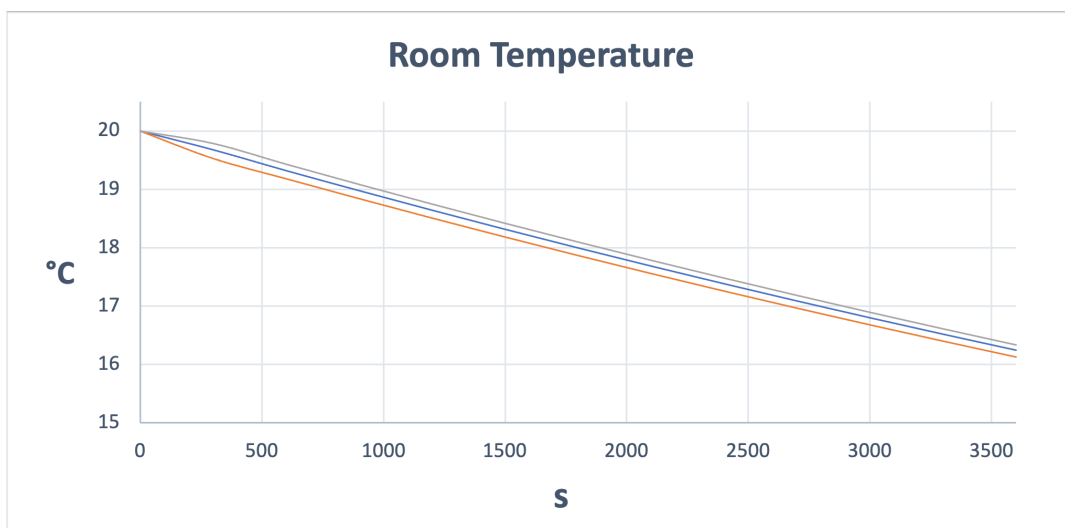


Figure 4.11. Temperature sensor in three different positions of the room with MoistAir as inlet

Two types of simulations were carried out, one with MoistAir as input (fig. 4.11), and the other with DryAir entering (fig. 4.12), finally they were compared.

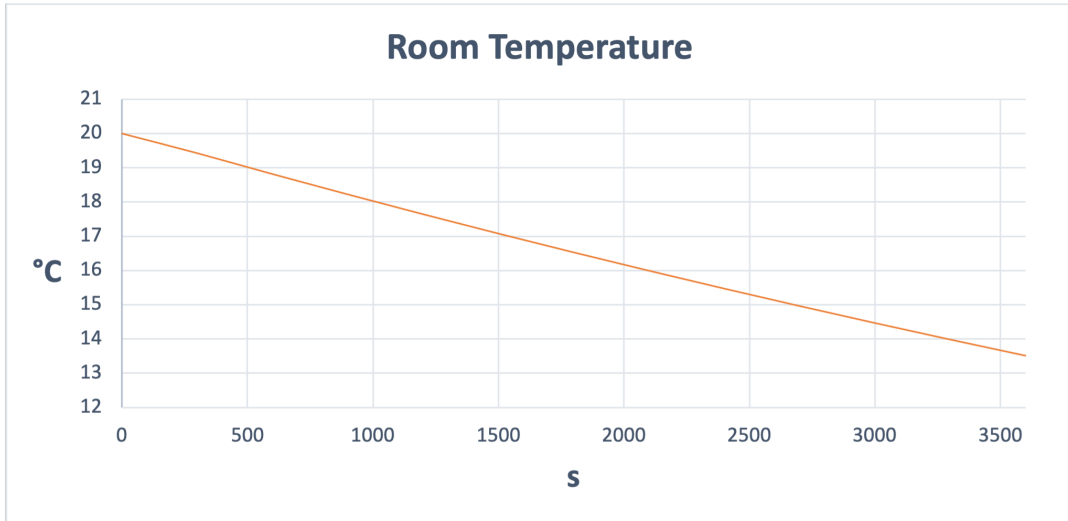


Figure 4.12. Temperature sensor in the center of the room with DryAir as inlet

Besides a good match as for temperature data, the model still exhibits some larger inaccuracies as for humidity. At present we assume these are related to the spatial discretization, and refinements for the involved equations are underway as future activities.

Chapter 5

Conclusion

This work has dealt with the current problem of the energy efficiency of buildings. In particular, we entered the field of the main software for the energy simulation of buildings, describing an overview on the main characteristics of the current instruments in circulation today. It has been underlined that the main limits of the latter can be overcome by the use of Equation Based Object Oriented languages such as Modelica.

Subsequently a substantial update was made to a present library with the implementation of moist air. In this way it is possible to take into account the variations in humidity, which in the previous version of the library were completely omitted.

Finally, some simulations were made that can testify the changes added and the improvements achieved.

Obviously, the changes implemented do not affect the modularity of the library, which can be used at various levels of detail and complexity and in several types of applications.

Acronyms

HVAC	Heating, Ventilation, and Air Conditioning
CFD	Computational Fluid Dynamics
OOM	Object Oriented Modeling
ES	Energy Simulation
BIM	Building Information Modeling
CAD	Computer Aided Manufacturing
NS	Navier-Stokes
CD	Convective-Diffusive

Bibliography

- [1] V. Harish and A. Kumar, “A review on modeling and simulation of building energy systems,” *Renewable and sustainable energy reviews*, vol. 56, pp. 1272–1292, 2016.
- [2] “Efficienza energetica nell’edilizia. european commission. <https://ec.europa.eu/info/news/focus-energy-efficiency-buildings-2020-feb-17-it>,” 2020.
- [3] M. Bourdeau, X. Guo, and E. Nefzaoui, “Buildings energy consumption generation gap: A post-occupancy assessment in a case study of three higher education buildings,” *Energy and Buildings*, vol. 159, pp. 600–611, 2018.
- [4] M. Levine, D. Üрге Vorsatz, K. Blok, L. Geng, D. Harvey, S. Lang, G. Levermore, A. Mongameli, S. Mirasgedis, A. Novikova, J. Rilling, and H. Yoshino, *Residential and Commercial Buildings*, 01 2007, pp. 387–446.
- [5] M. Adjali, J. Arfvidsson, T. Asaeda, R. Balendran, E. Barber, W. Beckman, L. Bellia, A. Bodalal, M. Bojic, M. Bojic *et al.*, “Building and environment” volume 35.”
- [6] Y. Hamada, M. Nakamura, K. Ochifuji, S. Yokoyama, and K. Nagano, “Development of a database of low energy homes around the world and analyses of their trends,” *Renewable Energy*, vol. 28, pp. 321–328, 2003.
- [7] “Breaking the ”heating barrier”. learning from the first houses without conventional heating.”

- [8] H. Elmqvist, M. Otter, and S. Mattsson, "Physical system modeling with modelica," *Control Engineering Practice*, vol. 6, pp. 501–510, 1998.
- [9] "Modelica association. modelica home page." [Online]. Available: <http://www.modelica.org/>
- [10] M. Wetter and C. Haugstetter, "Modelica versus trnsys – a comparison between an equation-based and a procedural modeling language for building energy simulation," *Proceedings of SimBuild*, vol. 2, no. 1, 2006. [Online]. Available: <http://www.ibpsa-usa.org/index.php/ibpusa/article/view/220>
- [11] M. Bonvini, "Efficient modelling and simulation techniques for energy related system level studies in buildings," 2013.
- [12] R. Kosonen and F. Tan, "Assessment of productivity loss in air-conditioned buildings using pmv index," *Energy and buildings*, vol. 36, no. 10, pp. 987–993, 2004.
- [13] P. Wargocki, D. P. Wyon, J. Sundell, G. Clausen, and P. O. Fanger, "The effects of outdoor air supply rate in an office on perceived air quality, sick building syndrome (sbs) symptoms and productivity," *Indoor air*, vol. 10, no. 4, pp. 222–236, 2000.
- [14] "CEN EN 15251:2007. indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality. thermal environment, lighting and acoustics. European Committee for Standardization. Brussels." 2007.
- [15] "ISO standard 7730-1994. moderate thermal environments – determination of the PMV and PPD indices and specification of the conditions for thermal comfort. International Standards Organization. Geneva. Switzerland." 1994.

-
- [16] D. B. Crawley, F. C. Winkelmann, W. F. Buhl, and A. E. Erdem, “What next for building energy simulation— a glimpse of the future,” in *Proc. IBPSA 97*, 1997, pp. 395–402.
- [17] D. Crawley, L. Lawrie, F. Winkelmann, W. Buhl, Y. Huang, C. Pedersen, R. Strand, R. Liesen, D. Fisher, M. Witte, and J. Glazer, “Energyplus: Creating a new-generation building energy simulation program,” *Energy and Buildings*, vol. 33, no. 4, pp. 319–331, Apr. 2001, funding Information: For more than 20 years, the US government supported development of two building energy simulation programs, DOE-2 and BLAST. BLAST [1] , sponsored by the US Department of Defense (DOD), has its origins in the NBSLD program developed at the US National Bureau of Standards (now NIST) in the early 1970s. DOE-2 [2] , sponsored by the US Department of Energy (DOE), has its origins in the Post Office program written in the late 1960s for the US Post Office. The main difference between the programs is load calculation method — DOE-2 uses a room weighting factor approach while BLAST uses a heat balance approach. Both programs are widely used throughout the world.
- [18] P. Sahlin, L. Eriksson, P. Grozman, H. Johnsson, A. Shapovalov, and M. Vuolle, “Whole-building simulation with symbolic dae equations and general purpose solvers,” *Building and Environment*, vol. 39, no. 8, pp. 949–958, 2004.
- [19] P. Sahlin, M. Ashrae, E. Simulation, and T. G. Ab, “The methods of 2020 for building envelope and hvac systems simulation - will the present tools survive?” 2000.
- [20] “Objectmath home page.” [Online]. Available: <http://www.ida.liu.se/>
`\protect\begin\group\immediate\write\@unused\def\MessageBreak'\let\protect\edefComposedcharacterscanonlyberenderedcorrectly,whentheoption'combine'isactivated\errhelp\let\def\MessageBreak'(ucs)\def\errmessagePackageucsError:`

Please activate option 'combine'. See the eucspackagedocumentation for explanation.

Type $\langle \text{return} \rangle$ for immediate help \endgroup $\sim \{ \}$ pelab/omath/

- [21] P. Fritzson, L. Viklund, O. Herber, and D. Fritzson, "High-level mathematical modeling and programming," *IEEE Software*, vol. 12, no. 4, pp. 77–87, 1995.
- [22] "Elmqvist h., d. brock, and m. otter.dymola — user's manual."
- [23] M. Andersson, "Object-oriented modeling and simulation of hybrid systems," Ph.D. dissertation, 1994. [Online]. Available: <https://lup.lub.lu.se/search/ws/files/4520459/8566313.pdf>
- [24] "The neutral model format for building simulation, version 3.02."
- [25] P. I. Barton and C. C. Pantelides, "Modeling of combined discrete/continuous processes," *AIChE Journal*, vol. 40, no. 6, pp. 966–979, 1994. [Online]. Available: <https://aiche.onlinelibrary.wiley.com/doi/abs/10.1002/aic.690400608>
- [26] K. Boulkroune, Y. Candau, G. Piar, and A. Jeandel, "Validation of a building thermal model by using allan. simulation software," *Energy and buildings*, vol. 22, no. 1, pp. 45–57, 1995.
- [27] T. Ernst, S. Jähnichen, M. Klose, and T. Ernst, "The architecture of the smile/m simulation environment," in *Proc. 15th IMACS World Congress on Scientific Computation, Modelling and Applied Mathematics*, vol. 6. Citeseer, 1997, pp. 653–658.
- [28] C. Maffezzoni and R. Girelli, "Moses: modular modelling of physical systems in an object-oriented database," *Mathematical and Computer Modelling of Dynamical Systems*, vol. 4, no. 2, pp. 121–147, 1998.
- [29] "Modelica newsletter," 2009. [Online]. Available: <https://www.modelica.org/publications/newsletters/2009-1>

- [30] J. Batteh and M. Tiller, "Implementation of an extended vehicle model architecture in modelica for hybrid vehicle modeling: development and applications," in *Proceedings of the 7th International Modelica Conference; Como; Italy; 20-22 September 2009*, no. 043. Citeseer, 2009, pp. 823–832.
- [31] M. Wetter and C. Haugstetter, "Modelica versus trnsys—a comparison between an equation-based and a procedural modeling language for building energy simulation," *Proceedings of SimBuild*, vol. 2, no. 1, 2006.
- [32] M. Wetter, "Modelica library for building heating, ventilation and air-conditioning systems," Lawrence Berkeley National Lab.(LBNL), Berkeley, CA (United States), Tech. Rep., 2009.
- [33] L. Liao and E. Ai Lin Teo, "Organizational change perspective on people management in bim implementation in building projects," *Journal of management in engineering*, vol. 34, no. 3, p. 04018008, 2018.
- [34] S. Azhar, J. Brown, and R. Farooqui, "Bim-based sustainability analysis: An evaluation of building performance analysis software," in *Proceedings of the 45th ASC annual conference*, vol. 1, no. 4. Citeseer, 2009, pp. 276–292.
- [35] "Designbuilder documentation (2019) retrieved from designbuilder website:." [Online]. Available: <http://www.designbuilder.co.uk/>
- [36] "Equa simulation ab (2015) ida indoor climate and energy." [Online]. Available: <http://www.equa.se/en/ida-ice>
- [37] "Simulation and energy plus general considerations." [Online]. Available: http://pcc5746.pcc.usp.br/Textos_Tecnicos/PCC%205746%20Simula%C3%A7%C3%A3o%20EnergyPlus.PDF

- [38] H. S. Rallapalli, “A comparison of energyplus and equest whole building energy simulation results for a medium sized office building,” Ph.D. dissertation, Arizona State University, 2010.
- [39] [Online]. Available: TRNSYSofficialwebsite:<https://sel.me.wisc.edu/trnsys/>
- [40] [Online]. Available: eQuestwebsite:<http://energy-models.com/equest>
- [41] EnerLogic and J. J. H. . Associates, “equest - the quick energy simulation tool.” [Online]. Available: <http://www.doe2.com/equest/>
- [42] “Autodesk (2013) green building studio’s validation testing through ashrae standard 140-2011.” [Online]. Available: <http://autodesk.typepad.com/bpa/2013/09/green-building-studios>
- [43] [Online]. Available: <https://gbs.autodesk.com/GBS/>
- [44] [Online]. Available: <https://openei.org/wiki/Ecotect>
- [45] L. Yang, B.-J. He, and M. Ye, “Application research of ecotect in residential estate planning,” *Energy and buildings*, vol. 72, pp. 195–202, 2014.
- [46] B. Arranz, E. Rodríguez-Ubiñas, C. Bedoya-Frutos, and S. Vega-Sánchez, “Evaluation of three solar and daylighting control systems based on calumen ii, ecotect and radiance simulation programmes to obtain an energy efficient and healthy interior in the experimental building prototype sd10,” *Energy and buildings*, vol. 83, pp. 225–236, 2014.
- [47] A. Marsh, “Ecotect manual: Building analysis program: Square one research ltd,” 2011.

- [48] T. Maile, M. Fischer, and V. Bazjanac, “Building energy performance simulation tools—a life-cycle and interoperable perspective,” *Center for Integrated Facility Engineering (CIFE) Working Paper*, vol. 107, pp. 1–49, 2007.
- [49] [Online]. Available: <http://www.buildup.eu/en/learn/tools/riuska>
- [50] M. Jokela, A. Keinanen, H. Lahtela, and K. Lassila, “Integrated building simulation tool riuska,” 1997.
- [51] [Online]. Available: https://www.vipenergy.net/English_Home.htm
- [52] [Online]. Available: <https://strusoft.com/products/vip-energy>
- [53] S. Attia, “State of the art of existing early design simulation tools for net zero energy buildings: a comparison of ten tools,” *Architecture et climat*, Tech. Rep., 2011.
- [54] P. Fritzson, *Introduction to modeling and simulation of technical and physical systems with Modelica*. John Wiley & Sons, 2011.
- [55] D. A. Arias, “Advances on the coupling between a commercial cfd package and a component-based simulation program,” *Proceedings of SimBuild*, vol. 2, no. 1, 2006.
- [56] I. Beausoleil-Morrison, “The adaptive coupling of heat and air flow modelling within dynamic whole-building simulation,” Ph.D. dissertation, Citeseer, 2000.
- [57] Z. Zhai, “Developing an integrated building design tool by coupling building energy simulation and computational fluid dynamics programs,” Ph.D. dissertation, Massachusetts Institute of Technology, 2003.
- [58] Q. Chen, “Ventilation performance prediction for buildings: A method overview and recent applications,” *Building and environment*, vol. 44, no. 4, pp. 848–858, 2009.

- [59] D. Crawley, L. Lawrie, F. Winkelmann, W. Buhl, A. Erdem, C. Pedersen, R. Liesen, D. Fisher, R. Strand, and R. Taylor, "What's next for building energy simulation—a glimpse of the future," in *PROCEEDINGS OF THE NATIONAL PASSIVE SOLAR CONFERENCE*, vol. 22. AMERICAN SOLAR ENERGY SOCIETY INC, 1997, pp. 309–314.
- [60] C. Pedersen, D. Fisher, R. Liesen, R. K. Strand, R. Taylor, W. F. Buhl, F. Winkelmann, L. Lawrie, and D. Crawley, "Energybase: The merger of blast and doe-2," in *Proceedings of IBPSA International Conference, Prague, Czech Republic*, vol. 3, 1997, pp. 1–8.
- [61] H. E. Feustel and A. Raynor-Hoosen, "Fundamentals of the multizone air flow model comis," *Technical Note TN*, vol. 29, 1990.
- [62] Z. Ren and J. Stewart, "Simulating air flow and temperature distribution inside buildings using a modified version of comis with sub-zonal divisions," *Energy and Buildings*, vol. 35, no. 3, pp. 257–271, 2003.
- [63] L. Mora, A. Gadgil, and E. Wurtz, "Comparing zonal and cfd model predictions of isothermal indoor airflows to experimental data." *Indoor air*, vol. 13, no. 2, pp. 77–85, 2003.
- [64] W. Zuo, J. Hu, and Q. Chen, "Improvements in ffd modeling by using different numerical schemes," *Numerical Heat Transfer, Part B: Fundamentals*, vol. 58, no. 1, pp. 1–16, 2010.
- [65] Z. Zhai and Q. Y. Chen, "Numerical determination and treatment of convective heat transfer coefficient in the coupled building energy and cfd simulation," *Building and Environment*, vol. 39, no. 8, pp. 1001–1009, 2004.

-
- [66] M. Trčka, J. L. Hensen, and M. Wetter, “Co-simulation of innovative integrated hvac systems in buildings,” *Journal of Building Performance Simulation*, vol. 2, no. 3, pp. 209–230, 2009.
- [67] —, “Co-simulation for performance prediction of integrated building and hvac systems—an analysis of solution characteristics using a two-body system,” *Simulation Modelling Practice and Theory*, vol. 18, no. 7, pp. 957–970, 2010.
- [68] M. Wetter, W. Zuo, and T. S. Noudui, “Recent developments of the modelica" buildings" library for building energy and control systems,” Lawrence Berkeley National Lab.(LBNL), Berkeley, CA (United States), Tech. Rep., 2011.
- [69] P. Ostlund, K. Stavaker, and P. Fritzson, “Parallel simulation of equation-based models on cuda-enabled gpus,” in *Proceedings of the 9th Workshop on Parallel/High-Performance Object-Oriented Scientific Computing*, 2010, pp. 1–6.
- [70] M. Ljubijankic, C. Nytsch-Geusen, J. Rädler, and M. Löffler, “Numerical coupling of modelica and cfd for building energy supply systems,” in *Proceedings of the 8th International Modelica Conference; March 20th-22nd; Technical Univeristy; Dresden; Germany*, no. 063. Citeseer, 2011, pp. 286–294.
- [71] M. Bonvini, A. Leva, and E. Zavaglio, “Object-oriented quasi-3d sub-zonal airflow models for energy-related system-level building simulation,” *Simulation Modelling Practice and Theory*, vol. 22, pp. 1–12, 2012.
- [72] E. Bender, “Numerical heat transfer and fluid flow. von s. v. patankar. hemisphere publishing corporation, washington – new york – london. mcgraw hill book company, new york 1980. 1. aufl., 197 s., 76 abb., geb., dm 71,90,” *Chemie Ingenieur Technik*, vol. 53, no. 3, pp. 225–225, 1981. [Online]. Available: <https://onlinelibrary.wiley.com/doi/abs/10.1002/cite.330530323>

- [73] H. K. Versteeg and W. Malalasekera, *An introduction to computational fluid dynamics: the finite volume method*. Pearson education, 2007.
- [74] Q. Chen and W. Xu, “A zero-equation turbulence model for indoor airflow simulation,” *Energy and buildings*, vol. 28, no. 2, pp. 137–144, 1998.
- [75] S. E. Mattsson, H. Elmqvist, and M. Otter, “Physical system modeling with modelica,” *Control Engineering Practice*, vol. 6, no. 4, pp. 501–510, 1998.