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Comparison of the two Building Simulation Environments TRNSYS and DesignBuilder

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Abstract

A multitude of simulation programs are currently used for thermal building simulations. Different programs are based on different physical models and use different numerical methods. The ASHRAE 140-2004 guideline provides a standard method to compare building simulation software. Building parameters (e.g. orientation and size of windows, shading devices...) of simple test buildings are modified systematically under well defined boundary conditions. Using that method, the capabilities of the programs to model the thermal behavior of certain building configurations can be compared with each other. The most common software tools have already been tested with the ASHRAE 140-2004 standard method. The results of that test, which are the annual heating and cooling energy demand and the peak heating and cooling load, are provided by the standard.

In this thesis, the building simulation environments TRNSYS and DesignBuilder are compared to each other in order to identify their strengths and weaknesses and their applicability to practical building simulation tasks. In Section 2 the physical models and the numerical methods, which were used in both programs, are presented and discussed. Simulations of some selected cases of the ASHRAE 140-2004 have been carried out. Simulation results are presented in Section 3. In addition to the standard method, detailed energy balances are compared. A detailed breakdown of heat gains and losses into heating demand, cooling demand, solar gains, transmission gains and losses, internal gains and infiltration gains and losses facilitates a better evaluation of the simulation programs. Differences in simulation results are traced back to differences in the underlying models and numerical methods.

In all simulated cases, TRNSYS showed a higher heating energy demand and a lower cooling energy demand. The differences in the annual results are in the order of ±10%. The main reasons for the differences can be found in the model for the external convection coefficient and in differing models and routines for solar radiation processing. The main difference in the models is that DesignBuilder uses a three-dimensional geometrical building model, whereas TRNSYS does not have explicit information about the building geometry. The geometrical building model allows deriving certain building properties automatically from the geometry, which is a big advantage in practical applications. A big advantage of TRNSYS is that it allows a much more flexible handling of the information flow in the program.

Kurzfassung

Gegenwärtig wird eine Vielzahl von Programmen zur thermischen Gebäudesimulation verwendet. Unterschiedliche Simulationsprogramme basieren auf unterschiedlichen physikalischen Modellen und verwenden unterschiedliche numerische Lösungsverfahren. Die Richtlinie ASHRAE 140-2004 bietet eine Standardmethode zum Vergleich von Gebäudesimulationsprogrammen. Dabei werden bei einfachen Testgebäuden unter definierten Randbedingungen systematisch Gebäudeparameter (z.B. Ausrichtung und Größe der Fenster, Beschattungsvorrichtungen,...) verändert und die Ergebnisse der Jahressimulationen verglichen. Damit können die Möglichkeiten der Programme zur Abbildung des thermischen Verhaltens bestimmter Gebäudekonfigurationen gegenübergestellt werden. Die meisten gängigen Simulationsprogramme wurden bereits nach ASHRAE 140-2004 getestet. Die Ergebnisse, der jährliche Heiz- und Kühlenergiebedarf sowie die maximale Heiz- und Kühlleistung, sind im Standard angeführt.

In dieser Arbeit werden die beiden Gebäudesimulationsprogramme TRNSYS und DesignBuilder miteinander verglichen. Dabei sollen die Stärken und Schwächen der beiden Programme herausgearbeitet werden. In Kapitel 2 werden die physikalischen Modelle und numerischen Methoden der Programme vorgestellt und diskutiert. Ausgewählte Fälle der ASHRAE 140-2004 werden simuliert. Die Ergebnisse werden in Kapitel 3 vorgestellt und diskutiert. Ergänzend zur Standardmethode werden hier die gesamten Energiebilanzen der Gebäude aufgeschlüsselt und verglichen. Die detaillierte Aufteilung der Wärmegewinne und Verluste in Heizwärmebedarf, Kühlbedarf, solare Gewinne, Transmissionsgewinne und -verluste, interne Gewinne und Infiltrationsverluste ermöglicht einen besseren Vergleich der Simulationsprogramme. Unterschiede in den Simulationsergebnissen werden auf Unterschiede in den Modellen und Berechnungsmethoden zurückgeführt.

Die Ergebnisse der TRNSYS Simulationen weisen durchwegs einen höheren Heizwärme- und einen niedrigerer Kühlbedarf auf. Die Unterschiede liegen in einer Größenordnung von ±10%. Hauptgründe für die Abweichungen sind unterschiedliche Modelle für den externen Konvektionskoeffizienten und unterschiedliche Berechnungsmethoden für die Solarstrahlung. Der Hauptunterschied der Modelle liegt darin, dass DesignBuilder ein dreidimensionales, geometrisches Gebäudemodell verwendet, währen TRNSYS keine explizite Information über die Gebäudegeometrie besitzt. Für die Praxis bringt ein geometrisches Modell den Vorteil, dass viele Gebäudeeigenschaften automatisch aus der Geometrie abgeleitet werden können, die damit nicht zusätzlich berechnet werden müssen. TRNSYS hat den Vorteil, dass es dem Nutzer viel mehr Flexibilität bietet, insbesondere bei der Gestaltung des Informationsflusses im Programm.

Preface

The work presented in this thesis has been carried out at the Institute of Thermal Engineering at the Graz University of Technology. It was supervised by Dr. Hermann Schranzhofer (Institute of Thermal Engineering, TU Graz), Dr. Wolfgang Streicher (Institute of Thermal Engineering, TU Graz) and Dr. Peter Knoll (Institute of Physics, KFU Graz).

I would like to thank my supervisors for good advises and an encouraging support.

Contents

1 Introduction to Building Energy Simulation

1.1 Why building energy simulation?

About 30% of the present end use energy demand in Austria is used for heating and cooling of buildings and for domestic hot water (DHW) generation (Figure 1). A large part of the energy used in buildings comes from fossil sources (Figure 2). Thus the building sector is a major contributor to the overall fossil fuel use and CO_2 emissions.
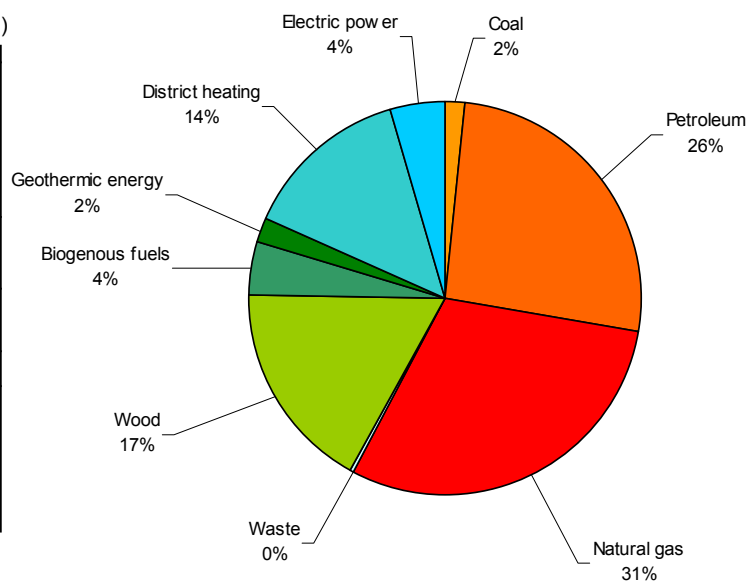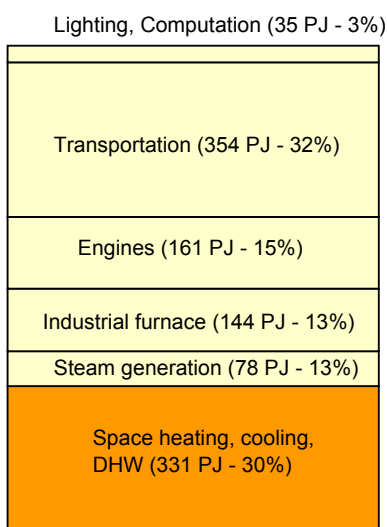
Figure 1: End use energy demand in Austria, (Statistik Austria, 2006)

Figure 2: Energy sources for heating, cooling and DHW generation in Austria, (Statistik Austria, 2006)

Figure 3 shows the specific heating energy demand for buildings of different type and age in Austria. Comparing the building stock with a state of the art technology, like the passive house, shows that there is a huge potential for energy saving in the building sector. This is consistent with European Commission's figures, which estimate, that with the implementation of energy efficient technologies in new and existing buildings, the energy consumed in buildings could be reduced by around 20% within the next 10 years (Kokogiannakis, 2002). Thus the development and design of sustainable, energy efficient buildings and energy systems is an important step towards a sustainable society.
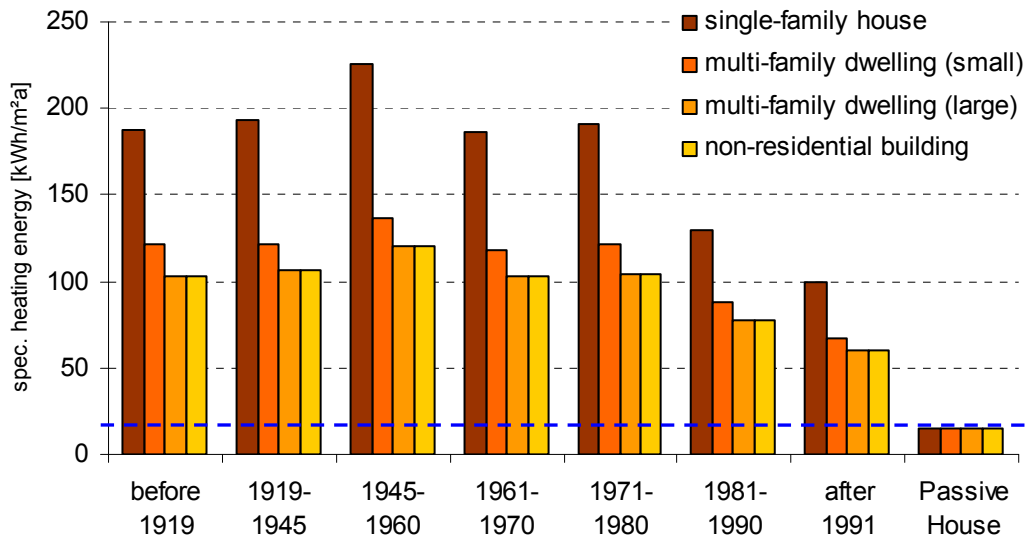
Figure 3: Specific heating energy demand for different buildings of different type and age in Austria (Meister, 1999)

Buildings are complex systems, consisting of numerous interacting components and subsystems, which are exposed to various, time dependent climatic and user induced influences. A building might consist of supporting structural elements, building envelope, windows, glazed facade, shading devices, active and passive solar elements, heating- cooling and air-supply systems, electrical systems, lighting systems and various control systems. It is influenced amongst others by solar radiation, outside temperature, wind and the behavior of the occupants. Especially the ambition in modern engineering to design and develop efficient, sustainable building components and energy systems often leads to a combination of different systems to benefit from synergies. Examples are combined heat and power generation or waste heat recovery. In such cases it is crucial to know how the systems interact and influence each other.

The complex geometry and the various, sometimes nonlinear interactions which appear in building systems make an analytical solution of the underlying equations impossible. Thus traditional design concepts are based on many simplifying assumptions like steady state, linearity or neglecting the interaction between components. In reality these assumptions are invalid most of the time. Due to the irregular, non-stationary excitation by weather variables and other influencing factors, a building is in a transient state almost any time. Steady state methods are not capable of describing the dynamical properties of the system and often lead to false estimations. Thus a dependable energy performance assessment requires dynamic techniques (Clarke, 2001).

Simulations in general are used in engineering and science for various reasons. The main objective of a simulation is to make predictions about the behavior of the system under consideration. In order to perform a simulation a mathematical model has to be build, which should capture the key features of the real system. Compared to traditional energy

modeling techniques, the models used in computer simulations are much more sophisticated, which allows to analyze the behavior of the system under almost realistic boundary conditions.

Computer simulations of the energetic behavior of buildings and their energy systems offer many advantages to engineering and science. They:

- show the dynamic behavior of the system without the need to build the system in reality and perform measurements. Thus simulations are orders of magnitude faster and less expensive than experiments.

- allow an investigation of the system at the desired length and time scale with the desired level of detail.

- allow energy performance assessment of buildings and building systems. Building simulations provide the basic data which can be processed to ecological and economical performance measures.

- provide decision support in the design process. Simulations allow the designer to test a range of design alternatives and show the consequences of the design decisions.

- allow a systematic optimization of building components and systems.

- allow sensitivity analysis by systematic parameter variation.

- allow a validation of simplified methods of calculation.

On the other hand computer simulations also entail some problems and restrictions:

- Uncertainty about the correctness of the results. Since all simulations are based on a mathematical model one can never be sure that the results represent the actual behavior of the real system. The results can differ due to inadequate modeling assumptions, errors in the solving algorithm, numerical errors or poor input data.

- Results rely heavily on the quality of the input data. This can cause major problems, because both main input factors, the climate and the behavior of the occupants, are hard to predict and show random fluctuations.

- Comprehensive simulations are time consuming and expensive compared to traditional simplified design methods. In industrial design problems each product can be simulated and tested comprehensively, because many identical products can be sold. In building design, a simulation can only be used for one single building, because usually every building is unique. Thus architects and engineers often still use traditional methods (Mach, 2008).

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1.2 Energy flow paths in a building

A building is affected by many external influences which give rise to the dynamic behavior of the system. In order to map that behavior, a proper building model has to consider various energy and mass transfer mechanisms inside and outside of the building. The following listing is based on Clarke (2001).

Transient conduction

In this context transient conduction describes the time dependent heat transfer through a structural component like a building envelope or the envelope of a heat storage tank. A fluctuation of heat flux at one boundary can be considered as a signal which is transmitted through the element. The thermal resistance and the heat capacity of the construction materials cause attenuation and a phase shift of the signal.

Some dynamical properties of massive components cannot be understood in terms of steady state concepts. Different arrangements of wall layers may perform differently even though they have the same U-value. An example is the utilization of an insulated massive wall as a solar heat storage. If the massive part is located at the innermost position and the thermal insulation is located at the outside, the wall can store solar energy which strikes its inner surface. Conversely, if the insulation is located at the inner side the radiation will cause a temperature rise of the inner surface temperature, which cannot propagate into the wall because of the properties of the insulation material.

The thermophysical properties which characterize the dynamical conduction behavior are conductivity, density and heat capacity. In whole building simulations these properties are usually assumed constant and isotropic.

Surface convection

This process describes the heat exchange between the surface of a solid material and the adjacent fluid. In the context of building simulation the convection on the external surface of a wall is mainly wind induced. On the inner surface natural and forced convection can take place. Natural convection occurs if temperature differences cause an instable density configuration in the fluid. Forced convection depends on the resulting flow field, induced by mechanical ventilation or zone-coupled flows.

In building simulation both, varying and constant surface coefficients are used, depending on the level of accuracy needed. Typically, convection coefficients are surface-averaged.

Internal surface longwave radiation exchange

The inner surfaces of a room emit longwave radiation according to their temperature and their emissivity. The resulting energy flow in the room depends on the relative position of the surfaces (view factor) and the nature of the surface reflection (diffuse, specular).

The heat flux out of a surface depends on convection and radiation. They are coupled because both have an effect on the surface temperature. Some simulation programs use simplified methods to compute combined convection/radiation coefficients.

External longwave radiation exchange

This process describes the longwave radiative energy exchange between external building surfaces and the sky vault, surrounding buildings and the ground. Key factors in this process are the effective sky temperature as a function of the cloud cover, temperature and relative position of surrounding buildings, temperature and relative position of the ground and external surface temperature of the building.

Shortwave radiation

The shortwave irradiation from the sun has a major impact on the energy balance of a building. Because of the angle dependence of the properties which characterize the shortwave energy transfer, one has to distinguish between beam radiation and diffuse radiation.

Some portion of the incident solar radiation on an opaque external surface will be absorbed and partially transmitted to the internal surface of the building envelope. The surface temperature of an external surface, exposed to direct solar radiation, may be significantly higher than the ambient temperature and thus may have a major impact on the transient conduction in the fabric.

At transparent building elements, the direct and diffuse radiation will be reflected, absorbed and transmitted at each layer. The absorbed flux increases the temperature of the component which gives rise to a convective, conductive and radiative heat transfer in both directions.

The transmitted radiation may be partially absorbed and reflected on internal surfaces or may leave the zone through a transparent surface. The absorbed portion gives rise to transient conduction, thus the solar energy is stored in the building element.

The magnitude of solar gains in a building depends heavily on shading objects. Shading may be caused by remote obstructions like trees or buildings, concave building geometry or shading devices. Shading devices can be fixed like overhangs or wingwalls or controllable like jalousies or blinds. In the later case the behavior of the occupants or the controlling system becomes an important factor and has to be considered in the model. The effectiveness of shading devices also depends heavily on whether they are positioned inside or outside of the building.

The properties which characterize the shortwave energy transfer in buildings are absorptivity, transmissivity and reflectivity. All of these properties depend on the angle of incidence and the spectral composition of the flux.

Air flow

In buildings, three air flow paths have to be considered: infiltration, zone-coupled flows and mechanical ventilation.

Infiltration is the intrusion of air from the outside into the building, which happens in two different ways. One is the movement of outside air through small cracks around windows and doors and in the fabric; the other is the airflow through intentional openings like windows and air vents, which is also called natural ventilation. Infiltration is caused by pressure differences and buoyancy forces associated with air temperature differences.

Zone-coupled flows are the airflows between coupled air volumes in the building. Like infiltration they are caused by pressure and temperature differences. Mechanical ventilation is used to satisfy fresh air requirements and to heat or cool a space.

Despite the complex and partially stochastic nature of infiltration and zone-coupled airflow, models of different complexity are used in practice. The models range from simple, fixed air change rates to comprehensive models which consider the energy, continuity and momentum equations (Navier-Stokes equation). In whole building energy simulation airflow is often modeled by a nodal network. The nodes in that model represent fluid volumes and the links represent the leakage paths.

Internal gains

In modern buildings heat gains from occupants, lighting, electrical equipment and the like can have a considerable effect on the energy balance of the building. Therefore it is important to have an appropriate model of these heat sources, which are called internal gains or casual gains. Typically the time dependent behavior is specified in fixed schedules. Internal heat may also be a function of other parameters, for example in the case of daylight responsive luminaire dimming.

Internal heat gains are separated into radiant and convective gains. Convective gains are considered as an instantaneous air load, longwave radiant gains are apportioned between the internal surfaces. Because of the construction capacity, radiant gains contribute to the air load with some time lag.
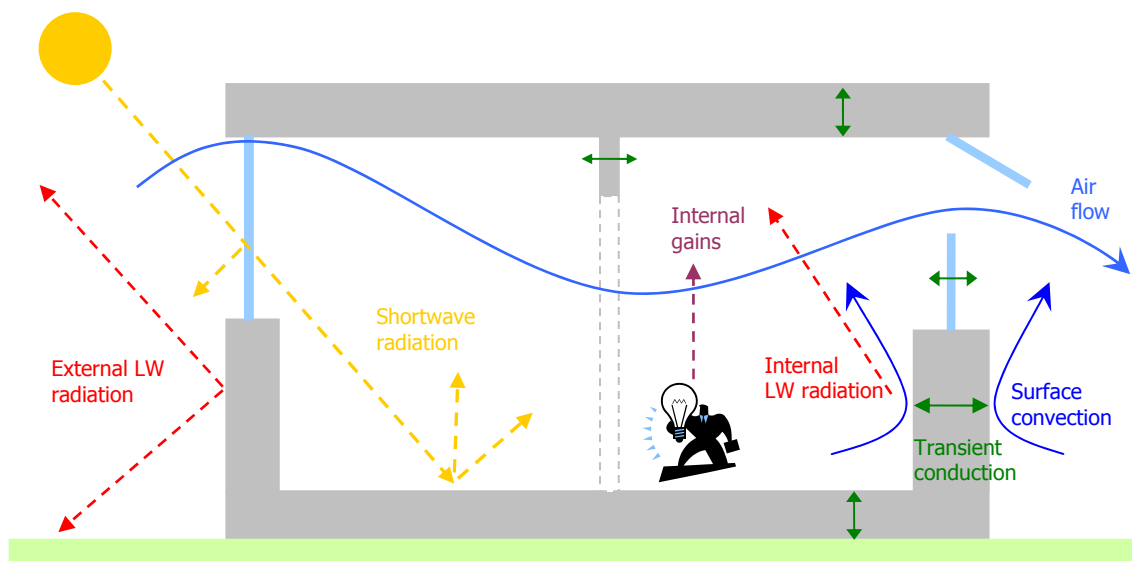
Figure 4: Energy flow paths in a building

1.3 Sequence of simulation steps

This section provides an overview on the main tasks that have to be performed in order to carry out a building energy simulation.

Building and energy system description

At first the appropriate type of simulation has to be chosen according to the simulation goals. Mach (2008) distinguishes three types of simulations associated with the thermal behavior of buildings and energy systems:

- Building simulation: Only the thermal behavior of the building is being simulated. HVAC systems are represented by idealized systems which provide the exact amount of energy needed to meet the desired setpoints.

- Plant simulation: Only the behavior of HVAC systems or energy plants is being simulated. The behavior of the building is given as a boundary condition.

- Combined building and plant simulation: The interplay of building and the HVAC system is being simulated. This is the most complex and computationally intensive type of simulation.

Depending on the type of simulation, building construction information, information about the HVAC system and information about the central plant has to be entered.

A building consists of one or more thermal zones which are coupled with each other and with the environment. A zone consists of an air volume of a uniform temperature and all surfaces bounding or inside that air volume. The zones are bounded by external or internal walls, floors, ceilings, roofs, windows or doors. These construction elements are composed of layers of various building materials (see Figure 5).

Figure 5: Hierarchical structure of the building description (Schranzhofer, 2008)

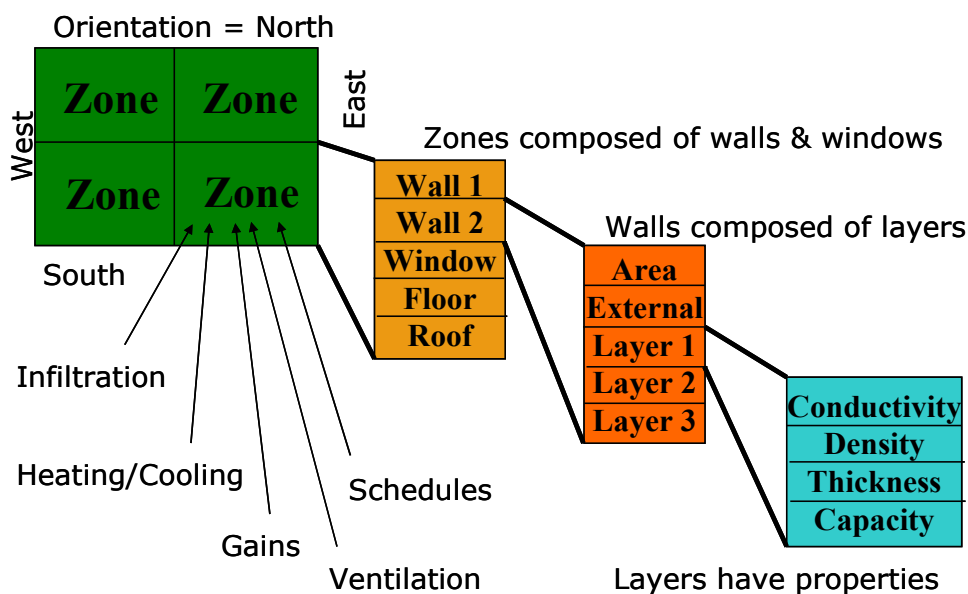Each level of description has its own parameters which need to be specified: the thermo-physical properties of the building materials, the size, structure and orientation of the building elements or the size and structure of the zones. Some simulation environments even require full geometric information about the whole building.

The information about the HVAC system and the central plant has to include information about the parts of the system (fans, pumps, heat exchangers, boilers, chillers…), their interactions and parameters for their operation (heating and cooling setpoints, operation schedules…).

Specifying of boundary conditions

In this context boundary conditions specify the external influences on the building system. One has to provide information on the following factors over the whole simulation period:

<u>Occupants</u>: Schedules for number of occupants in a zone and their metabolic rate according to their activity. Several guidelines (ÖNORM B 8110-T5; BFE, 1997; VDI 2078, 1996; VORNORM DIN V 18599-10, 2005; SIA- Merkblatt 2024, 2006) provide standard values for common situations.

<u>Lighting and other equipment</u>: Schedules for lighting and electrical equipment and their radiant and convective heat output.

<u>Weather</u>: Time series of appropriate weather data, including ambient temperature, wind, solar radiation and humidity. Depending on the goal of the simulation and the availability of data, either measured or synthetically generated weather data (e.g. Meteonorm) can be used.

Specifying the simulation parameters

Most building simulation programs allow to choose between several different physical models for surface convection, infiltration, natural ventilation and the like, in order to adjust the simulation to the actual situation. Some models are described in the sections 2.1 and 2.4.

In some cases also the numerical methods and algorithms have to be specified. In EnergyPlus for example heat conduction can be either simulated using conduction transfer functions or finite difference methods.

In any case the simulation parameters have to be specified. They include for example the simulation timestep, the run period, convergence limits and the maximum number of iterations. The simulation timestep can have a significant impact on the simulation results and has to be chosen carefully. A simulation with a timestep which is larger than the time constant of the process under consideration is not able to show the dynamic behavior of the process. On the other hand, a too small timestep leads to long computation times, a large amount of data and eventually to numerical instabilities due to round-off and

truncation errors, without gaining additional information. The timestep also has to be chosen with respect to the available input data.

Simulation

After providing all necessary information, the simulation process can be started. The procedure involves interpolation and processing of the weather data according to the specified models (see 2.3) and solving the dynamical equations according to the chosen building models.

The simulation time depends on the complexity of the models and the capabilities of the computer system. Typical simulation times for building simulations lie between some minutes and some hours, but may go up to even some days.

Post processing

After generating the specified output, the simulation results have to be processed and displayed in a proper way, so that they can be analyzed easily. This procedure is called post processing. Simulation output is usually provided at the simulation timestep. During post processing, hourly, daily, monthly and annual sums and mean values are calculated out of the raw data. In addition output variables can be aggregated in various ways, for example to calculate the heating demand of a storey or the whole building as sum over the heating demand of all thermal zones in that area.

Most programs have some features to process the simulation output and display the results, but in many cases the capabilities are very limited. Another opportunity is to export the raw data and then use a spread sheet program (e.g. MS Excel) or an external data processing software (e.g. Matlab, Origin). External data processing is much more flexible and allows the automation of frequently used processing tasks.

1.4 Common building energy software tools

1.4.1 TRNSYS

TRNSYS (Transient Systems Simulation Program) is a software package for simulating the thermal behavior of buildings including active and passive energy systems. The basic idea of TRNSYS is to model each piece of an energy system as an individual black box component. With this modular concept, complex systems can be simulated by connecting the inputs and outputs of the black boxes to one another.
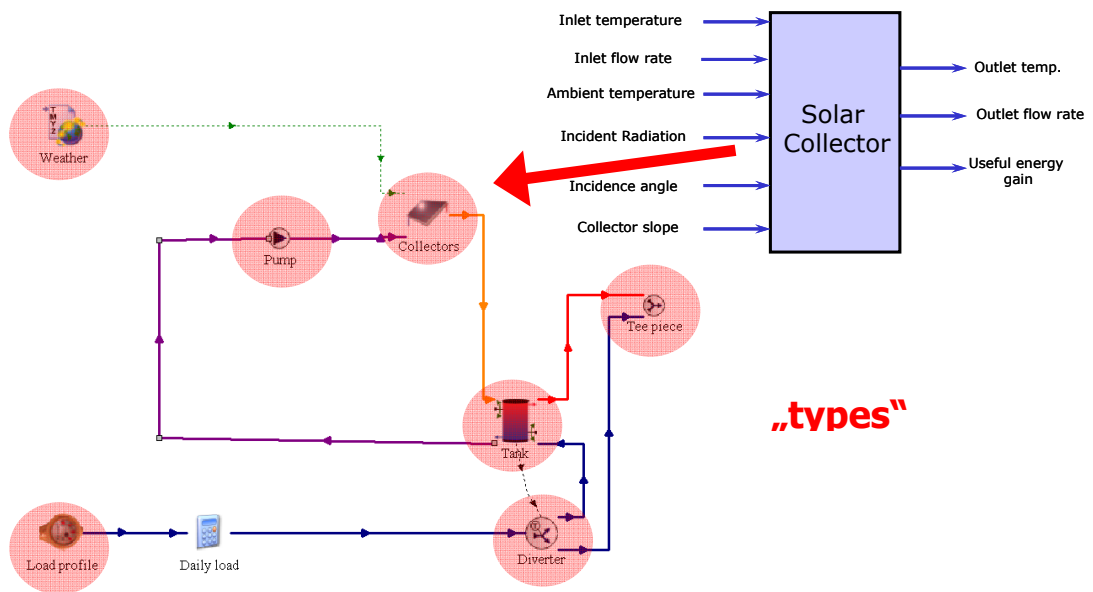
Figure 6: Modular concept of TRNSYS (Schranzhofer 2008)

TRNSYS was developed at the Solar Energy Laboratory (SEL) at the University of Wisconsin for simulating thermal solar systems. The first commercial version came on the market in 1975. Since that time TRNSYS has been expanded into a full building energy modeling package. The source code of the kernel and the component models are available for the users. Users can program their own modules (Types), to fit them to their specific needs, which through the years has led to a very big number of available components. Thus TRNSYS often provides multiple models for the same element, which may vary in complexity, in the required input data and therefore in the time to integrate the module in the simulation. The user has the advantage to choose how simple or detailed the model has to be, depending on the nature and the scope of the investigated problem.

The DLL-based (Dynamic Link Library) architecture of TRNSYS allows users and developers to use all common programming languages (Fortran, C++, PASCAL, etc.) to add new components. TRNSYS can be connected to other application like MS Excel, Origin or Matlab for pre- or post-processing. It is even possible to integrate external programs through interactive calls during the simulation. The TRNSYS engine is programmed in FORTRAN and compiled into Windows Dynamic Link Library (DLL).

TRNSYS uses a sequential modular approach. The main program manages the module subroutines, determines the sequence of computation and the associated convergence criteria (Figure 7).
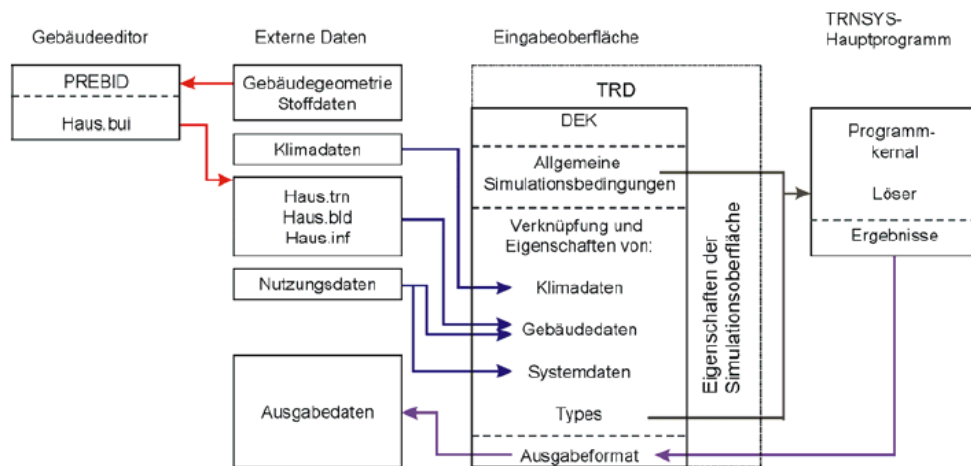
Figure 7: Main TRNSYS components and program sequence (Heimrath, 2007)

The central file in TRNSYS-simulation is the so-called "deck file", with the extension *.dck. This file contains all necessary information about the simulated system: which components are used, how the components are connected, simulation start- and stop time, simulation time step, etc. If a building or a part of a building is being simulated, the program also needs a building file (* .bui) which contains all necessary building parameters. The TRNSYS kernel reads these input files and calculates the output. The input files are normal text files (ASCII) and can be generated and edited using a graphical user interface or a plain text editor.
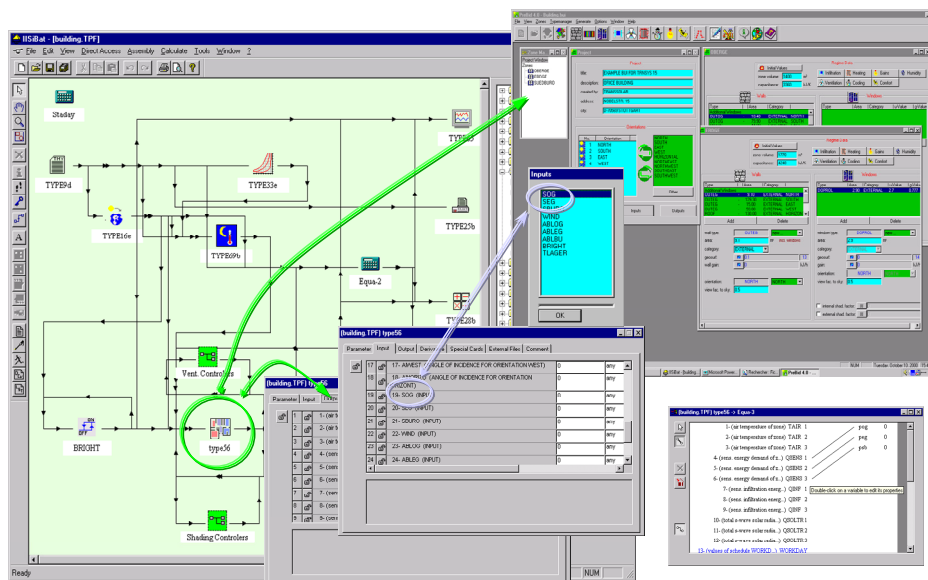
Figure 8: TRNSYS graphical user interfaces, TRNSYS studio and TRNBuild

In TRNSYS all systems such as heating or air-conditioning systems are provided not as components themselves but as a collection of parts (pumps, pipes, fans, heat storages, heat exchangers etc.) which makes the program very flexible.

All TRNSYS simulations presented in this thesis have been carried out with TRNSYS version 16.01.0034.

1.4.2   EnergyPlus

EnergyPlus is a building energy simulation program released by the U.S. Department of Energy (DoE) in 2001. It has a modular structured code and is based on the simulation programs BLAST (Building Loads Analyses and Systems Thermodynamics) and DOE-2. EnergyPlus enables the simulation of the thermal behavior of multizone buildings and their energy systems.

EnergyPlus has been developed at the Lawerence Berkeley National Laboratory (LBNL) as a simulation engine which can be embedded in a third-party interface (Figure 9). So EnergyPlus has no graphical user interface, it is operated via input and output text files. The source code of EnergyPlus is available for public inspection and revision.
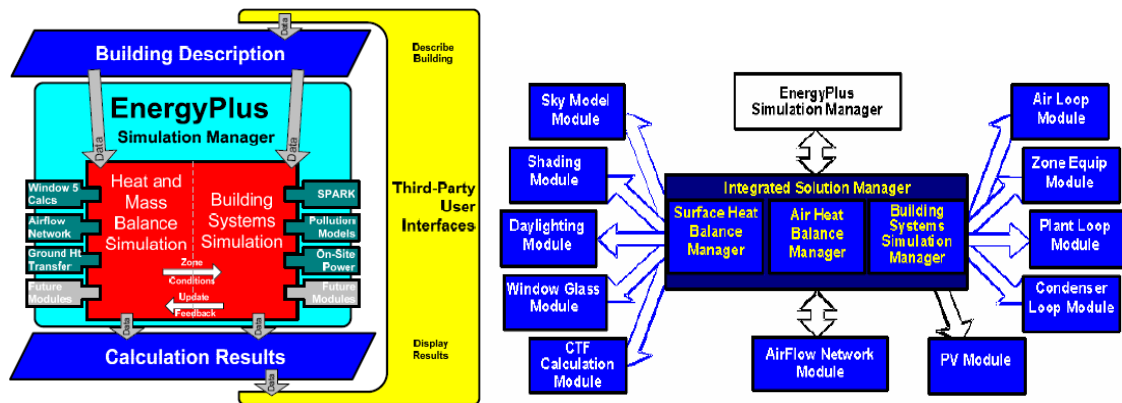
Figure 9: EnergyPlus structure and main components (LBNL 2007)

In EnergyPlus the whole building system is divided into three main parts: Zone, System and Plant. Since EnergyPlus is an integrated simulation, these three parts are solved simultaneously. The entire system consists of many interacting modules which are integrated and controlled by the Integrated Solution Manager. Fluid loops are divided into supply and demand sides which are reconciled using a Gauss-Seidel iteration scheme.

The schematic subroutine calling tree shows the overall structure of the program (LBNL, 2006):

►ProcessInput (InputProcessor)

►ManageSimulation (SimulationManager)

　►ManageWeather (WeatherManager)

　►ManageHeatBalance (HeatBalanceManager)

　　►ManageSurfaceHeatBalance(HeatBalanceSurfaceManager)

　　►ManageAirHeatBalance (HeatBalanceAirManager)

　　　►CalcHeatBalanceAir (HeatBalanceAirManager)

　　　　►ManageHVAC (HVAC Manager)

The HVAC part of EnergyPlus is divided into a number of simulation blocks for the air system, the zone equipment, the plant supply, and the condenser demand. At every simulation timestep, the blocks are simulated repeatedly until the conditions on each side of the interface match up (Figure 9).

The main input file is the input data file (IDF), an ASCII file which contains information about the building and the HVAC system to be simulated. The IDF-file can be edited either with a normal text editor or with the IDF-editor, a simple "interface" which is supplied with the EnergyPlus installation (Figure 10).

Figure 10: EnergyPlus IDF-editor

The EnergyPlus input is structured into classes. For each class, fields are defined, which describe the characteristics of the class objects. Objects are the instances of a class. For

example to create a new wall, one has to create a new object of the "Surface:HeatTransfer"-class and assign the string "Wall" to the "SurfaceType"-field.

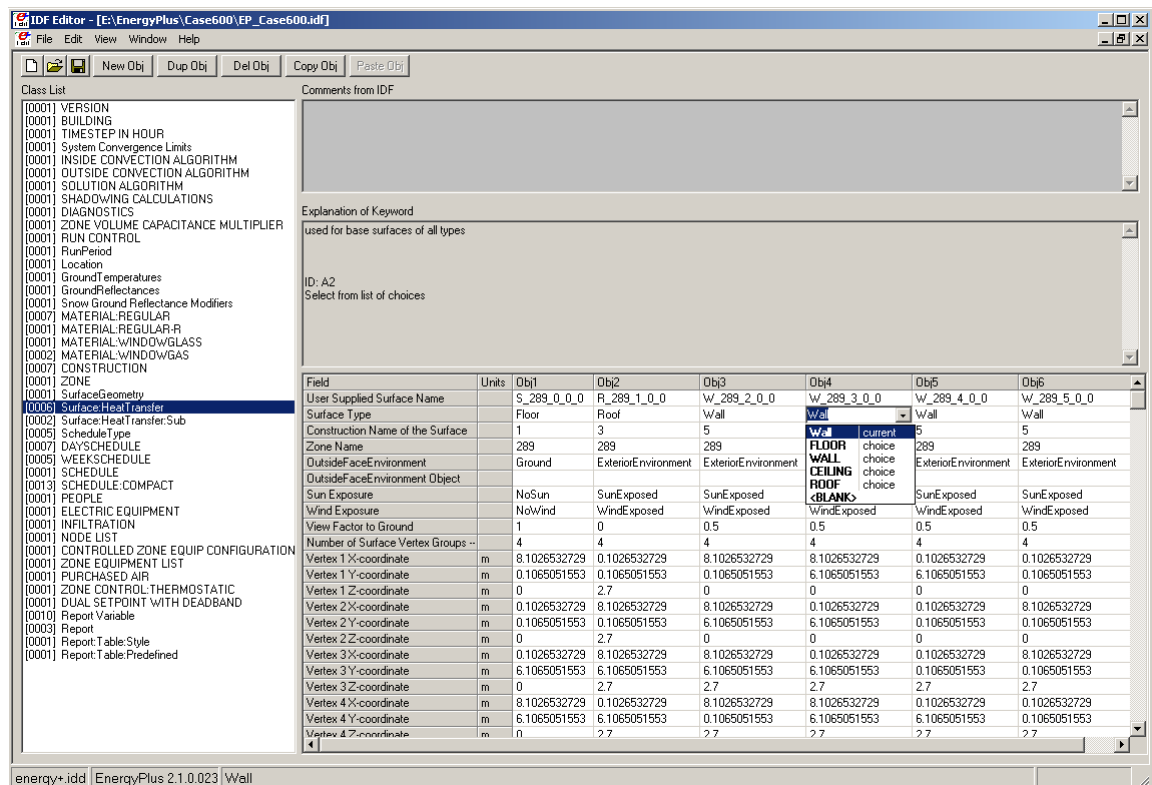Some fields of an object may contain references to other objects. With this feature it is possible to create a hierarchical building description (Figure 5). For example the "Construction Name of the Surface"-field of an "Surface:HeatTransfer"-object refers to a "CONSTRUCTION"-object. Each "Layer"-field of that object refers to a "Material"-object (Table 1).

Table 1: Examples for EnergyPlus classes, objects and fields

C L A S S	F I E L D	OBJECT1	OBJECT2
Material:Regular	Name	WoodSiding	Fiberglass quilt
	Roughness	Rough	Rough
	Thickness	0.012	0.066
	Conductivity	0.14	0.04
	Density	530	12
	Specific Heat	900	840
	Absorptance:Thermal	0.9	0.9
	Absorptance:Solar	0.6	0.6
	Absorptance:Visible	0.6	0.6
CONSTRUCTION	Name	WallConst01	…
	Outside Layer	WoodSiding	
	Layer #2	Fiberglass quilt	
	…	…	
Surface:HeatTransfer	User Supplied Surface Name	Ext_Wall_1	…
	Surface Type	Wall	
	Construction Name of the Surface	WallConst01	
	Zone Name	Zone1	
	Outside Face Environment	Exterior Envir.	
	Sun Exposure	SunExposed	
	Wind Exposure	WindExposed	
	View Factor to Ground	0.5	
	Number of Surface Vertex Groups	4	
	Vertex1 X-coordinate	8.1026532729	
	Vertex1 Y-coordinate	0.1065051553	
	Vertex1 Z-coordinate	0	
	Vertex2 X-coordinate	8.1026532729	
	…	…	
ZONE	Zone Name	Zone1	
	Relative North	28	
	X Origin	0	
	Y Origin	0	
	Z Origin	0	
	Volume	128	
	ZoneInsideConvectionAlgorithm	Detailed	
	ZoneOutsideConvectionAlgorithm	Detailed	

Since EnergyPlus uses a three-dimensional building model all vertex points of all surfaces have to be entered properly. One can imagine that it is impossible to do that manually for all but very simple buildings. Thus various tools and interfaces for creating and running EnergyPlus input files exist (DesignBuilder, ECOTECT…).

1.4.3 DesignBuilder

DesignBuilder is a building modeling environment which uses the EnergyPlus simulation engine to calculate energy performance data.

Figure 11: DesignBuilder user interface
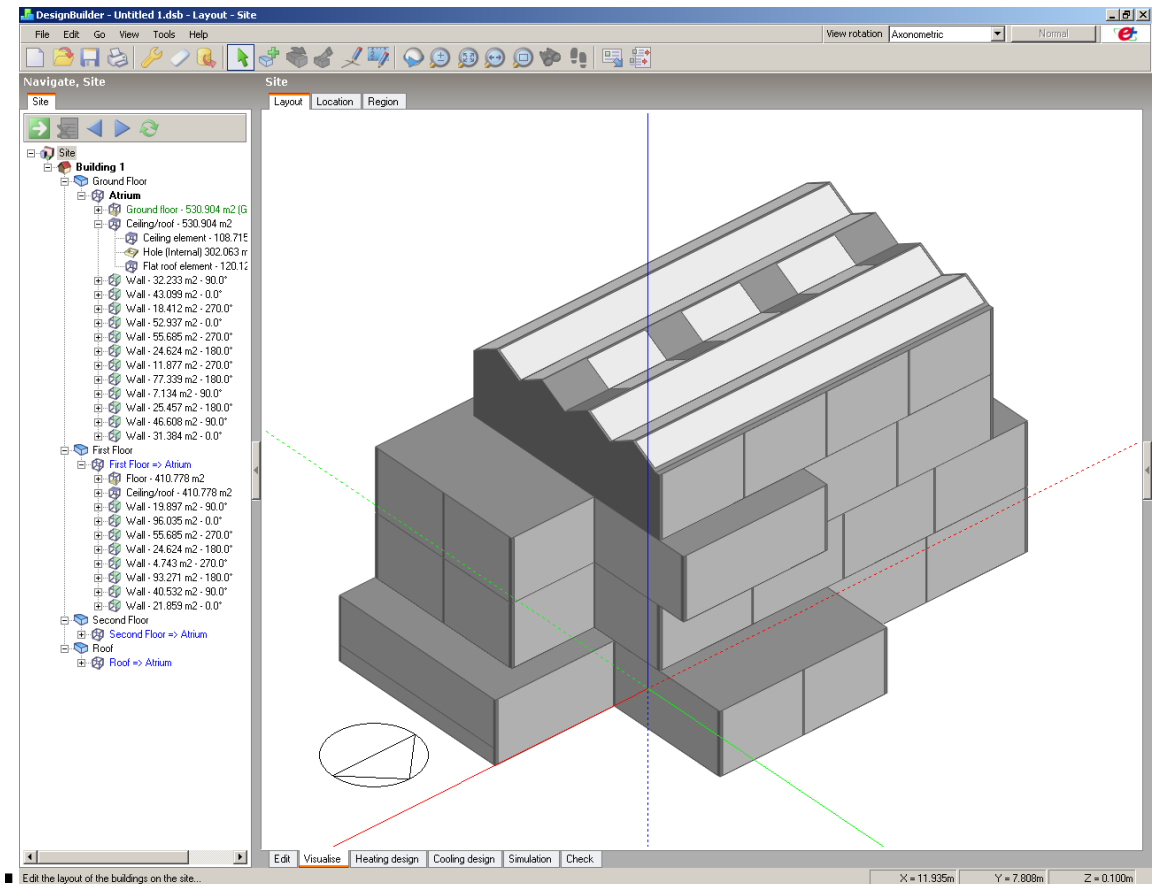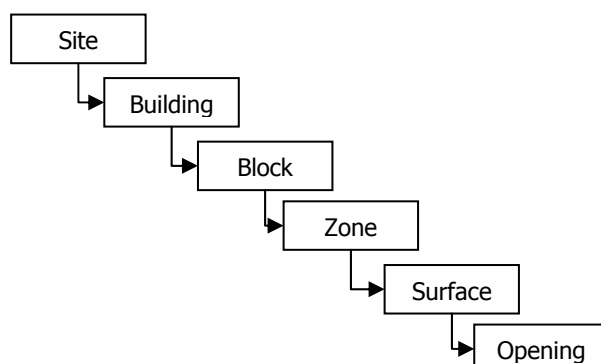
DesignBuilder models are organized in a hierarchy:

Data is inherited from the level above in the hierarchy. To each level in the hierarchy, constructions, activities, schedules and setpoints are assigned, which are also valid for the subjacent levels. For example, if a different wall construction is assigned to the zone-level all walls in the zone inherit the construction (surface-level).

At the site-level, properties of the building site are specified, for example elevation above the sea, site orientation, weather data, surface and ground properties.

Blocks are the basic geometric elements which are used to assembly the building. Usually a block is created by drawing the horizontal perimeter and then extruding the perimeter into a three-dimensional shape. Blocks can easily be modified by stretching them or cutting them using arbitrary planes. By drawing internal partitions, blocks can be divided into zones.

After drawing the geometry of the building, DesignBuilder automatically calculates the surface areas of the heat transfer surfaces and the air volumes of the zones.

The simulation can be started directly from the DesignBuilder interface. EnergyPlus runs in the background and returns the simulation results to DesignBuilder, where they can be displayed.

Since not all features of EnergyPlus are accessible via the DesignBuilder interface, it is also possible to create an EnergyPlus IDF file of the DesignBuilder model. This IDF file then can be executed externally with the EnergyPlus simulation engine.

All DesignBuilder simulations presented in this thesis have been carried out with Design-Builder version 1.4.0.049 incorporating EnergyPlus version 2.1.2.023. To avoid confusion and complicated phrasing, in this thesis all features of EnergyPlus which are accessible via the DesignBuilder interface are referred to as DesignBuilder features, although they are actually EnergyPlus features.

1.5 ASHRAE 140-2004

The ASHRAE 140-2004 is a Standard Method of Test (SMOT) which can be used to identify differences in the simulation results of building energy simulation programs. Different output values may be caused by algorithmic differences, modeling limitations, input differences, or coding errors.

The tests are based on the principle of comparing the performance of one program against the performance of other programs. Since building software operates in an immense parameter space it is impossible to evaluate all aspects of the software. So the tests are designed to indicate serious flaws or modeling limitation of the programs.

The tests consist of a series of test case buildings which are simulated with different software. The results are compared to each other and if possible to analytical or quasi-analytical solutions. The standard also provides a diagnostic logic to determine the source of the predictive differences.

The building thermal envelope and fabric load base case is a low mass, rectangular single zone building with no partitions. The "basic" cases are designed to test the ability of the software to model the effects of structural and operational variations on building envelope loads. Following variations are considered: window orientation, shading devices, thermostat setback, and night ventilation. These variations are applied to a low mass construction with lightweight walls, floor, and roof (Cases 600 through 650) and a high mass construction with masonry walls and concrete slab floor (Cases 900 through 960). The high mass basic tests include an additional configuration with a sunspace. The free-float basic tests (Cases 600FF, 650FF, 900FF, and 950FF) analyze the ability of the programs to model zone temperatures in low-mass and high-mass buildings without heating or cooling systems. All configurations are considered with and without night ventilation.
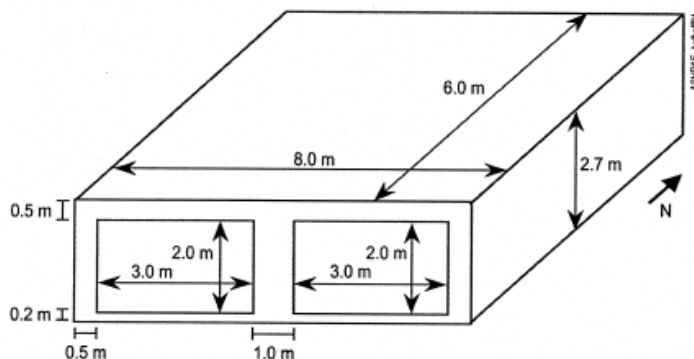
Figure 12: Building thermal envelope and fabric load base case (ASHRAE, 2004)

The "in-depth" Cases 195 through 320 are designed to analyze the ability of the programs to model building envelope loads for a non-deadband on/off thermostat control configuration. Following variations are considered: no windows, opaque windows, exterior infrared emittance, interior infrared emittance, infiltration, internal gains, exterior shortwave absorptance, south solar gains, interior shortwave absorptance, window orientation, shading devices, and thermostat setpoints. These detailed tests can be used to isolate the effects of specific algorithms.

The "in-depth" Cases 395 through 440, 800, and 810 are for deadband thermostat control configuration. Following variations are considered: no windows, opaque windows, infiltration, internal gains, exterior shortwave absorptance, solar gains, interior shortwave absorptance, and thermal mass.

The HVAC equipment cases are designed to test the ability of the program to model the performance of space cooling equipment by varying sensible internal gains, latent internal gains, zone thermostat setpoint, and dry-bulb temperature.

2 Models for Building Energy Simulation

2.1 Fundamental models for heat transfer

In this section, fundamental physical models for heat transfer are presented and their relation to thermal building simulation is discussed.

2.1.1 Conduction

Heat conduction is the transfer of thermal energy through matter, from a region of higher temperature to a region of lower temperature, without any mass transfer. Fourier's law gives a relationship between the gradient of the temperature field T and the heat flux $\dot{\vec{q}}$. The proportionality factor λ is called thermal conductivity. (Herwig, 2006)

$$\dot{\vec{q}} = -\lambda\,grad\left(T\right) \tag{1.1}$$

From the first law of thermodynamics and the continuity equation one can derive the following relation:

$$\rho c\,\frac{\partial T}{\partial t} = -div\left(\dot{\vec{q}}\right) \tag{1.2}$$

A combination of (1.1) and (1.2) gives the so-called heat equation.

$$\frac{\partial T(\vec{x},t)}{\partial t} = \frac{\lambda}{\rho c}\Delta T(\vec{x},t) \tag{1.3}$$

$T(\vec{x},t)$ temperature field
λ thermal conductivity
ρ density
c specific heat capacity
Δ Laplace operator; $\Delta = \vec{\nabla}\cdot\vec{\nabla} = \partial^2/\partial x_1^2 + \ldots + \partial^2/\partial x_n^2$

In most thermal building simulations c, ρ and λ are considered to be constant over space and time. Materials are assumed to be isotropic conductors, thus the thermal conductivity tensor reduces to the scalar thermal conductivity λ.

The heat conduction through the building envelope is usually approximated as a one dimensional heat transfer problem. In this case equation (1.3) reduces to

$$\frac{\partial T(x,t)}{\partial t} = \frac{\lambda}{\rho c}\frac{\partial^2 T(x,t)}{\partial x^2} \qquad (1.4)$$

The heat equation is a partial differential equation of parabolic type. The following boundary conditions may occur on each surface of a material layer (Keller, 1997):

Dirichlet boundary conditions:

$$T(x_s,t) = f(t) \qquad (1.5)$$

The time varying temperature $f(t)$ is imposed on the surface $(x = x_s)$. In case of the heat equation this type is also referred to as isothermal boundary condition.

Von Neumann boundary conditions:

$$\left.\frac{\partial T(x,t)}{\partial x}\right|_{x=x_s} = q(t) \qquad (1.6)$$

The time varying heat flux $q(t)$ is imposed on the surface $(x = x_s)$. In case $q(t) = 0$, this type is called adiabatic boundary condition.

Mixed boundary conditions:

$$T(x_s,t) + \frac{\lambda}{h}\left.\frac{\partial T(x,t)}{\partial x}\right|_{x=x_s} = f(t) + \frac{1}{h}q(t) \qquad (1.7)$$

This type appears, if the surface is coupled to a heat bath of temperature $f(t)$ and the heat flux $q(t)$ is imposed on the surface. h is the heat transfer coefficient between the surface and the heat bath. This is the generic case in thermal building simulations, where the surrounding air temperature is considered to be $f(t)$ and solar energy absorbed on the surface is considered to be $q(t)$.

The dimensionless Biot Number (Bi) is used to characterize transient heat transfer problems. It relates the heat transfer between a body and the heat bath to the heat conduction inside the body.

$$Bi = \frac{hL_c}{\lambda} \qquad (1.8)$$

The characteristic length L_c is given by the ratio of the volume of the body divided by the surface area of the body.

The general solution of the one dimensional heat equation (1.4) for a homogeneous wall of thickness d, mixed boundary conditions on both surfaces ($x_1 = 0$, $x_2 = d$) and initial conditions ($T(x,0) = g(x)$) is given by

$$T(x,t) = u(x,t) + v(x,t) \tag{1.9}$$

$$u(x,t) = \sum_{n=1}^{\infty} \left[\frac{1}{N_n} \left(\int_0^d g(x')X_n(x')dx' \right) e^{-\frac{t}{\tau_n}} X_n(x) \right] \tag{1.10}$$

$$v(x,t) = \frac{\lambda}{\rho c} \sum_{n=1}^{\infty} \left[\frac{1}{N_n} \left(\int_0^t e^{-\frac{t-t'}{\tau_n}} F_n(t')dt' \right) X_n(x) \right] \tag{1.11}$$

The eigenvalues μ_n are given by the transcendental equation

$$\tan(\mu_n) = \frac{(\beta_1 + \beta_2)\mu_n}{\beta_1\beta_2\mu_n^2 - 1} \tag{1.12}$$

$$\beta_m = \frac{\lambda}{h_m d} = \frac{1}{Bi_m} \qquad m = 1,2 \tag{1.13}$$

The eigenfunctions $X_n(x)$ are

$$X_n(x) = \mu_n \cos\frac{\mu_n x}{d} + \frac{1}{\beta_1} \sin\frac{\mu_n x}{d} \tag{1.14}$$

The time constant is given by

$$\tau_n = \frac{\rho c d^2}{\lambda \mu_n^2} \tag{1.15}$$

The convolution functions $F_n(t)$ are

$$F_n(t) = \frac{1}{\lambda} \left[\mu_n \left(h_1 f_1(t) + q_1(t) \right) + \left(\mu_n \cos\mu_n + \frac{1}{\beta_1} \sin\mu_n \right) \left(h_2 f_2(t) + q_2(t) \right) \right] \tag{1.16}$$

The norm factor N_n is given by

$$N_n = \int_0^d X_n^2(x)dx \qquad (1.17)$$

One can see, that even though a general solution to equation (1.4) exists, the solution is not easily applicable to practical situations. In building heat transfer calculations the forcing functions $f(t)$ and $q(t)$ usually consist of many spectral components, which all have to be considered in (1.16). Equation (1.4) only describes the behavior of a single layer. In practical situations many multilayer constructions, which are coupled to each other via different heat exchange mechanisms have to be considered, which makes the situation much more complex. Though such calculations are possible in principle (Boland, 2002) they are not applicable in many practical situations.

2.1.2 Convection

Convective heat transfer refers to the transport of heat by fluid motion. In general the motion of fluids is described by the Navier-Stokes equations, which consist of conservation equations for mass, momentum and energy (Stöcker, 2005).

Continuity equation:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0 \qquad (1.18)$$

Momentum equation:

$$\frac{\partial (\rho \vec{v})}{\partial t} + \nabla \cdot (\rho \vec{v} \cdot \vec{v}) + \nabla p = \rho \vec{f} + \nabla \underline{\tau} \qquad (1.19)$$

Energy equation:

$$\frac{\partial e}{\partial t} + \nabla (\vec{v} e + \vec{v} p) = \dot{q} + \rho \vec{f} \cdot \vec{v} + \lambda \Delta T + \nabla \cdot (\underline{\tau} \cdot \vec{v}) \qquad (1.20)$$

ρ	density
$\vec{v}$	velocity
p	static pressure
T	temperature
e	inner energy per volume
$\dot{q}$	internal heat sources
$\vec{f}$	volumetric forces (gravity,...)
$\underline{\tau}$	stress tensor (friction)
λ	thermal conductivity

This system of partial differential equations consists of three equations for five state variables ρ, $\vec{v}$, p, T and e. Two additional equations can be governed from the equations of state of the fluid. In case of an ideal gas this gives:

$$e = \frac{p}{\kappa - 1} + \rho \frac{\vec{v}^2}{2} \qquad (1.21)$$

$$T = \frac{\kappa - 1}{R} \left(\frac{e}{\rho} - \frac{\vec{v}^2}{2} \right) \qquad (1.22)$$

R gas constant

κ adiabatic exponent

The Navier-Stokes equations are a system of nonlinear partial differential equations. Depending on the physical nature of the problem, equations (1.18) to (1.22) can be simplified in various ways, for example by assuming incompressible fluids, neglecting friction, assuming stationarity or assuming constant material properties. Analytical solutions to the Navier-Stokes equations can only be calculated in highly simplified cases, thus in practical situations numerical methods like CFD (Computaional Fluid Dynamics) are used.

Fluid motion in fluids, subjected to gravity, can be caused by pressure gradients or by density gradients. If the driving force for convection is an imposed pressure difference, it is called forced convection. If convection is caused by density differences, it is called natural convection.

Much of the complexity and the uncertainty in building simulations is associated with the complexity in fluid flow. For example the calculation of the external and internal convective heat transfer coefficient, infiltration, thermal stratification of room air and natural ventilation. In most building simulation situations it is not possible to solve the Navier-Stokes equations numerically, because CFD simulations are computationally expensive and need a lot of additional information about geometrical and thermal boundary conditions, which is not always available. Instead of that many simplifying assumptions are made, in order to incorporate convective heat transfer in thermal building models. These assumptions have to be chosen carefully, in a way that on one hand the physical situation is characterized properly and on the other hand a solution can be obtained with a reasonable effort (3.2.7). Some models, which are commonly used in building simulations, are discussed in the following paragraphs.

Convective coupling between two fluid volumes

This model describes the convective heat transfer between two well mixed fluid volumes A and B, each of them represented by a single temperature value T_A and T_B. The fluid flow

from A to B is given in terms of a volumetric flow rate $\dot{v}$. The fluid properties ρ and c_p are considered to be constant.

$$\dot{q}_{AB} = \dot{v}\rho c_p \left(T_B - T_A\right) \tag{1.23}$$

In building simulations (1.23) is used to model convective heat transfer between two zones or between a zone and the external air.

Surface convection

Surface convection refers to the heat transfer between a surface and a fluid. There are a variety of models used for surface convection depending on:

- flow type (laminar, turbulent)

- driving force (natural convection, forced convection, mixed convection)

- thermal boundary conditions ($\dot{q}_{surf} = const.$, $T_{surf} = const.$,…)

- geometrical boundary conditions (horizontal plane, vertical plane, tube,…)

In most cases surface convection is expressed by a simple relationship between the convective heat flow rate $\dot{q}_{conv}$ and the temperature difference between the surface T_{surf} and the fluid T_{fluid}.

$$\dot{q}_{conv} = h_{conv} \left(T_{fluid} - T_{surf}\right) \tag{1.24}$$

The whole complexity induced by convection now lies in the model for the convection coefficient h_{conv}. The coefficient is a function of the properties of the fluid, the thermal state of fluid and the surface, the flow conditions of the fluid and the geometry of the surface, which often results in a nonlinear relationship between the heat flow rate and the temperature difference. Very often empirical correlations between the influencing factors (temperature difference, wind speed and direction, form factors…) and the convection coefficient h_{conv} are used (see 2.4.3, 2.4.4). Though convection coefficients actually are a function of the position, they typically are assumed to be constant over a heat transfer surface.

Since the heat transfer coefficient also appears in the calculation of the Biot-number (1.8), which characterizes transient heat transfer, surface convection may have a significant impact on heat storage in and heat transfer through the building envelope.

Network model for fluid flow

With this model one dimensional fluid flow can be calculated, by relating the volumetric flow rate to imposed pressure differences. The pressure differences between two nodes can be calculated using Bernoulli's equation:

$$\Delta p = \left(p_n - p_m \right) + \frac{\rho}{2} \left(v_n^2 - v_m^2 \right) + \rho g \left(z_n - z_m \right)$$

(1.25)

Δp	pressure difference between nodes n and m
p_n, p_m	entry and exit static pressures
v_n, v_m	entry and exit air velocities
z_n, z_m	entry and exit elevations
ρ	density
g	acceleration due to gravity

Bernoulli's equation can be derived from the Navier-Stokes equations for a one-dimensional inviscid, incompressible fluid, subjected to gravity, by the use of vector algebra.

The convective heat flow rates between two nodes are coupled to the fluid flow rates by equation (1.23).

This type of convection model can be used to model infiltration and pressure induced air-flow through the building (see 2.4.11).

2.1.3 Radiation

Thermal radiation refers to the temperature dependent electromagnetic radiation which is emitted by a body with a temperature $T \neq 0K$. The radiation behavior of different materials is characterized by their absorptance α, emissivity ε, reflectivity ρ and transmittance τ. In general these properties are a function of the wavelength λ, polar angle ϑ, azimuth angle φ and the temperature T.

Due to the similar physical mechanisms for absorption and emission the following relation is always true (Kirchhoffs law):

$$\alpha_{\lambda\omega} \left(\lambda, \vartheta, \varphi, T \right) = \varepsilon_{\lambda\omega} \left(\lambda, \vartheta, \varphi, T \right)$$

(1.26)

Black body radiation

A black body is a body with idealized radiation properties. The absorptance of a black body is $\alpha = 1$. Irradiation of all wavelengths is absorbed by the black body, thus there is no transmission or reflection of radiation ($\tau = \rho = 0$). Of all surfaces, black bodies have the highest emittance, independent of their temperature.

Black bodies obey Lambert's cosine law, which offers a relationship between emittance and luminosity. As a result of that black bodies appear with the same brightness (luminosity) from every direction, which is called diffuse radiation.

The spectral density of the hemispherical emittance (energy per unit time per unit surface area per unit wavelength emitted into the hemisphere) is given by Planck's law:

$$L_\lambda = \frac{2\pi h c^2}{\lambda^5 \left(e^{\frac{hc}{k\lambda T}} - 1 \right)} \tag{1.27}$$

L_λ	spectral density of the emittance
h	Planck's constant
k	Boltzmanns constant
c	velocity of light
T	absolute temperature
λ	wavelength

L_λ is a function of temperature and wavelength. With rising temperature, the spectral maxima of L_λ occur at ever smaller wavelengths, which is expressed by Wien's law, which can be derived from (1.27).

$$\lambda_{max} T = 2{,}8978 \cdot 10^{-3}\, mK \tag{1.28}$$

In building simulations two temperature regions are important. The radiant temperature of the sun is $T = 5800\ K$, thus the maximum is at $\lambda_{max} \approx 0.5 \mu m$, which is in the middle of the visible light part of the spectrum. The maximum for room temperature $T = 293\ K$ lies in the infrared part of the spectrum $\lambda_{max} \approx 9.9 \mu m$. The radiation properties $(\alpha, \rho, \tau, \varepsilon)$ of real materials usually depend on the wavelength. Thus in building simulation solar radiation and infrared radiation are considered separately.

Integration of (1.27) over the whole spectrum results in the hemispherical emittance (Stefan-Boltzmann law).

$$M = \int L_\lambda d\lambda = \sigma T^4 \tag{1.29}$$

If two black bodies face each other, both emit radiation according to their temperature and absorb the incoming radiation. The resulting radiation heat flow, is the difference between the emitted and the absorbed radiation, and can be expressed as

$$\dot{Q}_{12} = \sigma A_1 F_{12} \left(T_2^4 - T_1^4 \right) \tag{1.30}$$

The view factor F_{ij} expresses the geometrical configuration of the two surfaces i and j. Between the view factors, certain relationships exist, which can be utilized (view factor algebra). For example view factors fulfill the following reciprocity relation:

$$A_1 F_{12} = A_2 F_{21} \tag{1.31}$$

For n surfaces, which form a closed cavity the following is true:

$$\sum_{j=1}^{n} F_{ij} = 1 \tag{1.32}$$

Grey Lambertian surface

As mentioned above, real materials may show significant deviation from the idealized behavior of the back body. One radiation model, which is commonly used in building simulations, is the grey Lambertian surface. These surfaces combine the properties of grey surfaces (ε independent of λ) and the properties of Lambertian surfaces (ε independent of ϑ and φ).

$$\alpha_{grey,Lamb}(T) = \varepsilon_{grey,Lamb}(T) < 1 \tag{1.33}$$

Grey Lambertian surfaces are a good approximation for dielectrics, thus they are an adequate model for radiation heat transfer in most building simulation situations.

The hemispherical emittance obeys Planck's law multiplied by the emissivity

$$M_{grey,Lamb} = \varepsilon_{grey,Lamb} \sigma T^4 \tag{1.34}$$

For two grey surfaces which exchange radiation, the resulting heat flow can be expressed similar to (1.30):

$$\dot{Q}_{12} = \varepsilon_1 \varepsilon_2 \sigma A_1 F_{12} \left(T_2^4 - T_1^4 \right) \tag{1.35}$$

Since grey surfaces don't absorb all irradiation ($\varepsilon < 1$), reflections occur. If there are more than two surfaces under radiation exchange, the calculation of radiation exchange gets more complex. Two surfaces can't be calculated independent of the others, because reflections of other surfaces have to be considered. The radiosity of a surface is the sum of the emitted radiation and the reflected radiation. For a surface k under radiation exchange with $N-1$ surfaces, the following expression can be derived (Keller, 1997):

$$\sum_{j=1}^{N} \left(\frac{\delta_{kj}}{\varepsilon_j} - F_{kj} \frac{1-\varepsilon_j}{\varepsilon_j} \right) \cdot \dot{q}_j = \sum_{j=1}^{N} \left(\delta_{kj} - F_{kj} \right) \sigma T_j^4 \tag{1.36}$$

$\dot{q}_j$ resulting radiation heat flux from surface j to all other surfaces

T_j absolute temperature of surface j

ε_j emissivity of surface j

F_{kj} view factor between surface k and j

δ_{kj} Kronecker delta

This can also be written in matrix notation.

$$\{A\}\,\vec{\dot{q}} = \{B\}\,\sigma\bar{T}^4 \tag{1.37}$$

From (1.37) the resulting heat flux can be calculated by matrix inversion.

$$\vec{\dot{q}} = \{A\}^{-1}\{B\}\,\sigma\bar{T}^4 \tag{1.38}$$

Transparent surfaces

Some materials used in building construction, like glass or certain synthetics, are able to partially transmit electromagnetic radiation. The irradiated heat flux is partially transmitted, absorbed and reflected. The spectral transmittance is given by

$$\tau_{\lambda,\omega} = 1 - \alpha_{\lambda,\omega} - \rho_{\lambda,\omega} \tag{1.39}$$

$\tau_{\lambda,\omega}$ spectral transmittance

$\alpha_{\lambda,\omega}$ spectral absorptance

$\rho_{\lambda,\omega}$ spectral reflectivity

The transmission properties usually depend heavily on the wavelength of the radiation and the incidence angle. Glass for example is transparent for visible light ($\lambda \approx 0.5\mu m$) but nearly opaque for longwave radiation ($\lambda \approx 10\mu m$).

The dependence of reflectance and transmittance on the incidence angle at a surface between two materials of different refraction indices is given by Fresnel's equations.

$$\begin{aligned}\rho_{\parallel} &= \frac{\tan^2(\theta_i - \theta_t)}{\tan^2(\theta_i + \theta_t)} \\[2mm] \rho_{\perp} &= \frac{\sin^2(\theta_i - \theta_t)}{\sin^2(\theta_i + \theta_t)}\end{aligned} \tag{1.40}$$

$$\begin{aligned}\tau_{\parallel} &= 1 - \rho_{\parallel} \\ \tau_{\perp} &= 1 - \rho_{\perp}\end{aligned} \tag{1.41}$$

θ_i	incidence angel
θ_t	transmission angel
$\rho_\parallel, \rho_\perp$	reflectivity for polarisation parallel/normal to the plane of incidence
$\tau_\parallel, \tau_\perp$	transmittance for polarisation parallel/normal to the plane of incidence

Reflection depends on the polarization of the radiation. Since solar radiation is assumed to be non-polarized, the irradiation can be treated as half parallel, half normal polarized. The angles are connected by the law of Snellius

$$n_1 \sin \theta_1 = n_2 \sin \theta_2 \tag{1.42}$$

Equations (1.40) and (1.41) only describe the reflection at one surface. In order to calculate the transmission through a material layer, multiple reflections have to be considered.

The absorption in the material is given by the Beer-Lambert law

$$I_x = I_0 e^{-\alpha' x} \tag{1.43}$$

I_x	intensity as a function of the path length x
I_0	intensity at the surface
x	path length in the material
α'	absorption coefficient

2.2 Numerical methods for thermal building simulation

Analytical solutions to the models presented in section 2.1 are only available in highly simplified cases. Numerical methods allow using more complex geometries and boundary conditions, which may help to avoid oversimplification of the physical reality. In this section numerical methods which are relevant for thermal building simulations are discussed.

2.2.1   Finite difference method

The central idea of the finite difference method is to approximate the derivatives appearing in differential equations by finite differences on a regular grid in space and time. This results in a finite system of equations, which can be solved numerically. There are two different types of methods, explicit and implicit methods. Explicit methods calculate the state of the system at a later time from the state of the system at the present time, while implicit methods find it by solving an equation which uses both, the present and the later state of the system, or only the later state of the system. Implicit methods require extra computing and are harder to implement, but are often necessary due to stability and accuracy problems.

In the field of thermal building simulation, finite difference methods are often used to simulate heat conduction problems. One method, which is often used, is the Cranck-Nicholson method. The method is an implicit method, which uses a first-order central difference for the time derivative at time $t + a\Delta t / 2$ and a second-order central difference for the space derivative at position n (Figure 13).
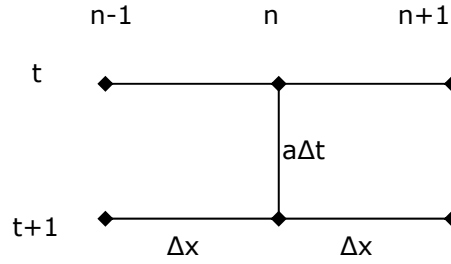

Figure 13: Discretisation scheme for the Cranck-Nicholson method

The resulting discretisation for the one dimensional heat equation (1.3) is given by (Streicher, 2006):

$$\frac{1}{a\Delta t}(T_n^{t+1} - T_n^t) = \frac{1}{2\Delta x^2}(T_{n-1}^t - 2T_n^t + T_{n+1}^t) + \frac{1}{2\Delta x^2}(T_{n-1}^{t+1} - 2T_n^{t+1} + T_{n+1}^{t+1})$$ (1.44)

$$a = \frac{\lambda}{\rho c}$$

This leads to a linear set of equations for the unknown temperatures T^{t+1} at time $t+1$, which has to be solved for every timestep.

$$A\vec{T}^{t+1} = \vec{b}$$ (1.45)

$\vec{T}^{t+1} = \left(T_1^{t+1}, \ldots, T_N^{t+1}\right)^{\mathrm{T}}$ unknown temperatures at time t+1

$\vec{b}$ function of the known temperatures at time t

A tridiagonal coefficient matrix

The coefficient matrix A is tridiagonal, which means it has nonzero elements only in the main diagonal and the secondary diagonals. Tridiagonal linear systems can be efficiently solved by utilizing an appropriate algorithm (e.g. Selder), avoiding a costly full matrix inversion.

In case that one of the parameters λ, c_p or ρ is a function of temperature, the finite difference equations become nonlinear. If an implicit method is used, this implies that at every

timestep a nonlinear equation has to be solved, which can be done by using an iterative method (e.g. Gauss-Seidel method). An example can be found in section 2.4.2.

Finite difference methods are impractical in case of curvilinear regions, which require proper interpolation of the approximations at grid points in the vicinity of the boundary. Finite element methods (FEM) are better suited to solve partial differential equations on complex shaped regions (Hoffmann et. al., 2006).

2.2.2 Conduction transfer functions (CTF)

In finite difference methods all nodal temperatures are calculated at every timestep, even though in annual building simulations only the temperatures and the heat flow on the surfaces are of interest. Conduction transfer functions (CTF) reduce the computational effort by relating the output of a linear, time-invariant system to a time series of current and past inputs and outputs. They are frequently used to simulate one-dimensional heat conduction through building elements. The basic form of a conduction transfer function is given by:

$$\dot{q}_i = \sum_{k=0}^{n_b} b^k T_o^k - \sum_{k=0}^{n_c} c^k T_i^k - \sum_{k=1}^{n_d} d^k \dot{q}_i^k$$

$$\dot{q}_o = \sum_{k=0}^{n_a} a^k T_o^k - \sum_{k=0}^{n_b} b^k T_i^k - \sum_{k=1}^{n_d} d^k \dot{q}_o^k$$

(1.46)

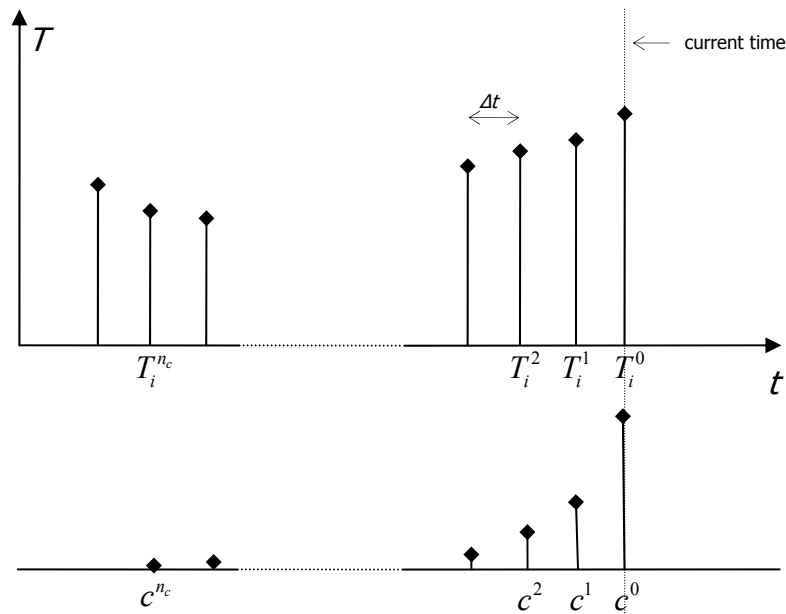|	
T_i^k, T_o^k	inside and outside temperature at time $t - k\Delta t$
q_i^k, q_o^k	heat flux at inside and outside surface at time $t - k\Delta t$
a^k	outside CTF coefficients, $a^0, \ldots, a^{n_a}$
b^k	cross CTF coefficients, $b^0, \ldots, b^{n_b}$
c^k	inside CTF coefficients, $c^0, \ldots, c^{n_c}$
d^k	flux CTF coefficients, $b^1, \ldots, b^{n_b}$

Figure 14: Timeseries of inside temperatures and inside CTF coefficients

With equation (1.46) for example the current heat fluxes at the inside surface can be calculated by a weighed sum over the current and n_b past outside surface temperatures minus a weighed sum over the current and n_c past inside surface temperatures (Figure 14) minus a weighed sum over the n_d past heat fluxes at the inside surface. The fluxes and temperatures are weighed by their associated CTF coefficients. Note that the summation index k starts at $k=0$ for the temperature timeseries but at $k=1$ for the heat flux timeseries. The number of CTF coefficients (n_a, n_b, n_c, n_d) depends on the thermal properties of the wall and the time step. Conduction transfer functions for heavy constructions in combination with a small time step can cause numerical instabilities due to the large number of coefficients needed. The conduction transfer coefficients (a^k, b^k, c^k, d^k) only have to be calculated once, at the beginning of the simulation.

The conduction transfer functions are an advancement of the response factor method, which uses only temperature time series to calculate the current heat fluxes. The problem with the response factor method is that it needs an infinite number of terms for an exact solution. In the conduction transfer method, similarities of higher order terms are used to replace them with flux history terms (LBNL, 2007).

In the next section, two different methods to derive the CTF coefficients are described, the Laplace method and the state space method.

Laplace method

The Laplace method is based on a combination of Laplace- and z-transform. The derivation of the Laplace method presented in this paragraph is based on the description presented by Meyer (2001).

The Laplacian of the one-dimensional heat equation (1.4) is given by

$$\frac{\partial^2 T(p,x)}{\partial x^2} = p\frac{\lambda}{c_p\rho}T(p,x) - \frac{\lambda}{c_p\rho}T(0,x) \tag{1.47}$$

The one-dimensional heat equation can be solved analytically in the frequency domain. In order to calculate the heat transfer through a single layered wall, the spatial coordinates have to be introduced in the general solution. This can be written in terms of a linear transmission matrix

$$\begin{pmatrix} T(x,p) \\ \dot{q}(x,p) \end{pmatrix} = \begin{pmatrix} \cosh\left(\sqrt{pa}\cdot x\right) & -\dfrac{d}{\lambda\sqrt{pa}}\sinh\left(\sqrt{pa}\cdot x\right) \\ -\dfrac{\lambda\sqrt{pa}}{d}\sinh\left(\sqrt{pa}\cdot x\right) & \cosh\left(\sqrt{p\dfrac{\lambda}{\rho c}}\cdot x\right) \end{pmatrix}\begin{pmatrix} T(0,p) \\ \dot{q}(0,p) \end{pmatrix} \tag{1.48}$$

$T(x,p)$ temperature in the frequency domain

$\dot{q}(x,p)$ heat flux in the frequency domain

$a = \dfrac{\lambda}{\rho c_p}$ thermal diffusivity

d thickness of the layer

For a multi-layered construction consisting of N homogeneous elements, the overall transmission matrix is the product of the transmission matrices of the elements.

$$\begin{pmatrix} T(x,p) \\ \dot{q}(x,p) \end{pmatrix} = \begin{pmatrix} a_N & b_N \\ c_N & d_N \end{pmatrix}\cdots\begin{pmatrix} a_1 & b_1 \\ c_1 & d_1 \end{pmatrix}\begin{pmatrix} T(0,p) \\ \dot{q}(0,p) \end{pmatrix} \tag{1.49}$$

Since the determinant of the transmission matrix is equal to one, equation (1.49) can be rewritten, to express the heat fluxes as a response to temperature excitations on both sides.

$$\begin{pmatrix} \dot{q}(x,p) \\ \dot{q}(0,p) \end{pmatrix} = \frac{1}{b}\begin{pmatrix} d & -1 \\ 1 & -a \end{pmatrix}\begin{pmatrix} T(x,p) \\ T(0,p) \end{pmatrix} \tag{1.50}$$

The temperature excitations are given by the discrete weather data. A triangular pulse is assigned to each data point which results in a linear interpolation of the sampling points (see Figure 15). A triangular pulse can be represented as a sum of ramp excitations. If the

response of the system to a ramp excitation is known, the response to an arbitrary linear interpolated signal can be calculated by superposition. The Laplace transform of a ramp excitation is given by

$$r(t) = t \cdot u(t) \xleftrightarrow{\;L\;} r(p) = \frac{1}{p^2} \tag{1.51}$$

The temperature functions in (1.50) can be written in terms of (1.51) and be transformed back by means of residue theory.
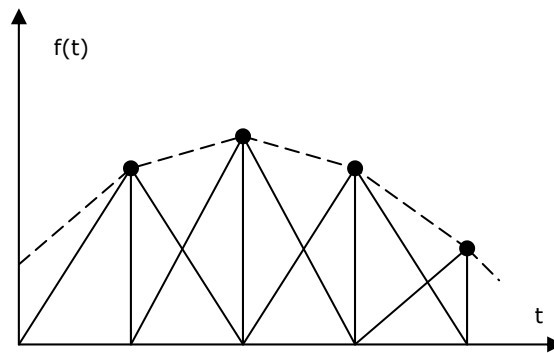

Figure 15: Triangular pulse representation of a piecewise linear function

In order to reduce the number of coefficients necessary for a required accuracy, Stephenson and Mitalas introduced a recursive description of the system. The output of the system is expressed as a function of the current input and past in- and outputs, similar to (1.46). In order to calculate the coefficients of that function the transfer function which is associated with the ramp excitation is transformed by a z-transform. The coefficients can be found by determining the roots of the transfer function in the z-domain.

State-space method

The state-space method is based on the work of Seem (1987). The method is based on a spatial discretisation of the heat transfer problem. Spatial discretisation reduces the heat equation (1.3), which is a partial differential equation, to a set of ordinary differential equations. In case of constant thermophysical properties, the system is linear and time-invariant.

Equation (1.52) shows a state space representation of a continuous, linear, time-invariant system with n states, p inputs and m outputs

$$\begin{aligned} \dot{\bar{x}} &= A\bar{x} + B\bar{u} \\ \bar{y} &= C\bar{x} + D\bar{u} \end{aligned} \tag{1.52}$$

$\bar{x}$	state vektor, $\bar{x} \in R^n$
$\bar{u}$	input vector, $\bar{u} \in R^p$
$\bar{y}$	output vector, $\bar{y} \in R^m$
A, B, C, D	system-, input-, output-, feedforward- matrix

The state of the system is determined by the nodal temperatures. The input vector contains the inside and outside temperatures ($p=2$), the output vector the heat fluxes through the inside and outside surface ($m=2$).

The solution to a system of first-order differential equations with constant coefficients is given by

$$\bar{x}_{t+\delta} = e^{A\delta}\bar{x}_t + \int_t^{t+\delta} e^{A(t+\delta-\tau)}B\bar{u}(\tau)d\tau \qquad (1.53)$$

$\bar{x}_{t+\delta}$	state vektor at time $t + \delta$
t	discrete point in time
δ	timestep
$e^{A\delta}$	exponential matrix
$\bar{u}(\tau)$	input vector between time t and $t + \delta$

The first term on the right hand side of (1.53) is called force-free response, it gives the time evolution of the system without excitation by the input. The second term is called the forced response, it integrates the response of the state variables to the input between times t and $t+\delta$. Inputs are modeled as continuous, piecewise linear functions.

$$\bar{u}(\tau) = \bar{u}_t + \frac{\tau - t}{\delta}(\bar{u}_{t+\delta} - \bar{u}_t) \qquad (1.54)$$

Substituting equation (1.54) into equation (1.53) and solving the integrals for the piecewise linear input functions, results in an expression which relates the states at time $t+\delta$ to the states at time t and the inputs at the times t and $t+\delta$. This expression still contains information about all nodal temperatures. To reduce the computational effort, matrix algebra and the so called forward shift operator are used to relate states to previous inputs. Finally this results in a transfer function equation, which relates the current output to the current input and past in- and outputs.

$$\bar{y}_t = \sum_{j=0}^{n} S_j \bar{u}_{t-j\delta} - \sum_{j=0}^{n} e_j \bar{y}_{t-j\delta}$$

$$S_j = f(A, B, C, D), \, S_j \in R^{m \times p}$$ (1.55)

$$e_j = g(A, B, C, D), \, e_j \in R$$

The transfer function coefficients in (1.55) may become insignificant as j increases. Seem (1987) describes methods to reduce the number of significant coefficients and efficient algorithms to deal with the matrices in equation (1.55).

The state space method can also be applied to two- and three-dimensional heat transfer problems (Seem, 1987).

2.3 Models for thermal boundary conditions

In this section, physical models for the thermal boundary conditions are presented. These models are necessary to derive proper boundary conditions for the building model, from the available data.

2.3.1 Solar radiation

The thermal radiation of the sun can be approximated by black body radiation of $T = 5800 \, K$. Although the entire spectrum of the sun spans from X-rays to radio waves, almost the whole energy is contained within the range $0.20 - 10 \mu m$. The intensity of the extraterrestrial solar radiation, integrated over all wavelengths, is called solar constant. Since the distance between the sun and the earth changes throughout the year, the intensity of the solar radiation is also not constant. The solar constant ($I_0 = 1353 \, Wm^{-2}$) is the mean value of that yearly variation. The incoming radiation interacts with the atmosphere in various ways. Effects like scattering, absorption, reemission and reflection cause a change in the intensity, the spectrum and the direction of the solar radiation. These processes depend on cloud cover, humidity, presence of aerosols and pollutants and the incidence angle. As a result solar irradiation can be divided into direct solar radiation and diffuse solar radiation. Direct solar radiation or solar beam radiation refers to radiation from the direction of the sun and diffuse radiation refers to the scattered and reflected parts of solar radiation (Kaltschmitt, Streicher, Wiese, 2006).

The following terms are often used in connection with thermal building simulation and should be explained:

- **Global horizontal radiation:** Total hemispherical irradiation on horizontal plane. Global horizontal radiation is the sum of horizontal beam radiation and horizontal diffuse radiation.

- **Direct normal radiation:** Irradiation only from the direction of the sun on a plane which is tracking the sun. The surface normal of the plane always points in the direction of the sun.

- **Horizontal beam radiation:** Irradiation only from the direction of the sun on a horizontal plane. Horizontal beam radiation is the projection of direct normal radiation on the horizontal.

- **Horizontal diffuse radiation:** Total hemispherical irradiation on horizontal plane minus the horizontal beam radiation

Radiation data files for building simulation may consist of different combinations of these parameters. Typically, hourly values for global horizontal and direct normal radiation or global horizontal and horizontal diffuse radiation are given. The task is to calculate values for beam and diffuse radiation at each simulation timestep and for every surface orientation used in the simulation.

The first step is usually the interpolation of the horizontal radiation data to adjust the hourly values to the timestep used in the simulation. This sounds quite straight forward, but may cause some unexpected problems (see 3.2.6).

If only the global horizontal radiation is available, a global-to-beam irradiance model can be used to estimate the fraction of beam radiation. A detailed description of three global-to-beam irradiance models can be found in Ineichen (2008).

The beam radiation on a tilted surface is simply the direct normal radiation times the cosine of the incidence angle. The calculation of the diffuse radiation on a tilted surface is more complicated, because of the unknown angular distribution of the diffuse radiation. The following diffuse radiation models are widely used in building energy simulations (Loutzenhiser et. al., 2006):

- **Isotropic sky model:** The isotropic sky model is the simplest model, which assumes that diffuse radiation is uniformly distributed over the sky dome and reflections on the ground are diffuse. The isotropic sky model gives good results for overcast skies but underestimates the irradiance under clear and partly overcast conditions.

- **Hay-Davies model:** In the Hay-Davies model diffuse radiation is composed of an isotropic and a circumsolar component. The circumsolar component accounts for the increased diffuse radiation from the direction of the sun under clear sky conditions. The portion of the diffuse radiation treated as circumsolar is given as a function of the anisotropy index A:

$$A = \frac{I_{direct,norm}}{I_{extraterrestrial}} \tag{1.56}$$

The remaining portion of diffuse radiation is treated as isotropic radiation. Reflections from the ground are assumed to be diffuse.

- Reindl model: The Reindl model introduces a third component for diffuse radiation, which accounts for horizontal brightening. Diffuse radiation is distributed among the three components, according to the anisotropy index A. The Reindl model provides slightly higher diffuse irradiances than the Hay-Davies model.

- Perez model: The Perez model also uses three components for diffuse radiation: isotropic sky dome, circumsolar brightening and horizontal brightening. Compared to the other models it is more computationally intensive. The calculation is based on empirically derived coefficients, which depend on the sky condition parameters clearness ε and brightness Δ and on the zenith angle Θ.
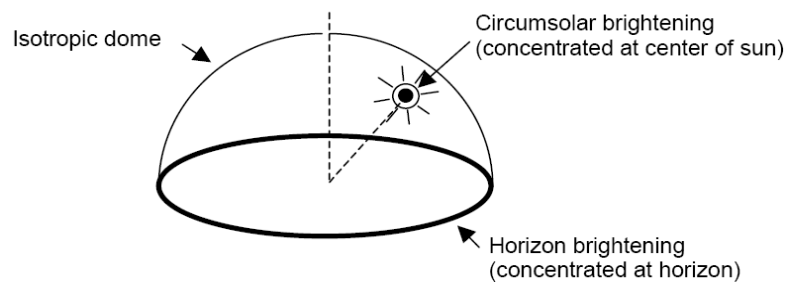

Figure 16: Components of the Perez diffuse sky model (LBNL, 2007)

Loutzenhiser et. al. (2006) carried out an empirical validation and a detailed sensitivity analysis of the models mentioned above. The isotropic sky model showed the largest deviations from the measured values (~15% mean absolute difference), the Perez model showed the best results (~7% mean absolute difference).

Andersen et. al. (2004) compared the irradiation on inclined surfaces, calculated with five different diffuse radiation models with radiation data, measured at the Technical University of Denmark. Variations in surface orientation and slope showed that the tested anisotropic models (Perez, Reindl, Hay-Davies) produce good results for all orientations and time periods, except vertical surfaces facing south and east in the summer time.

2.3.2 Longwave radiation

External building surfaces exchange longwave radiation with surrounding objects, the ground and the sky. The net longwave radiation exchange can be calculated with equation (1.35).

In absence of an atmosphere, surfaces would radiate to the interplanetary space at a temperature of approximately 3 K. The various gases in the atmosphere emit longwave radiation downwards, according to their emission characteristics and their temperatures. In order to calculate the radiation exchange with the sky, a temperature is assigned to the sky, the fictive sky temperature or effective sky temperature. Various empirical models exist, which relate the sky temperature to air temperature, the amount of moisture in the atmosphere (relative humidity or wet bulb temperature) or the cloud cover fraction. Some models are discussed in Clarke (2001) and Davies (2004).

In order to estimate the surface temperature of the ground and the surrounding objects, the simplest method is to use the ambient air temperature as a first approximation. A more comprehensive method is the concept of sol-air temperature (Clarke, 2001):

$$T_{grd} = T_{air} + \frac{1}{R_{so}}(\alpha_{grd}I_{glob,hor} - q_{lw}) \qquad (1.57)$$

T_{grd}	ground temperature
T_{air}	air temperature
$I_{glob,hor}$	global horizontal radiation
α_{grd}	ground absorptivity
q_{lw}	net longwave radiation exchange ground-sky
R_{so}	combined convective/radiative ground surface layer resistance

In order to calculate the longwave radiation exchange with the sky (q_{lw}), the effective sky temperature has to be known.

2.4 Models in TRNSYS and DesignBuilder

2.4.1 Thermal zone models

TRNSYS

In TRNSYS energy flows between the air node of a thermal zone and the surrounding surfaces are modeled with the star network, according to Seem (1987). This method uses an artificial node (star node) to consider the combined effect of longwave radiation and convection from the wall. The air node is coupled to the star node but not to all other surface nodes. Figure 17 shows an example for a zone with four surface nodes. The combined heat transfer coefficients for the "surface node to star node" and the "star node to air node" heat transfer are calculated based on the convection and radiation coefficients which are explained in the subsequent sections.
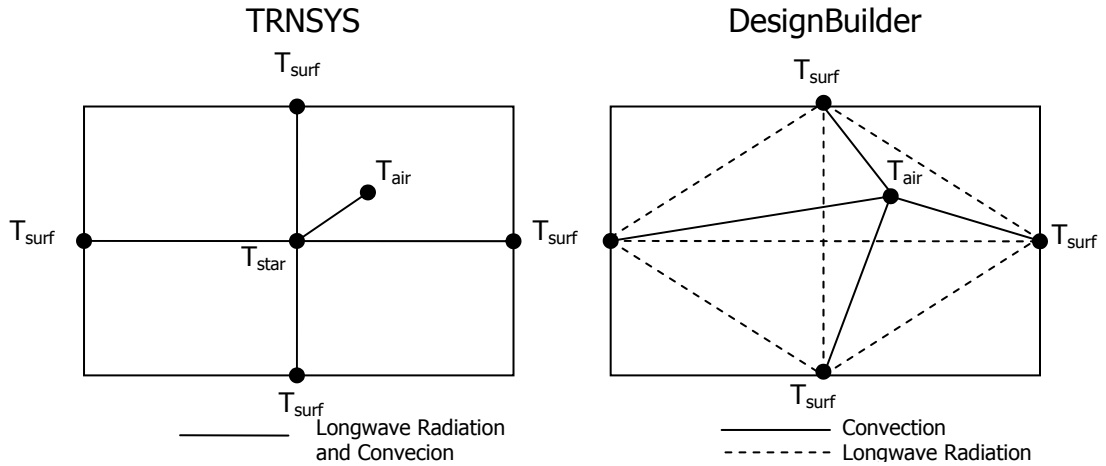
Figure 17: Thermal zone models of TRNSYS and EnergyPlus

DesignBuilder

DesignBuilder calculates the longwave radiation between the surface nodes and convection to the air node separately (Figure 17). The number of longwave radiation terms n_{LW} have a quadratic dependence on the number of surface nodes n_{surf}.

$$n_{LW} \sim n_{surf}^2 \tag{1.58}$$

The thermal zone model in DesignBuilder is more computationally intensive than in TRNSYS, especially for a large number of surface nodes.

2.4.2 Conduction

TRNSYS

TRNSYS uses conduction transfer functions to model conductive heat transfer. The transfer coefficients are calculated with the Laplace transform method, as described in section 2.2.2.

For walls and other massive constructions the heat flow at the surface is given by equation (1.46).

For constructions which are considered to have no thermal mass (e.g. windows), the heat flux is determined by the current temperatures. The heat transfer coefficients are given by the U-values.

$$a^0 = b^0 = c^0 = d^0 = U$$
$$a^k = b^k = c^k = d^k = 0 \quad \text{for } k > 0 \tag{1.59}$$

In TRNSYS the time interval for which heat flux values are calculated is called timebase. The simulation timestep has to be smaller or equal to the timebase of the walls.

$$n \cdot \Delta t = \Delta TB \tag{1.60}$$

Δt simulation timestep
ΔTB CTF timebase (timestep for CTF calculations)
$n \in \mathbb{N}$

The timebase is a user defined input value, which is valid for all constructions. The timebase has to be chosen with regard to the time-constants of the constructions and the simulation timestep. Typical values are 1h for standard constructions, 2-4h for heavy constructions and 0.5h for lightweight constructions (SEL, 2006).

If the timebase is larger than the time-constant of a construction the calculation of the transfer function coefficients is stopped. Such a lightweight construction can be replaced by a construction neglecting thermal mass, according to (1.59). If the timebase is large, compared to the time constant of the construction, the number of transfer coefficients also gets very large, which can cause numerical instabilities, due to round-off and truncation errors.

DesignBuilder

DesignBuilder also uses conduction transfer functions to model conductive heat transfer. The transfer coefficients are calculated with the state space method as described in section 2.2.2.

The resulting heat flow on the surface is given by

$$\dot{q}_i = \sum_{k=0}^{n_b} b^k T_o^k - \sum_{k=0}^{n_c} c^k T_i^k + \sum_{k=1}^{n_d} d^k \dot{q}_i^k$$
$$\dot{q}_o = \sum_{k=0}^{n_a} a^k T_o^k - \sum_{k=0}^{n_b} b^k T_i^k + \sum_{k=1}^{n_d} d^k \dot{q}_o^k \tag{1.61}$$

Equation (1.61) is similar to (1.46) but note the positive sign associated with the flux terms, which is different from the definition used in TRNSYS. This results in coefficients of opposite sign.

The state space method provides better accuracy and stability at short time steps than the Laplace method. Still numerical instabilities occur when simulating heavy constructions at time steps less than 0.1 h.

In DesignBuilder the time step used for the transfer functions is the same as the time step for the zone energy balance. The zone time step is a user input which is valid for all zones

and fixed over the whole simulation period. If the user defined time step is smaller than the smallest stable time step, EnergyPlus uses a method which generates an additional time series with the same time step, but a phase shift, in order to calculate temperature and flux values between the time steps. (LBNL, 2007).

In addition to the CTF method, EnergyPlus also allows the use of a finite difference method to calculate heat conduction through the envelope. This method allows to use temperature dependent values for λ and c_p, which is necessary to simulate for example phase changing materials (PCM). The algorithm uses an implicit finite difference scheme coupled with an enthalpy-temperature function.

$$\frac{\rho c_p}{\lambda \Delta t}(T_n^{t+1} - T_n^t) = \frac{1}{\Delta x^2}(T_{n-1}^{t+1} - 2T_n^{t+1} + T_{n+1}^{t+1}) \tag{1.62}$$

$$h_n = f(T_n) \tag{1.63}$$

$$c_p = \frac{h_n^{t+1} - h_n^t}{T_n^{t+1} - T_n^t} \tag{1.64}$$

$$\lambda = \lambda_0 + \lambda_1(T_n - 20) \tag{1.65}$$

T_n^t nodal temperature at position n and time t

h_n^t enthalpy at position n and time t

c_p specific heat capacity

λ conductivity at temperature T

λ_0 conductivity at 20°C

λ_1 change in conductivity per degree temperatur difference from 20°C
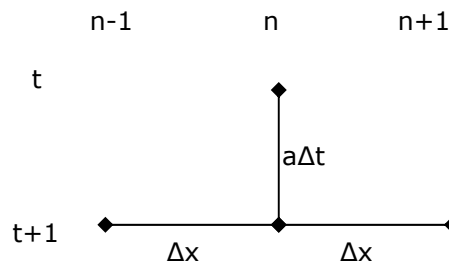

Figure 18: Discretisation scheme for the EnergyPlus finite difference method

The grid is generated automatically by the program. There are four types of nodes: external surface nodes, internal surface nodes, interior nodes and material interface nodes. A Gauss-Seidel iteration scheme is used to update the node temperatures. At each iteration the en-

thalpies (1.63) are updated and used to calculate the heat capacity (1.64). This feature is not accessible via the DesignBuilder interface, but available using EnergyPlus directly.

2.4.3 Internal surface convection

TRNSYS

TRNSYS calculates a combined convective and radiative heat flux from the inside wall surfaces to the fictive star node and a convective heat flux from the star node to the zone air node (SEL, 2006). Seem (1987) shows a method to calculate the combined heat transmission resistances using the convective heat transfer coefficient. TRNSYS provides two options:

- <u>User defined</u>: The heat transfer coefficient can be entered as a constant or an externally calculated timeseries.

- <u>Internally calculated</u>: The time dependent heat transfer coefficient is calculated internally, using a natural convection model, which correlates the coefficient with the temperature difference between surface and the zone air.

$$h_{conv,in} = A(T_{surf} - T_{air})^B \tag{1.66}$$

$h_{conv,in}$	internal convective heat transfer coefficient
T_{surf}	surface temperature
T_{air}	zone-air temperature
A, B	natural convection coefficients

The parameters A, B depend on surface orientation and the direction of the heat flow.

In case of a time dependent heat transfer coefficient, the star network has to be recalculated every timestep.

DesignBuilder

In DesignBuilder internal convection and longwave radiation are calculated separately. The program provides five models for interior surface convection:

- <u>Detailed</u>: This natural convection model correlates the heat transfer coefficient to the temperature difference between surface- and the zone air temperature. It is basically the same as the internal convection model in TRNSYS, but it additionally allows arbitrary surface orientation.

- <u>Simple</u>: This model uses constant convection coefficients depending on the surface orientation.

- CIBSE: This model uses constant convection coefficients according to CIBSE standard values.

- Ceiling diffuser: This forced convection model correlates the heat transfer coefficient to the air change rate in the zone.

$$h_{conv,in} = A + B \cdot ACH^C \tag{1.67}$$

$h_{conv,in}$ convective heat transfer coefficient
ACH air change rate
A, B, C forced convection coefficients

The parameters A, B, C depend on the surface orientation.

- Cavity: Model for convection in a narrow vertical cavity that is sealed and not ventilated. This applies for example to Trombe walls or the air gap between two window panes. The algorithm is based on the model provided by ISO 15099 which calculates convection depending on the aspect ratio of the cavity, Rayleigh number and Nusselt number.

EnergyPlus Engineering Reference (LBNL, 2007) provides a more detailed explanation of the models.

In the EnergyPlus input file it is also possible to enter user defined constant or scheduled convection coefficients, using the CONVECTIONCOEFFICIENTS object.

2.4.4 External surface convection

TRNSYS

The TRNSYS building model Type 56 has no internal model to calculate time dependent external heat transfer coefficients. The only way to calculate convection, for example depending on wind speed, is to calculate the coefficients with an external equation and use them as time dependent input values.

DesignBuilder

DesignBuilder provides six options to calculate external surface convection:

- Simple: This is the only model in DesignBuilder which yields a combined convection radiation heat transfer coefficient. Longwave radiation to the sky, ground and air are included. The heat transfer coefficient is calculated using surface roughness and windspeed.

$$h_{ext} = A + Bv_z + Cv_z^2 \tag{1.68}$$

h_{ext} combined external heat transfer coefficient

v_z local wind speed at heigth above ground of the surface

A, B, C material coefficients

The parameters A, B, C depend on surface roughness and the radiative properties of the surface.

- Detailed: In the detailed model, convection is split into forced convection and natural convection.

$$h_{conv,forc,ext} = 2.537 W_f R_f \left(\frac{P v_z}{A} \right)^{1/2} \tag{1.69}$$

$h_{conv,forc,ext}$ forced convection external heat transfer coefficient

W_f $W_f = 1$ for windward surfaces, $W_f = 0.5$ for leeward surfaces

R_f surface roughness multiplier

v_z local wind speed at heigth above ground of the surface

A surface area

P surface perimeter

$$h_{conv,nat,ext} = B \left(\left| T_{surf} - T_{air} \right| \right)^{1/3} \tag{1.70}$$

$h_{conv,nat,ext}$ natural convection external heat transfer coefficient

T_{surf} surface temperature

T_{air} outside air temperature

B surface parameter

Parameter B considers the slope of the surface and the direction of heat flow.

- BLAST Algorithm: In the current version the BLAST algorithm is identical to the Detailed algorithm.

- TARP Algorithm: In the current version the TARP algorithm is identical to the Detailed algorithm.

- MoWiTT Algorithm: The model applies to very smooth vertical surfaces (e.g. windows) in low rise buildings. It considers natural convection and forced convection.

- DOE-2 Algorithm: This model is a combination of the MoWiTT algorithm and the BLAST algorithm.

All heat transfer models for external surfaces in DesignBuilder additionally consider the cooling effect of rain. If the weather data indicates rain, all exterior surfaces exposed to wind are assumed to be wet. The heat transfer coefficient is set to 1000 W/m²K and the wet bulb temperature is used as the outside temperature for the surface.

2.4.5 Internal surface longwave radiation exchange

TRNSYS

TRNSYS calculates a combined convective and radiative heat flux from the inside wall surface to the fictive star node, using the method of Seem (1987). The equivalent resistance is a function of the approximate average surface temperature and the surface area ratio. The approximate average surface temperature is a constant input value, thus the internal radiative heat transfer is linear and time invariant. All surfaces are considered as blackbodies.

$$q_{comb,s,i} = \frac{1}{R_{equiv,i}}\left(T_{s,i} - T_{star}\right) \tag{1.71}$$

$$R_{equiv,i} = F\left(T_{s,appr}^3, \frac{A_{s,i}}{\sum_k A_{s,k}}\right)$$

$q_{comb,s,i}$	combined radiative and convective heat flux, surface i to star node
$T_{s,i}$	temperature at surface i
T_{star}	temperature at star node
$T_{s,appr}$	approximate average surface temperature, $T_{s,appr} = const.$
$R_{equiv,i}$	equivalent resistance
$A_{s,i}$	surface area of surface i
$F()$	function given by the star network method (Seem, 1987)

DesignBuilder

As mentioned above, DesignBuilder calculates internal convection and longwave radiation separately. Basic modeling assumptions are that all longwave radiation properties are grey, all radiation is diffuse and the zone air is completely transparent to longwave radiation.

Longwave radiation exchange is calculated for each surface using:

$$q_{LW,i,j} = A_i F_{i,j}\left(T_i^4 - T_j^4\right) \tag{1.72}$$

$q_{LW,i,j}$	longwave radiation heat flux between surface i and j
T_i, T_j	surface temperature surface i and j
$F_{i,j}$	radiation exchange coefficient between surface i and j
A_i	surface area

DesignBuilder approximates the direct view factor from surface *i* to surface *j* as the ratio of area *j* to the sum of all areas "seen" by surface *i*. Surfaces are considered to be "seen" by another surface if they face the surface with more than 10 degrees or if they are roof, floor

or ceiling surfaces. The radiation exchange coefficients $F_{i,j}$ include all exchange paths between the surfaces of the enclosure, namely reflection, absorption and re-emission.

2.4.6 External surface longwave radiation exchange

TRNSYS

TRNSYS calculates a combined convective and radiative heat flux from the external surface to the environment. Basic modeling assumptions are that all longwave radiation properties are grey and all radiation is diffuse. The model accounts for radiation exchange with the ground and the sky. The ground is assumed to have the same temperature as the surrounding air. The spatial relationship between surface and surrounding is expressed in view factors. Typical values are $f_{sky} = 0.5$ for vertical surfaces and $f_{sky} = 1$ for horizontal surfaces facing the sky. The long-wave emissivity of outside surfaces is set to $\varepsilon = 0.9$ for walls and is read from the window library for windows.

$$q_{LW,o} = \sigma \varepsilon \left(T_{surf}^4 - T_{fsky}^4 \right) \tag{1.73}$$

$$T_{fsky} = f_{ground} T_{air} + f_{sky} T_{sky} \tag{1.74}$$

$q_{LW,o}$	longwave radiation heat flux to the external surface
T_{surf}	surface temperature
T_{air}	outside air temperature
T_{sky}	fictive sky temperature
T_{fsky}	effective sky temperature
f_{sky}	view factor surface to sky
f_{ground}	view factor surface to ground, $f_{ground} = 1 - f_{sky}$
ε	long-wave emissivity of outside surface
σ	Stephan-Boltzmann constant

Equation (1.73) and (1.74) show the basic assumptions made for radiative heat exchange, which are combined with a model for convective heat transfer to yield a combined convective and radiative heat exchange.

DesignBuilder

DesignBuilder calculates external convection and longwave radiation separately. Basic modeling assumptions are that all longwave radiation properties are grey, all radiation is diffuse. The model accounts for radiation exchange with the ground, the surrounding air and the sky. The ground is assumed to have the same temperature as the surrounding air. The spatial relationship between surface and surrounding is expressed in view factors. View factors are internally calculated by DesignBuilder based on the tilt angle of the surface.

$$q_{LW,o} = \varepsilon\sigma f_{ground}\left(T_{surf}^4 - T_{ground}^4\right) + \varepsilon\sigma f_{sky}\left(T_{surf}^4 - T_{sky}^4\right) + \varepsilon\sigma f_{air}\left(T_{surf}^4 - T_{air}^4\right) \quad (1.75)$$

$q_{LW,o}$	longwave radiation heat flux to the external surface
T_{surf}	surface temperature
T_{air}	outside air temperature
T_{sky}	fictive sky temperature
T_{ground}	ground temperature
T_{fsky}	effective sky temperature
f_{sky}	view factor surface to sky
f_{air}	view factor surface to air
f_{ground}	view factor surface to ground
ε	long-wave emissivity of outside surface
σ	Stephan-Boltzmann constant

If a surface is shaded by an obstruction, the sky longwave incident is multiplied by a shading factor. The radiation exchange with the obstruction is added to the radiation from the ground.

2.4.7 Shortwave radiation – external distribution

TRNSYS

The solar gains of an external opaque surface are calculated using the solar absorptance.

$$q_{sol,ext} = \alpha_{ext} I_{tot,tilt} \quad (1.76)$$

α_{ext}	solar absorptance of the external surface
$q_{sol,ext}$	absorbed solar heat flux to the external surface
$I_{tot,tilt}$	total radiation on tilted surface

The total radiation on the tilted surface is the sum of the beam radiation and diffuse radiation. Diffuse radiation is the sum of diffuse radiation from the sky, which is calculated with a diffuse sky model and ground reflected diffuse radiation. Ground reflected diffuse radiation is calculated with the ground reflectance, which depends on ground surface properties and snow cover. In TRNSYS, solar radiation on tilted surfaces is calculated in radiation processors (e.g. Type 16) or weather data processors (e.g. Type 15) based on the available weather data.

TRNSYS accounts for shading by external objects like mountains or remote buildings (Type 64, Type 67) and shading by attached objects like overhangs and wingwalls (Type 34).

In order to calculate a shading factor for beam radiation and diffuse radiation Type 67 needs a description of the horizon seen by the surface in terms of surface angles and obstruction height angles. If the solar altitude angle is less than the corresponding obstruction height angle, the factor for beam radiation is 0, otherwise it is 1. The factor for diffuse radiation is the ratio of the amount of sky visible with shading objects to the amount of sky visible without shading objects, which is a number between 0 and 1. Thus Type 67 implicitly assumes an isotropic distribution of the diffuse solar radiation. The surface angles and obstruction height angles are stored in an external file which is read in by Type 67. Type 64 is similar to Type 67 and is useful if all of the defined orientations use the same information of angular heights of obstructions.

Type 34 calculates the solar radiation on a vertical surface shaded by an overhang or a wingwall. This type can also be used to calculate the effect of self shading of a building with a concave shape.

$$I_{tot} = f_i I_{beam} + F_{A-S} I_{diff,sky} + F_{A-G} I_{diff,gnd} \qquad (1.77)$$

I_{tot}	average solar radiation incident on a shaded receiver
I_{beam}	beam radiation incident on the receiver surface
$I_{diff,sky}$	sky diffuse radiation incident on the receiver surface
$I_{diff,gnd}$	ground reflected diffuse radiation incident on the receiver surface
f_i	fraction of the receiver area irradiated by beam radiation
F_{A-S}	receiver radiation view factor to the sky
F_{A-G}	receiver radiation view factor to the ground

The fraction of the receiver area irradiated by beam radiation (f_i) depends on the position of the sun and the geometrical shading configuration and has to be calculated for every timestep. Type 34 uses an ASHRAE algorithm to determine f_i. For calculation of receiver radiation view factors to the ground (F_{A-G}) and the sky (F_{A-S}), diffuse radiation is assumed to be isotropic. The way the receiver surface is defined may have a significant influence on the simulation results (3.3.1).

DesignBuilder

The solar gain of an exterior surface is the sum of the absorbed solar beam radiation, diffuse radiation from the sky and diffuse radiation from the ground.

$$q_{so} = \alpha \left(I_{beam} \cos(\theta) \frac{A_s}{A} + I_{sky} F_{ss} + I_{ground} F_{sg} \right) \qquad (1.78)$$

α	solar absorbtance of the surface
A	area of the surface
A_s	sunlit area
θ	incidence angle
I_{beam}	intensity of beam radiation
I_{sky}, I_{ground}	intensity of sky/ground diffuse radiation
F_{ss}, F_{sg}	angle factor between surface and sky / surface and ground

The sky diffuse radiation is a superposition of the three Perez components, isotropic sky dome, sky horizon brightening and circumsolar brightening. The proportions of this distribution depend on the position of the sun and the state of the atmosphere, defined in the weather data (2.3.1).

Since DesignBuilder utilizes a full geometrical description of the building, self shading of the building and shadow patterns from fixed shading, surrounding buildings and remote obstructions can be calculated properly. Shading of diffuse radiation from the sky dome and the sky horizon is calculated by apportioning the radiation on 144 points covering the sky dome and calculating the shading from each direction. Since these parts of the diffuse radiation are independent from the position of the sun the ratio of irradiance on a particular surface with obstructions to the irradiance without obstructions has to be calculated only once in a simulation. The shading of the diffuse irradiation from the circumsolar brightening has to be calculated for every timestep, according to the current position of the sun

DesignBuilder provides three modes to calculate exterior solar distribution:

- Minimal Shadowing: No exterior shadowing is calculated, except for window and door reveals.

- Full exterior: Shadow patterns on exterior surfaces caused by detached shading, wings, overhangs, and exterior surfaces of all zones are calculated.

- Full exterior with reflections: This mode also calculates reflections on exterior shadowing surfaces, exterior building surfaces and the ground. Reflected beam and diffuse radiation from the ground are calculated even if "full exterior with reflections" is not used. In case it is used the shadowing of the ground reflected radiation is taken into account. Opaque building surfaces are assumed to be diffusely reflecting, while windows and glass doors are assumed to be specularly reflecting. Reflections of beam and diffuse radiation are calculated using a ray-tracing method.

2.4.8 Shortwave radiation – transmission

TRNSYS

TRNSYS utilizes a 2-band solar radiation window model, which means the external solar radiation is split into a visual and a non visual part. The visual part is calculated as the black

body radiation at a temperature of 5800 K for a wave length band between 380 nm and 780 nm. This leads to a visual fraction of 46.6 % for diffuse and direct solar radiation. The reflection and absorption in glazing panes are calculated separately for both radiation parts. The visible and the non visible part are summed up to get the total solar radiation values which are used for load and temperature calculations.

Each glazing layer absorbs and reflects parts of the solar radiation depending on absorption and transmission properties of the material. TRNSYS needs absorption and transmission values hemispherically for diffuse radiation and in 10° steps of the solar incidence angle for direct solar radiation. These values are usually calculated with the WINDOW software (LBNL, 2001) and imported to TRNSYS via an ASCII file.

Since solar radiation may enter and leave a zone through several external or internal windows, an iterative loop for all windows of the zone is performed until all entering solar radiation is either absorbed or transmitted back to the outside. After the solar radiation is distributed, surface temperature and window pane temperature calculations are performed.

DesignBuilder

In DesignBuilder the optical properties of a glazing system are given by the transmittance, reflectance and absorptance properties of the individual layers at normal incidence. The angular dependences of these properties are calculated internally as a function of the wavelength, thus the optical properties have to be given separately for the visible range ($\bar{\lambda} = 575nm$) and the solar range ($\bar{\lambda} = 898nm$). The overall transmittance and absorptance values of the glazing system are calculated by solving recursion relations that account for multiple reflections between the glazing panes. They are calculated in 10° steps of the solar incidence angle φ and then fit to a 5th -order polynomial in $\cos\varphi$ for later use in the simulation.

In EnergyPlus optical and thermal glazing data additionally can be imported from WINDOW 5.x using the 'Construction from Window5 Data File' object.

2.4.9   Shortwave radiation – internal distribution

TRNSYS

Incoming direct solar radiation is distributed according to user defined distribution coefficients ("geosurf").

$$I_{beam,abs,i} = f_{geosurf,i}\alpha_{s,i} \sum_{k} I_{beam,trans,k} \qquad (1.79)$$

$I_{beam,abs,i}$	solar beam radiation absorbed on surface i
$I_{beam,trans,k}$	solar beam radiation transmitted through window k
$f_{geosurf,i}$	solar beam radiation distribution coefficient for surface i
$\alpha_{s,i}$	solar absorbtance of surface i

All materials are assumed to be diffuse reflectors, thus reflected beam radiation is considered as diffuse radiation.

Diffuse radiation is distributed according to absorptance weighted area ratios.

$$I_{diff,abs,i} = f_{diff,i} \left(\sum_k I_{diff,trans,k} + \sum_m I_{diff,refl,m} \right) \tag{1.80}$$

$$f_{diff,i} = \frac{\alpha_{s,i} A_i}{\sum_i \left(1 - \rho_{diff,i}\right) A_i} \tag{1.81}$$

$$\rho_{diff,i} = 1 - (\tau_i + \alpha_{s,i}) \tag{1.82}$$

$I_{diff,abs,i}$	diffuse solar radiation absorbed on surface i
$I_{diff,trans,k}$	diffuse solar radiation transmitted through window k
$I_{diff,refl,m}$	diffuse solar radiation reflected by surface m
$f_{diff,i}$	diffuse solar distribution coefficient for surface i
A_i	area of surface i
$\rho_{diff,i}$	diffuse solar absorbtance of surface i
$\alpha_{s,i}$	solar absorbtance of surface i
$\tau_{diff,i}$	diffuse solar transmittance of surface i ($\tau_{s,i}$=0 for opaque surfaces)

DesignBuilder

DesignBuilder provides two modes to calculate the interior solar distribution:

- Minimal Shadowing: All beam radiation is assumed to fall on the floor, where it is partially absorbed according to the solar absorptance. The reflected part is added to the transmitted diffuse radiation.

- Full interior: The program calculates the beam radiation on each interior surface according to the direction of the beam irradiance and the geometry of the room. Beam radiation is considered to be uniformly distributed on the surface. Like in the minimal shadowing option, beam radiation is partially absorbed. The reflected part is added to the transmitted diffuse radiation. This option is only available for convex rooms.

Similar to TRNSYS, DesignBuilder assumes diffuse radiation to be distributed on all surfaces according to absorptance weighted area ratios (equations (1.80) to (1.82)). In equation (1.81) DesignBuilder additionally calculates a term which accounts for diffuse shortwave radiation generated by internal sources, like electric lighting.

2.4.10 Zone air temperature

TRNSYS

The TRNSYS building model (Type 56) assumes the air to be well mixed and uses one temperature node per zone. Like described in section 2.4.1, the air node is coupled to the star node via convective heat transfer.

DesignBuilder

DesignBuilder provides two models for zone air temperature

- Well mixed: The default option in DesignBuilder, uses one temperature node per zone. The air node is coupled to the zone surface nodes via convective heat transfer.

- Dynamic gradient: This option allows to model stratification within a zone by defining a temperature gradient. The gradient varies dynamically depending on one of the following five factors:

  o Outside temperature

  o Inside temperature

  o Inside-outside temperature difference

  o Heating load

  o Cooling load

  The user defines one temperature gradient for the maximum value and one for the minimum value of the influencing factor. If the influencing factor is in between these bounds, the gradient is interpolated linearly, if it is above the maximum or below the minimum value, the maximum respectively the minimum gradient is used.

  The mean air temperature T_{MAT} is obtained from heat balance calculation, and then following values are calculated, depending on the temperature gradient and the height:

  o T_{ai} air temperature adjacent to surface i

  o $T_{leaving}$ temperature of air leaving the zone, entering the air system

  o $T_{exhaust}$ temperature of air leaving the zone, entering the exhaust

o T_{stat} temperature of air sensed at the thermostat

The dynamic gradient can be used to model the effect of extracting relatively warmer air at the ceiling level or to include the effect of the vertical position of a thermostat sensor for HVAC control. Since the T_{ai} are used in the surface heat balance calculations, the temperature gradient also has an influence on the conduction gains and losses through the building envelope.

The dynamic gradient model is implemented by the 'RoomAir Temperature Pattern:Two Gradient Interpolation' object in EnergyPlus. The dynamic gradient model can only be applied, if the user has prior knowledge about the temperature gradient. EnergyPlus provides additional models to predict non uniform temperature distributions in certain room- and HVAC-configurations.

2.4.11 Infiltration, natural ventilation

TRNSYS

Infiltration rates in TRNSYS are given in terms of air changes per hour for each zone. The air entering the zone via infiltration is assumed to have outside conditions. The energy gains due to infiltration are:

$$\dot{Q}_{\text{inf}} = \dot{m}_{\text{inf}} C_p \left(T_a - T_i \right)$$
(1.83)

$$\dot{m}_{\text{inf}} = V_{zone} \rho_{air} ACH$$
(1.84)

$\dot{m}_{\text{inf}}$	mass flow rate of infiltration air
C_p	specific heat of the air
ρ_{air}	density of the air
T_a	ambient air temperature
T_i	zone air temperature
ACH	air change rate
V_{zone}	zone air volume

Natural ventilation can be modeled as infiltration or ventilation. Ventilation basically has the same effect as infiltration but allows defining the temperature and humidity of the air entering the zone. To model the effect of airflow between two zones one has to use the convective coupling option. In this case the coupling air mass flow rate between two zones has to be defined. Since TRNSYS does not check the air mass balance, one has to be careful in defining the flow rates.

To model the effect of external wind pressure, inside and outside temperature on natural ventilation it is possible to connect an external air flow model (COMIS) to Type 56 or to use the TRNFLOW building type, which integrates COMIS into Type 56. COMIS is a

multi-zone air flow model which considers the building as a network of nodes and airflow links. A node represents a room, a link represents a crack, an opening or the like. The air mass flow between two zones depends on the pressure difference and the flow coefficient associated with the openings (Weber, et. al. 2001).

DesignBuilder

DesignBuilder provides two ways to model infiltration and natural ventilation:

- Scheduled: Infiltration air change is explicitly defined by an ACH value, natural ventilation air change is defined by a maximum ACH value and a schedule. The energy flow to the air node is calculated like in TRNSYS ((1.83), (1.84)).

- Calculated: Infiltration and natural ventilation are calculated using the EnergyPlus AirflowNetwork model. The airflow between two nodes of the network is calculated based on the pressure difference:

$$\dot{V} = C\left(\Delta p\right)^n \tag{1.85}$$

$\dot{V}$	volumetric air flow
C	flow coefficient (related to size and shape of crack/opening)
Δp	pressure difference between two nodes
n	flow exponent (n=0.5 ...turbulent flow, n=1 ...laminar flow)

The pressure difference across a crack/opening is calculated using Bernoulli's equation:

$$\Delta p = \left(p_n - p_m\right) + \frac{\rho}{2}\left(v_n^2 - v_m^2\right) + \rho g\left(z_n - z_m\right) \tag{1.86}$$

Δp	pressure difference between nodes n and m
p_n, p_m	entry and exit static pressures
v_n, v_m	entry and exit air velocities
z_n, z_m	entry and exit elevations
ρ	air density
g	acceleration due to gravity

The EnergyPlus AirflowNetwork model is able to simulate the performance of an air distribution system and calculate multi zone airflows driven by wind and forced air flow during HVAC system operation.

For large vertical openings the model is able to calculate a bi-directional air flow through the opening (cross-mixing). Since the model assumes openings to be vertical or near vertical, large horizontal openings are only modeled very approximately.

2.4.12 Ground modeling

TRNSYS

In TRNSYS heat transfer through constructions adjacent to the ground can be modeled by defining the boundary temperature of the construction. These temperatures have to be estimated or calculated with an external program.

As a workaround, the heat flow through the ground sometimes is simulated by defining zones surrounding the basement, which represent the thermal properties of the soil. These zones are usually defined in horizontal layers. The outside boundary temperature of the ground layers, which is the undisturbed ground temperature, can be calculated with Type 77. This type calculates the ground temperature as a function of the depth below ground depending on the temperature variation of the surface temperature and thermal soil properties. Due to the large thermal mass of the ground layers, numerical instabilities can occur, especially when lightweight constructions are used in the building (see 2.4.2).

The TESS library provides different types to calculate ground coupling effects for slabs and basements. The types use a three-dimensional finite difference model of the soil (TESS, 2008).

DesignBuilder

In DesignBuilder heat transfer through constructions adjacent to the ground is modeled by defining the monthly average outside surface temperature of the construction. Since these temperatures are not affected by the simulated heat flux through the envelope, it might be useful to add a ground construction layer to the surface in contact with ground. The outside surface temperatures now apply to exterior surface of the ground construction layer, the inner surface of the layer is coupled to the building.

EnergyPlus provides two external programs to calculate ground heat transfer for simple, rectangular slabs and basements. Both programs use a 3-d finite difference method to calculate the outside surface temperatures of basement walls and floor slabs in contact with ground. Main input parameters are: weather data, thermal soil properties, construction properties and average indoor temperatures. For non-rectangular buildings an equivalent rectangular building is simulated, by utilizing the area to perimeter ratio.

2.4.13 Humidity modeling

Both programs provide models to calculate latent energy balances for the zone air. TRNSYS provides the Effective Capacitance Humidity Model and the Buffer Storage Humidity Model to calculate moisture exchange processes with relevant materials in the zone. EnergyPlus provides the Effective Moisture Penetration Depth Model and Moisture Transfer Functions. Since no latent effects are considered in this thesis, the models are not

explained here. More information can be found in the corresponding user manuals (LBNB, 2007, SEL, 2006).

2.4.14 Additional building modeling components

Both programs provide a large variety of additional models for specific, thermally relevant building components. Examples are transparent insulation, green roofs, naturally vented cavities, shading blinds, screens and louvers. More information can be found in the corresponding user manuals (LBNB, 2007, SEL, 2006).

2.5 Comparison of the models

One method used in this thesis is to compare the detailed annual energy balances of TRNSYS and DesignBuilder. Both programs have some predefined output variables which can be chosen to get information about the thermal processes in the building. Since these variables are partly defined in different ways, they can't be compared to each other directly. The next section describes the output variables which are used in this work and explains the differences between them.

2.5.1 Energy balance TRNSYS

Since version 16 TRNSYS provides automatic energy balances, which give actual values of the energy flows in the zone at hourly timesteps. The simulation timestep in our case is 15 minutes, so the correct method would be to take the hourly mean values and sum them up to an annual value. Both methods have been compared for output variables which were available in the automatic energy balance (hourly actual values) and as separate output variables (15 min timesteps). Since the difference in the annual sum is negligible (~ 0.5%), it was decided to take the automatic energy balance.

The annual energy balance for TRNSYS was calculated based on the automatic energy balance 4 (Energy balance for zones, NTYPE 904). The system boundaries for this balance are the inside surface nodes. Figure 19 shows the components of the energy balance for a single thermal zone with one transparent and three opaque surface nodes. Longwave and shortwave radiation acts upon the surface nodes, convection acts upon the zone air node.
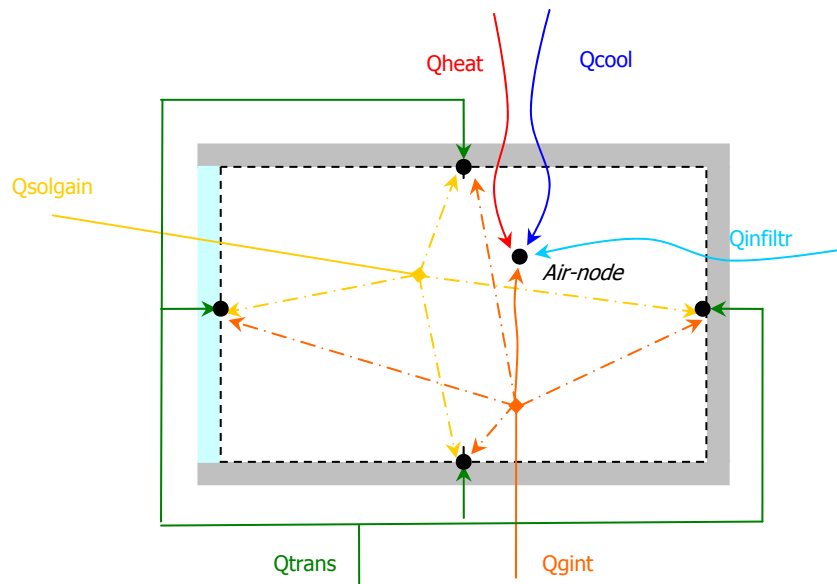
Figure 19: Energy balance components, TRNSYS

The automatic energy balance for zones in TRNSYS includes:

- Heating gains – Qheat: Convective and radiative energy supplied by the idealized heating system. Since the heating system used in ASHRAE 140 is purely convective, only this part is shown in Figure 19.

- Cooling losses – Qcool: Convective and radiative energy extracted by the idealized cooling system. Since the cooling system used in ASHRAE 140 is purely convective, only this part is shown in Figure 19.

- Internal gains – Qgint: Convective and radiative energy gains of people and equipment in the zone.

- Infiltration – Qinfiltr: Convective gains and losses caused by airflow from the outside into the building.

- Solar gains – Qsolgain: Solar radiation absorbed on all inside surfaces (opaque and transparent) of the zone.

- Transmission – Qtrans: This component includes all conductive heat flows from the surface nodes into the walls/windows. Since the system boundaries are the inner surface nodes, energy which is stored in the wall, appears as transmission loss.

- Diff: This component accounts for the difference between the heat flows into the zone and out of the zone at each timestep. A nonzero value in this component can be caused by a change of the inner energy of the zone (changing zone temperature) or by a numerical error which causes the energy balance to be nonzero. In

TRNSYS the energy balance of the zone is not always zero, because the matrix which represents the heat flow in the building is not inverted all the time but only if the tolerance is below a certain limit.

The values for annual gains and losses were computed by separately summing up the positive and negative hourly values of all components of the energy balance.

2.5.2 Energy balance DesignBuilder

The versions of DesignBuilder and EnergyPlus which have been used in this work don't provide a predefined energy balance for the thermal zones. In order to produce an energy balance, suitable output variables have to be chosen and summed up. The energy balance described below has been designed especially for the cases which were simulated in this work. This is not necessarily a good choice for other situations.
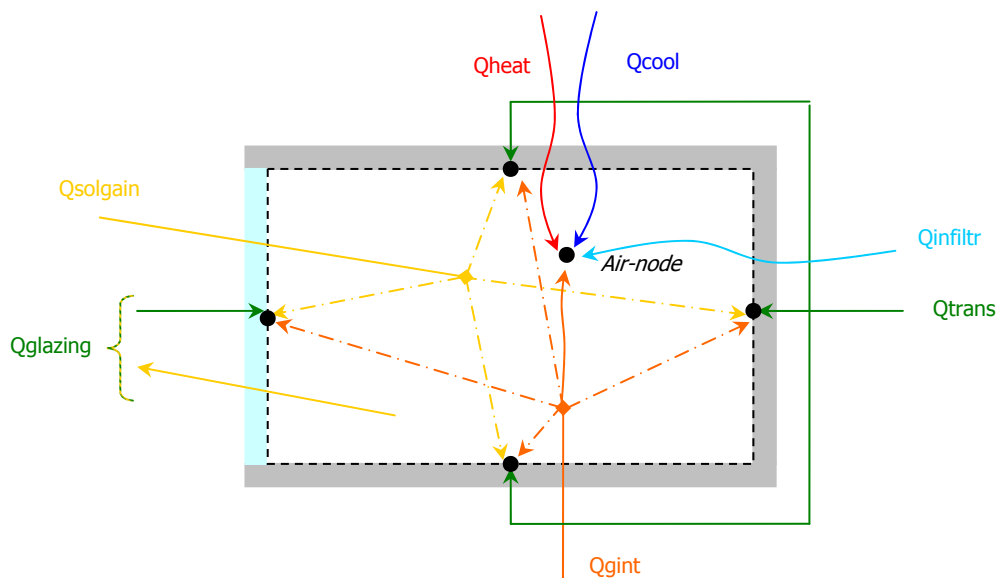
Figure 20: Energy balance components, DesignBuilder

DesignBuilder and EnergyPlus output variables which have been used to generate the heat balance have different names, but give the same results.

The energy balance generated with DesignBuilder or EnergyPlus output includes:

- ▪ <u>Heating gains – Qheat:</u> Convective and radiative energy supplied by the idealized heating system.
    - o DesignBuilder output variables:

$$Qheat = Zone / SysSensibleHeating$$

- o EnergyPlus output variables:

$$Qheat = Zone / SysSensibleHeatingRate$$

- ▪ Cooling losses – Qcool: Convective and radiative energy extracted by the idealized cooling system.

  - o DesignBuilder output variables:

$$Qcool = Zone / SysSensibleCooling$$

  - o EnergyPlus output variables:

$$Qcool = Zone / SysSensibleCoolingRate$$

- ▪ Internal gains – Qgint: Convective and radiative energy gains of people and equipment in the zone.

  - o DesignBuilder output variables:

$$Qgint = Miscellaneous$$

  - o EnergyPlus output variables:

$$Qgint = ZoneTotalInternalTotalHeatGain$$

- ▪ Infiltration – Qinfiltr: Convective gains and losses caused by airflow from the outside into the building.

  - o DesignBuilder output variables:

$$Qinfiltr = ExternalInfiltration$$

  - o EnergyPlus output variables:

$$Qinfiltr = ZoneInfiltrationSensibleHeatGain / Loss$$

- ▪ Solar gains – Qsolgain: Unlike in TRNSYS, solar gains refer to the solar energy that is transmitted through all windows into the zone, and not to the energy that is actually absorbed. The solar energy that is transmitted out of the zone is accounted for in the glazing component.

  - o DesignBuilder output variables:

$$Qsolgain = SolarGainsExteriorWindows$$

  - o EnergyPlus output variables:

$$Qsolgain = ZoneTransmittedSolar$$

- **Transmission – Qtrans**: Unlike in TRNSYS this component refers only to conductive heat flows into opaque surfaces.

  o DesignBuilder output variables:

  $$Qtrans = Walls + GroundFloors + Roofs$$

  o EnergyPlus output variables:

  $$Qtrans = ZoneOpaqueSurfaceInsideFaceConduction$$

- **Glazing – Qglazing**: The glazing heat gain is defined as the total heat gain from windows and glazing to the zone, excluding the solar radiation that is transmitted into the zone. In our case the glazing gains are the conductive gains through windows minus the shortwave radiation that leaves the zone.

  o DesignBuilder output variables:

  $$Qglazing = Glazing$$

  o EnergyPlus output variables:

  $$Qglazing = ZoneWindowHeatGain / Loss - ZoneTransmittedSolar$$

- **Diff**: This component refers to the difference between the heat flows into the zone and out of the zone at each timestep. A nonzero value in this component can be caused by a change of the inner energy of the zone (changing zone temperature) or by a numerical error which causes the energy balance to be nonzero. This issue is discussed in section 3.2.5.

3 Comparison of TRNSYS and DesignBuilder

Simple single zone buildings are simulated in TRNSYS and DesignBuilder. In this section, simulation results are compared with each other and with published results. Differences in the simulation results are traced back to differences in the building model. The buildings and the boundary conditions are based on the cases described in the ASHRAE 140 code.

3.1 ASHRAE 140 weather data

The ASHRAE 140 code provides a full-year weather data set. In order to test if the simulation codes are able to deal with extreme weather situations, a continental climate with cold clear winters and hot dry summers has been chosen. The weather data is from Denver, Colorado (39.8° North; 14.9° West; Altitude: 1609 m).

Figure 21 shows hourly values and the monthly mean values of dry bulb temperature and the global horizontal radiation at the site. The daily temperature variations between day and night are very big, sometimes more than 25°C. The yearly variation, which is the difference between the mean temperature of the coldest month (January, $\overline{T} = -1.7°C$) and the hottest month (July, $\overline{T} = 22.7°C$), is 24.4 °C. The absolute minimum temperature is -24.4 °C, the absolute maximum temperature is 34.0°C.
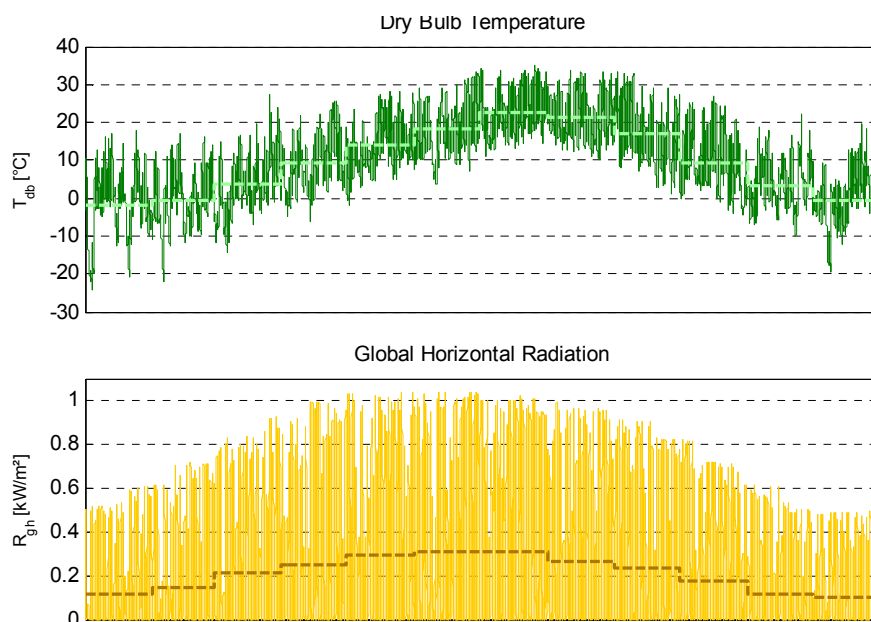
Figure 21: ASHRAE 140, weather data

The annual sum of global horizontal radiation is 1832 kWh/m²a, the maximum hourly value for global horizontal radiation is 1039 W/m². Figure 22 shows the monthly sums of solar irradiation on differently oriented surfaces calculated with DesignBuilder.
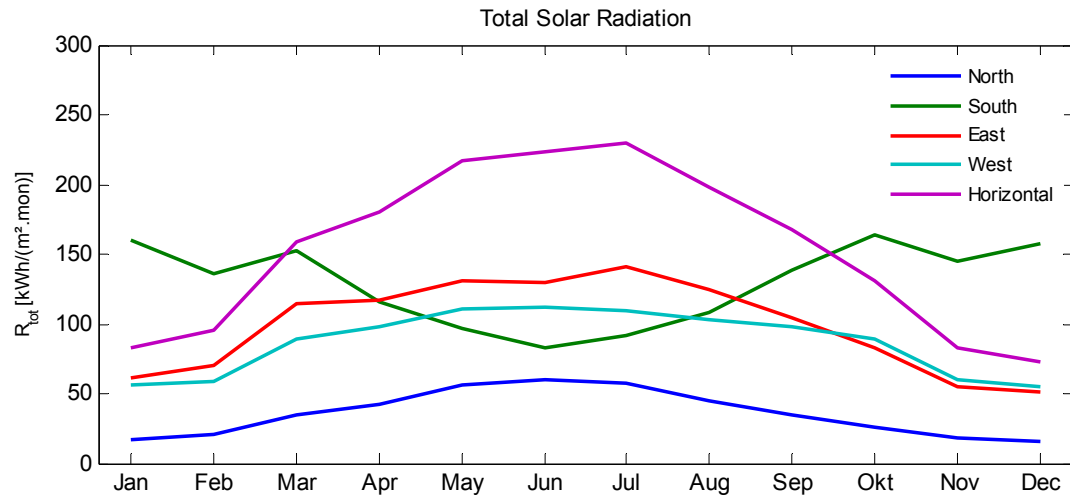
Figure 22: Monthly sum of total solar radiation on building surfaces

The weather data is supplied in TMY (Typical Meteorological Year) weather data format. The TMY format is explained in ASHRAE(2004).

3.2 Case 600 – lightweight base case

Case 600 is the base case of the ASHRAE 140 lightweight series. The building is a single storey building with rectangular-prism geometry ($8.0m \times 6.0m \times 2.7m$) and two south facing windows (each $3.0m \times 2.0m$). The building has a lightweight construction envelope (Table 3). The U-values in Table 2 have been calculated with an external heat transfer coefficient of 29.30 W/m²K and an internal coefficient of 8,29 W/m²K.
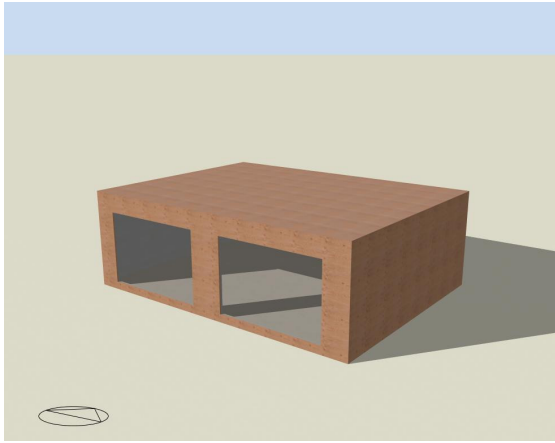
Figure 23: ASHRAE 140, Case 600

Table 3: Construction specifications, Case 600

	Construction	Thickness [cm]	U-Value [W/m²K]
Walls	Plasterboard	1.2	
	Fiberglass quilt	6.6	0.51
	Wood siding	0.9	
Floor	Timber flooring	2.5	
	Insulation	100.3	0.04
Roof	Plasterboard	1.0	
	Fiberglass quilt	11.2	0.32
	Roofdeck	1.9	
Window	Glass pane	0.3	
	Air gap	1.3	3.00
	Glass pane	0.3	

The air exchange is assumed to be constant with an air change rate of 0.5 ACH. Internal heat gains are assumed to be 200 W. 60% of the internal gains are radiative, 40% are convective. The heating and cooling system is an idealized system which has effectively infinite heating and cooling capacity and always supplies exactly the energy needed to meet the setpoints. The heating setpoint is 20°C, the cooling setpoint is 27°C.

3.2.1 Modeling notes - TRNSYS

Different simulation tools need different input values, so the ASHRAE 140 standard sometimes gives redundant information. Still there is some leeway in implementing the standard in a specific simulation program. The simulation assumptions made in this work are based on the experiences with ASHRAE 140 presented by Bradley et al. (2004a), Bradley et al. (2004b) and Hiller (2006).

Air density: The weather data used in the standard represents an altitude of 1609m above sea level. In order to get correct results for infiltration, the air density was manually adjusted to the altitude:

$$\rho_{air} = 0.9873 \, [kg/m^3] \qquad \text{(ASHRAE, 2004, Annex B3)}$$

Interior heat transfer coefficients: ASHRAE 140 provides fixed values for the combined interior heat transfer coefficients, but also states that if the program being tested automatically calculates interior heat transfer coefficients, they should be used. Bradley et al. (2004b) come to the conclusion that the method of calculating interior convection coefficients has a significant effect upon whole building results.

TRNSYS has an option to automatically calculate convective interior heat transfer coefficients. The procedure is based on equation (1.66) presented in section 2.4.3. The coefficients used (Table 4) are proposed by Hiller (2006).

Table 4: Parameters used for internal calculation of convective heat transfer coefficients in TRNSYS

	A (constant) [W/m²K]	B (exponent) [-]
Vertical surface (horizontal heat transfer)	1.60	0.30
Horizontal surface (upward heat transfer)	2.00	0.31
Horizontal surface (downward heat transfer)	1.08	0.31

The radiative part of the interior heat transfer is calculated automatically by TRNSYS, assuming blackbody radiation (see (1.71) in section 2.4.5). Thus it is not possible to meet the ASHRAE 140 specifications which give a value of $\varepsilon = 0.9$ for interior infrared emittance.

If the heat transfer coefficients are calculated internally, it is important to perform the calculation of the star network at every timestep, since the heat transfer coefficient is now time dependent. This can be done by setting the "star network calculation switch" parameter of Type56 to 1.

Exterior heat transfer coefficients: Like with interior heat transfer coefficients, ASHRAE 140 recommends to use automatically calculated heat transfer coefficients for exterior surfaces. TRNSYS has no internal model to calculate exterior surface coefficients, but it is possible to calculate the coefficients in an external equation and import the result to Type56. Annex B4 of the ASHRAE 140 standard provides a model to calculate the exterior combined radiative and convective heat transfer coefficient as a second order polynomial in wind speed. The model is identical to the simple exterior surface model used in DesignBuilder (1.68). ASHRAE 140 provides the polynomial coefficients for different surface types. Since these values represent the combined surface coefficient, they have to be disaggregated by subtracting the radiative part from the constant term of the polynomial. The radiative part is provided in Annex B5 of the standard.

Table 5: Polynomial coefficients for convective exterior heat transfer coefficients in TRNSYS

	A	B	C
Brick/rough plaster	7.86	4.065	0.028
Glass	3.60	3.330	-0.036

Ground coupling: The external heat transfer coefficient at the floor was set to HBACK=0.002, to effectively decouple the floor from the ground (Hiller, 2006). The boundary temperature was set to 10°C.

Timestep/Timbase: The simulation timestep was set to 0.25 h. The timebase for the conduction transfer functions was also set to 0.25 h (Bradley 2004b).

Window: The window used in the simulation is based on the ASH140 DBLE - window provided by the TESS-library. The angle dependent solar transmission values were modified according to Hiller (2006).

Interior solar distribution: According to Hiller (2006), all incoming solar radiation is assumed to be absorbed at the floor. The "geosurf" value for the floor is set to 1, for all other surfaces it is set to 0.

Diffuse radiation model: Diffuse radiation on tilted surfaces is calculated with the Reindl model.

Fictive sky temperature: In order to calculate the fictive sky temperature, the opaque sky cover, provided by the ASHRAE 140 weather data, is converted into the cloudiness factor. The fictive sky temperature is then calculated with Type69a, based on dry bulb and dew point temperature, direct and diffuse radiation and the cloudiness factor.

3.2.2 Modeling notes - DesignBuilder

The simulation assumptions made for DesignBuilder are based on published applications of ASHRAE 140 to earlier versions of DesignBuilder (DesignBuilder, 2006) and EnergyPlus (Henninger et al., 2004).

Air density: DesignBuilder automatically adjusts air density to air pressure values in the weather data.

Interior heat transfer coefficients: DesignBuilder automatically calculates convection coefficients. The "Detailed" inside convection algorithm was chosen (see section 2.4.3) Since DesignBuilder uses a grey body radiation model, the radiative part of the interior heat transfer is calculated with the correct infrared emittance $\varepsilon = 0.9$.

Exterior heat transfer coefficients: DesignBuilder automatically calculates convection coefficients. The "Detailed" outside convection algorithm has been chosen (section 2.4.4)

Ground coupling: DesignBuilder includes ground thermal properties in the calculation. In order to meet the specifications of the standard, the isolation was excluded from the floor

construction and defined as a ground construction material. The deep ground temperature then was set to 10°C.

Timestep/Timebase: The simulation timestep was set to 0.25 h. In DesignBuilder, the time step for the conduction transfer functions is the same as the simulation timestep.

Window: Thermal and optical window properties are chosen according to Henninger et al. (2004)

Interior solar distribution: The solar distribution option was set to "Full interior and exterior". The underlying models are explained in section 2.4.7 and 2.4.9.

Diffuse radiation model: In DesignBuilder diffuse radiation on tilted surfaces is calculated internally. DesignBuilder uses the Perez model.

Fictive sky temperature: The sky temperature is derived from the "Horizontal IR" values in the EnergyPlus weather data files.

3.2.3   Comparison with published results

In this section the simulation results from TRNSYS and DesignBuilder are compared to published ASHRAE 140 results, to show if the chosen simulation assumptions and the input values are correct.

There are various publications which show results from applying the ASHRAE 140 standard to different versions of TRNSYS. In the ASHRAE Standard 140-2004 (ASHRAE, 2004) TRNSYS 13.1 was used, Bradley et al. (2004a, b) used TRNSYS 15.2 and Hiller (2006) used TRNSYS 16.1. The results are shown in Figure 24 and Figure 25 . Since there is a lot of leeway in simulating a given building in a program like TRNSYS, the variation between the different results is mainly caused by differing modeling assumptions and not by the version of the program (Bradley et al., 2004a, b). To illustrate the range of variation between different simulation programs, the maximum and minimum results published in the ASHRAE standard are added.

	Annual Heating	Annual Cooling
	[kWh]	[kWh]
☐ ASHRAE 140 MIN	4296	6137
☒ TRNSYS 16.1 (Karitnig)	4858	6607
☐ TRNSYS 16.1 (Hiller)	4909	6587
☐ TRNSYS 15.3 (Bradley)	5250	6125
☐ TRNSYS 13.1 (ASHRAE 140)	4872	6492
☐ ASHRAE 140 MAX	5709	7964
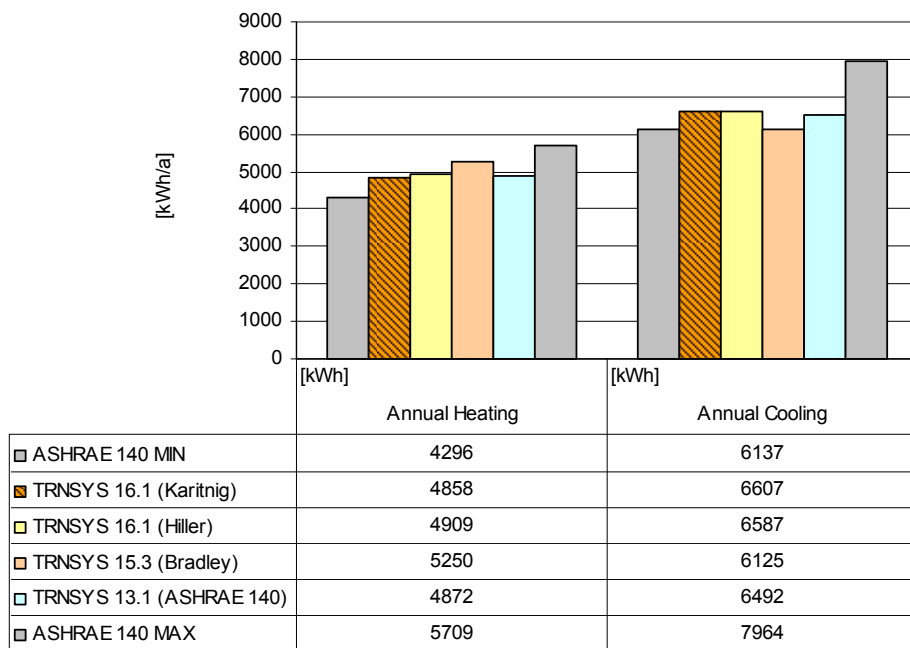
Figure 24: Annual heating and cooling energy, TRNSYS, Case 600

	Peak Heating	Peak Cooling
	[kW]	[kW]
☐ ASHRAE 140 MIN	3.40	6.00
☒ TRNSYS 16.1 (Karitnig)	3.93	6.72
☐ TRNSYS 16.1 (Hiller)	3.93	6.76
☐ TRNSYS 15.3 (Bradley)	3.90	6.40
☐ TRNSYS 13.1 (ASHRAE 140)	4.00	6.50
☐ ASHRAE 140 MAX	4.15	6.85
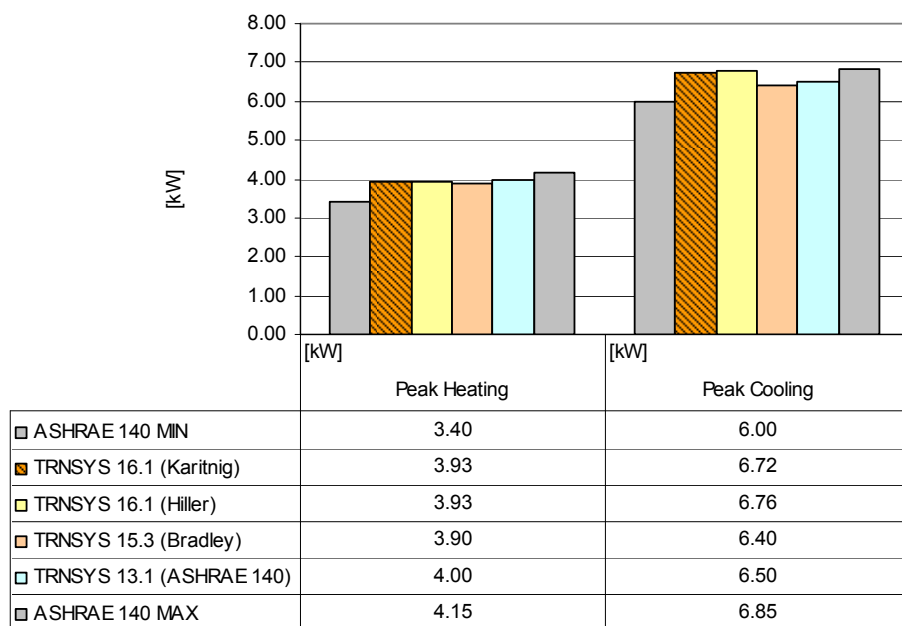
Figure 25: Peak heating and cooling load, TRNSYS, Case 600

The results agree with the results of other versions and are virtually identical to the results of Hiller (2006) which used the same TRNSYS version. This gives confidence in using proper simulation assumptions and correct input values.

For DesignBuilder there was only one published result for ASHRAE 140 available (DesignBuilder Software Ltd., 2006). The standard was applied to DesignBuilder version 1.2.0, which incorporated EnergyPlus version 1.3.0.

	Annual Heating	Annual Cooling
	[kWh/a]	[kWh/a]
▣ ASHRAE 140 MIN	4296	6137
▢ DesignBuilder 1.2.0	4498	6918
▨ DesignBuilder 1.4.0 (Karitnig)	4478	7211
▣ ASHRAE 140 MAX	5709	7964
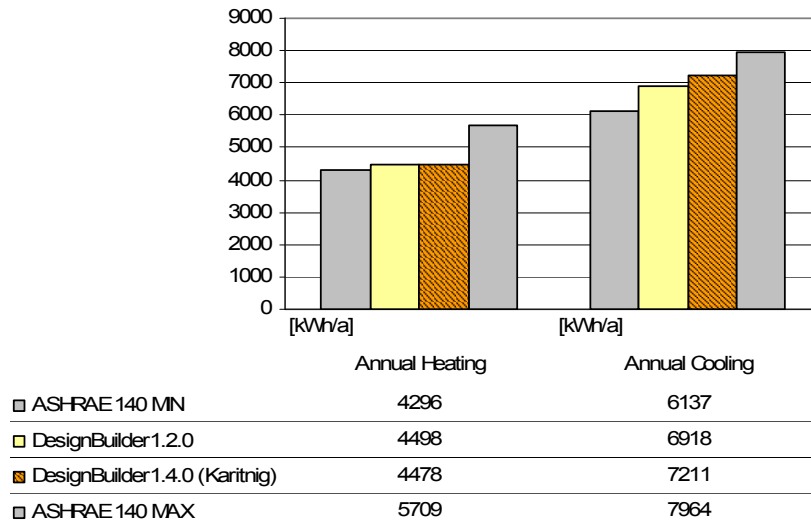
Figure 26: Annual heating and cooling energy, DesignBuilder, Case 600

	Peak Heating	Peak Cooling
	[kW]	[kW]
▣ ASHRAE 140 MIN	3,40	6,00
▢ DesignBuilder 1.2.0	3,83	6,63
▨ DesignBuilder 1.4.0 (Karitnig)	3,82	6,75
▣ ASHRAE 140 MAX	4,15	6,85
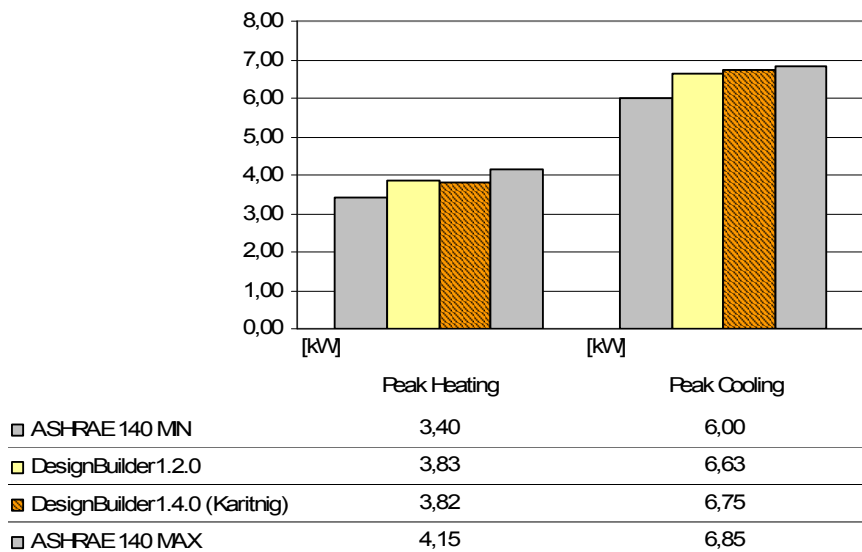
Figure 27: Peak heating and cooling load, DesignBuilder, Case 600

The results with the current DesignBuilder version 1.4.0, incorporating EnergyPlus version 2.1.0 agree with the published results for DesignBuilder version 1.2.0 and lie within the range of variation of the eight programs tested in the ASHRAE 140 standard (Figure 26, Figure 27).

	Annual Heating [kWh/a]	Annual Cooling [kWh/a]
ASHRAE 140 MIN	4296	6137
TRNSYS 16.1	4858	6607
DesignBuilder1.4.0	4478	7211
ASHRAE 140 MAX	5709	7964
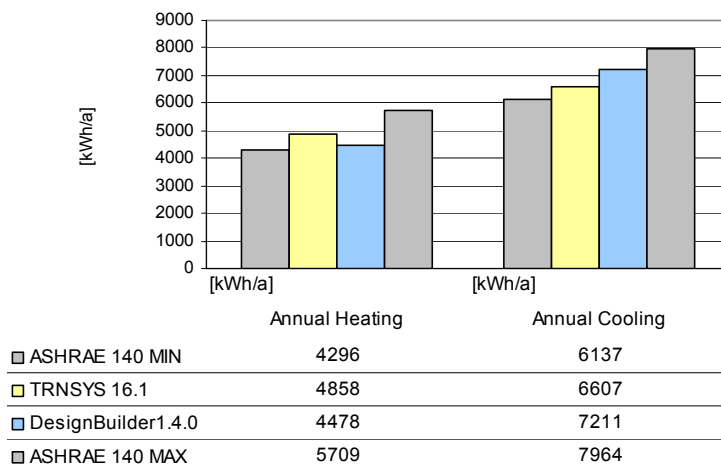
Figure 28: Comparison of annual heating and cooling energy, Case 600

The annual heating energy calculated with TRNSYS is about 380 kWh (8.5 %) higher than in DesignBuilder (Figure 28). The annual cooling energy calculated with DesignBuilder is about 604 kWh (9.1 %) higher than in TRNSYS. The peak heating and cooling values are nearly the same for both simulation programs (see Figure 29).

	Peak Heating [kW]	Peak Cooling [kW]
ASHRAE 140 MIN	3.40	6.00
TRNSYS 16.1	3.93	6.72
DesignBuilder1.4.0	3.82	6.75
ASHRAE 140 MAX	4.15	6.85
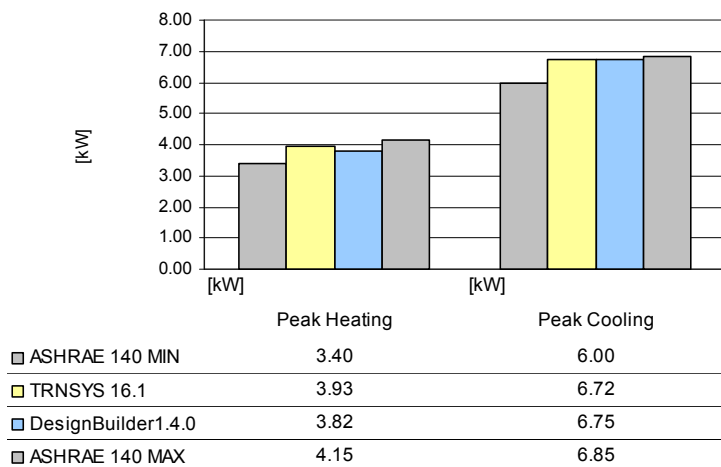
Figure 29: Comparison of peak heating and cooling energy, Case 600

3.2.4   Comparing detailed energy balance

Figure 30 and Figure 31 show the detailed annual energy balance for Case 600, calculated with TRNSYS and DesignBuilder. To generate comparable results, both simulations have been run with a 0.25 hour timestep. The energy balance was computed using the hourly output data, according to section 2.5.
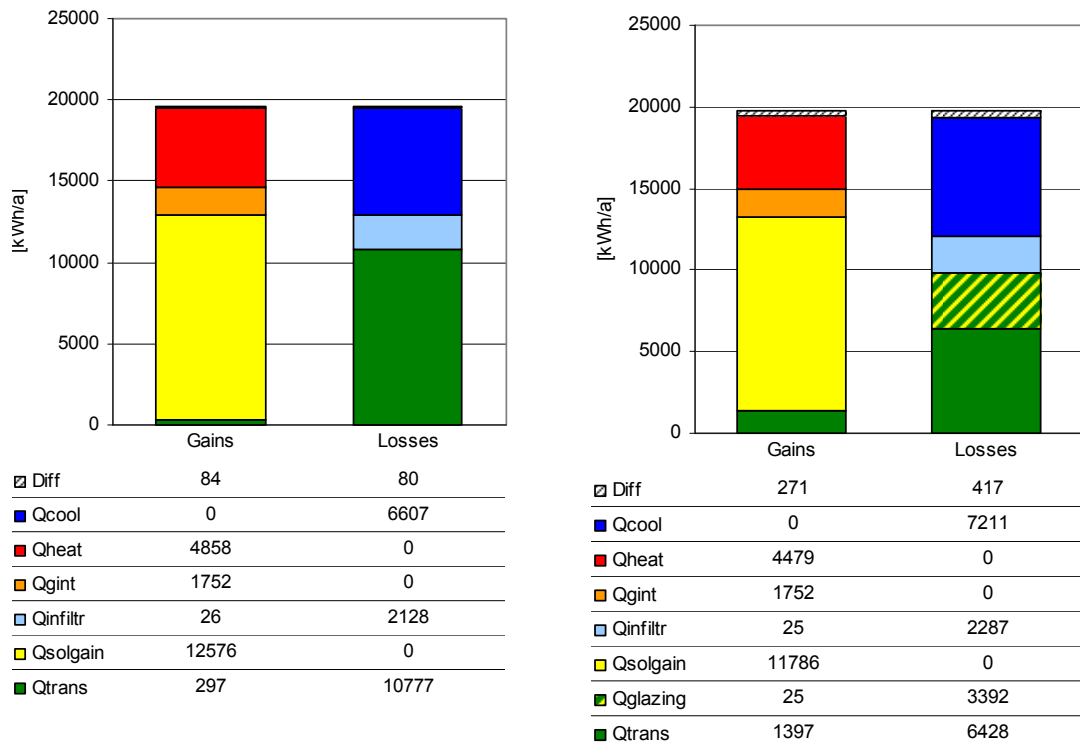
Figure 30: Energy balance TRNSYS, Case 600   Figure 31: Energy balance DesignBuilder, Case 600

As explained in section 2.5, "Diff" refers to the integral over the algebraic difference between gains and losses at every timestep. So this accounts for the change of the inner energy of the zone due to temperature changes and errors in the energy balance at a particular timestep. Because of the incompatibility of some EnergyPlus output variables (section 3.2.5), the differences in the energy balance in DesignBuilder are significantly bigger than in TRNSYS. Since this does not contribute much to the overall sum, this error can be neglected.

The overall transmission losses in DesignBuilder, which are approximated by the sum of transmission losses through opaque ("transmission") and transparent ("glazing") surfaces, are smaller than transmission losses in TRNSYS. The transmission gains are significantly different. The gains in DesignBuilder are approximately five times higher than in TRNSYS. This difference is analyzed in section 3.2.7.

DesignBuilder indicates a higher cooling and a lower heating energy demand than TRNSYS. Since infiltration and internal gains are similar in both programs, the difference can only be caused by solar gains and transmission.

3.2.5   Problems with the energy balance in DesignBuilder

As explained in section 2.5.2 DesignBuilder does not provide a predefined energy balance for thermal zones. The balance presented in 3.2.4 has been generated by combining DesignBuilder output variables. Since these output variables are not designed to be used as complementary components of an energy balance, this entails some problems.
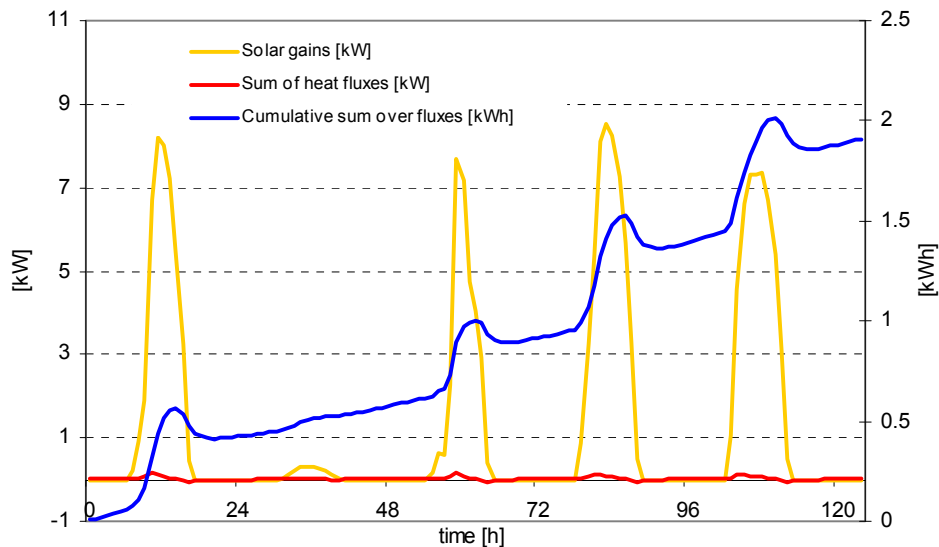
Figure 32: Problem with energy balance DesignBuilder

In order to investigate this problem, the heating and cooling setpoint of case 600 has been changed to 20°C. Since the room temperature is constant and no phase changing processes occur in the zone, the sum over all heat fluxes entering and leaving the zone should be zero at all times. Figure 32 shows that during the day the sum over all heat fluxes is positive. Furthermore it shows that the cumulative sum over the heat fluxes ("time integral"), which represents the change in the inner energy of the zone, is constantly growing. This is in contradiction to the constant room temperature.

The correlation of the energy imbalance with solar radiation indicates that there is a problem with the solar energy output variables. This was confirmed by another simulation. After removing all windows, the energy balance was correct.

The DesignBuilder helpdesk (www.designbuilder.co.uk) stated that the reason for this imbalance is that the EnergyPlus output variable for solar gains represents the solar energy transmitted and not the solar energy absorbed in the zone. Obviously the solar radiation that leaves the zone is not included correctly in the calculation of the glazing gains, as described in 2.5.2.

Since the over-all error in the annual energy balance is comparatively small (~2%), the inconsistency associated with solar gains and glazing output is neglected.

3.2.6   Analyzing solar radiation

To explain the difference between the solar gains of TRNSYS and DesignBuilder (Figure 30, Figure 31), the solar radiation has been analysed. Since the weather data for both programs are based on the same weather data file, the solar radiation was expected to be the same, but in fact some differences occurred.

The weather data for the ASHRAE 140 building envelope tests is provided in typical meteorological year data format (TMY). The actual file, "DRYCOLD.TMY", only contains information about direct normal solar radiation and total horizontal radiation. Various models and correlations can be used to calculate diffuse radiation on the horizontal and on tilted surfaces based on direct normal solar radiation and total horizontal radiation (see 2.3.1).

Figure 33 shows diffuse radiation on the horizontal calculated with DesignBuilder and TRNSYS over a period of two days. On cloudy days with high diffuse radiation (left), both timeseries are similar, but on days with a clear sky (right) they are significantly different. The timeseries calculated with TRNSYS additionally shows strange oscillations, especially on days with low diffuse radiation.
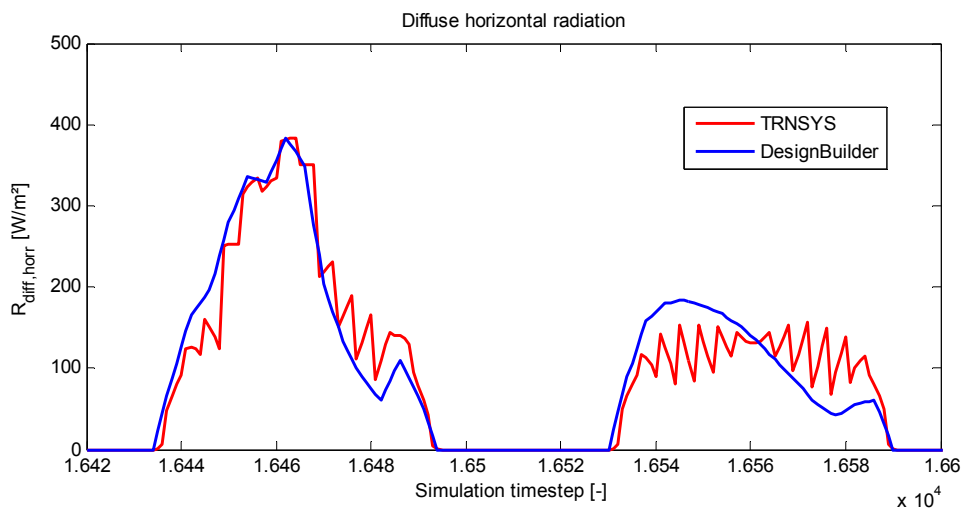
Figure 33: Diffuse radiation on horizontal, TRNSYS and DesignBuilder

The difference can be explained by the different interpolation routines, which were used to interpolate the hourly weather data. Figure 34 shows the original hourly radiation data (direct normal radiation, global horizontal radiation) and the interpolated radiation used in TRNSYS and DesignBuilder.
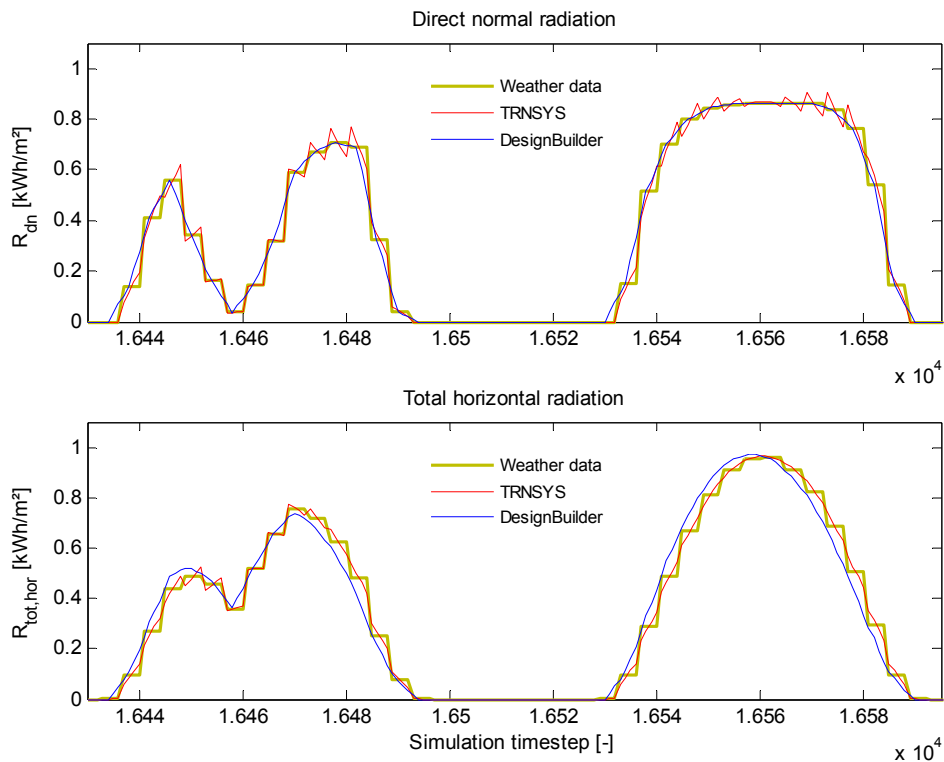
Figure 34: Direct normal and total horizontal radiation, TRNSYS and DesignBuilder

In TRNSYS the original TMY-file was used as an input for the weather data processor Type15-1, which incorporates the functions of the Type16 radiation processors. Type16 uses the curve for extraterrestrial radiation to interpolate radiation data. The data at each sub hourly timestep is calculated by multiplying the original radiation value with a factor which represents the ratio of the time integral of the extraterrestrial radiation over the simulation timestep to the time integral of the extraterrestrial radiation over the interval of the data. The extraterrestrial radiation at a particular point in time can be calculated by a relatively simple geometrical relationship between the position of the site (latitude, longitude) and the position of the sun. The time integral over the extraterrestrial radiation can be solved analytically, thus a numerical value for any integration interval can be obtained easily.
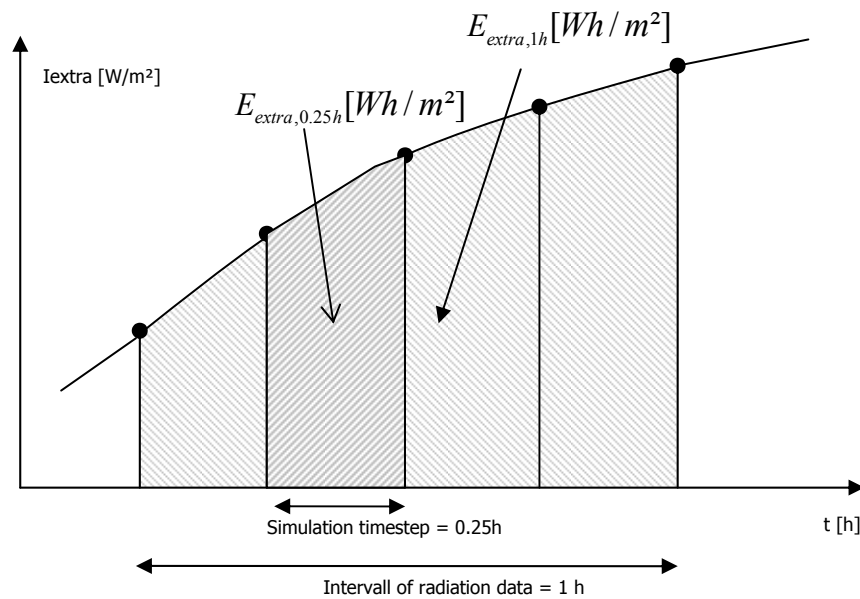
Figure 35: Radiation interpolation method, TRNSYS Type 16

Figure 35 shows an example for hourly radiation data and a simulation timestep of 0.25 h. The radiation at each timestep ($I_{0.25h}$) is given by

$$I_{data,0.25h} = I_{data,1h} \cdot \underbrace{\frac{E_{extra,0.25h}}{E_{extra,1h}} \cdot 4}_{\text{scaling factor}}$$

Figure 36 shows the original data and the interpolated global horizontal and direct normal radiation, generated by TRNSYS Type 16. The same scaling factor is used for both. If the shape of the radiation data is similar to the extraterrestrial radiation, the values are interpolated smoothly (global horizontal radiation), but if the shape is different, the scaling factor leads to a pronounced spike at every fourth timestep. Since the diffuse horizontal radiation is calculated, based on these two interpolated timeseries, the spikes also occur in the diffuse radiation.

Earlier versions of Type 16 utilized a radiation smoothing algorithm, but due to problems associated with radiation smoothing, this option has been disabled in TRNSYS 16 (SEL, 2006).

The interpolation method used in Type 16 is very questionable, because of the artificial spikes it produces. The relative deviation of the interpolated diffuse radiation values from

the hourly mean values is in some cases higher than 50%. Looking at Figure 36, the original hourly mean values seem to be better input values than the interpolated ones.
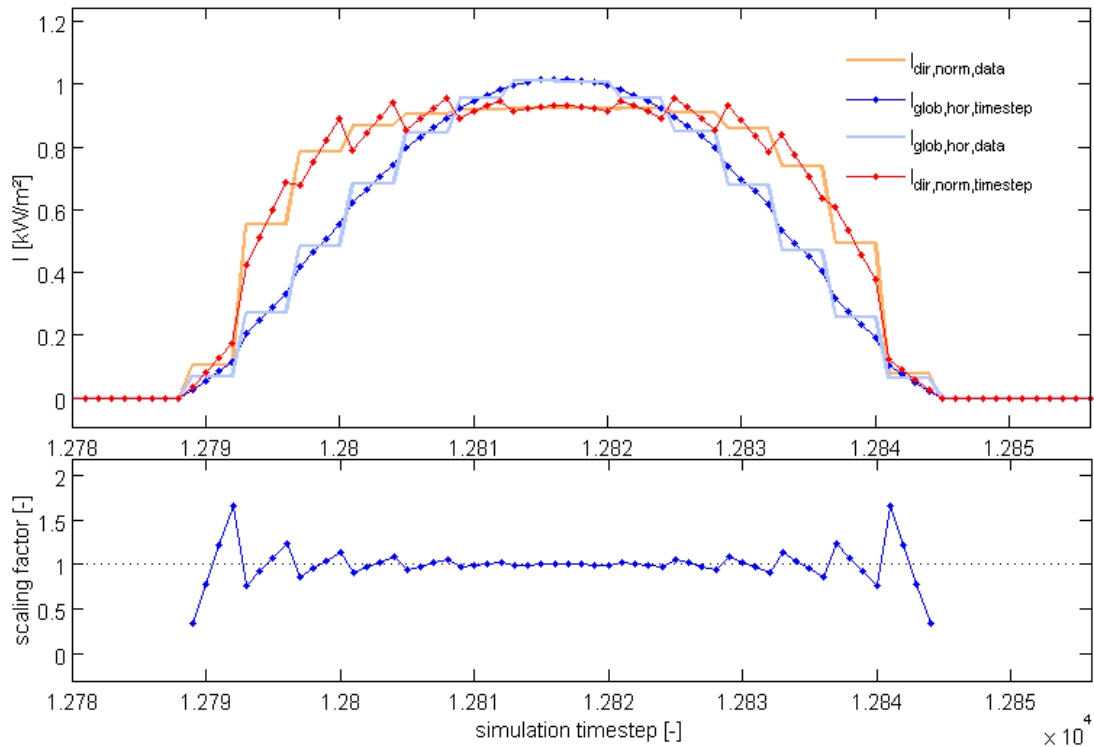
Figure 36: Original and interpolated global horizontal and direct normal radiation, TRNSYS

DesignBuilder needs weather data in form of the EnergyPlus weather file format (EPW). The original TMY-file has to be converted to an EPW-file, which can be done either by DesignBuilder's internal weather data converter or the external weather data converter which is provided with EnergyPlus. The converting procedure includes radiation data interpolation and the calculation of diffuse horizontal radiation.

DesignBuilder uses a simple weighted interpolation scheme for all weather data values:

$$Value_{TimeStep} = Value_{LastHour} \cdot Weight_{LastHour} + Value_{ThisHour} \cdot Weight_{ThisHour}$$

$$Weight_{ThisHour} = \frac{CurrentTimeStep}{\#TimeSteps\_in\_Hour}$$

$$Weight_{LastHour} = 1 - Weight_{ThisHour}$$

(1.87)

Figure 34 and Figure 33 show the results of the interpolation process and the calculation of diffuse radiation. The radiation data is interpolated smoothly, but the total horizontal radiation in Figure 34 shows a time shift. The peak of the interpolated total horizontal radiation appears approximately 40 minutes earlier than the peak of the original data. This

time shift only appears with the total horizontal radiation, direct normal radiation is interpolated correctly.

The diffuse radiation is calculated as the difference between the (shifted) total radiation and the (un-shifted) direct radiation. The incorrect, asymmetrical shape of the diffuse radiation can be explained by this time shift of the total radiation.
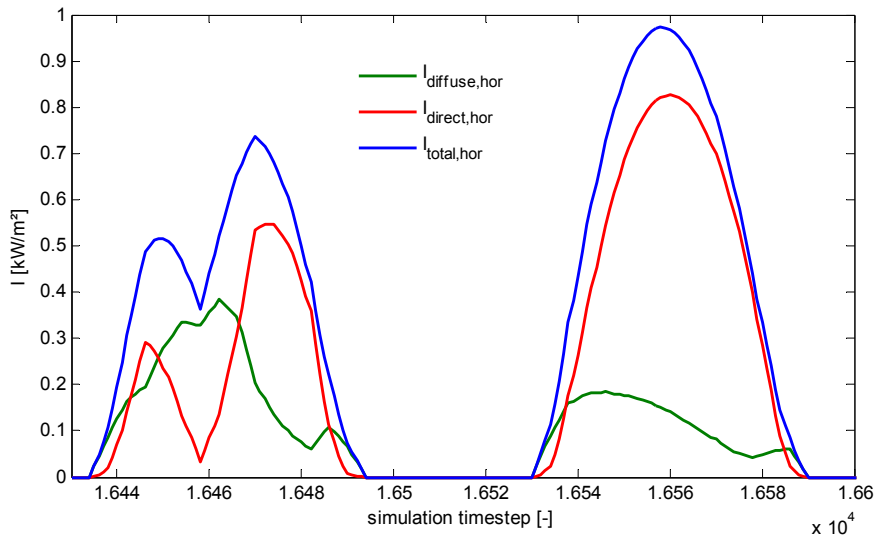
Figure 37: Diffuse, direct and total horizontal radiation, DesignBuilder

Figure 38 shows the annual sum of the total radiation on differently oriented surfaces, calculated with TRNSYS and DesignBuilder. The total horizontal radiation calculated with TRNSYS is equal to the value given by the ASHRAE standard, which means that the interpolation routine does not change the annual sum. The values calculated with DesignBuilder show small deviation from the correct value (~0.5%). The differences between the programs are significantly bigger for vertical surfaces. It is interesting to note that there is a large difference between the results calculated with the Perez model of TRNSYS and the Perez model of DesignBuilder.
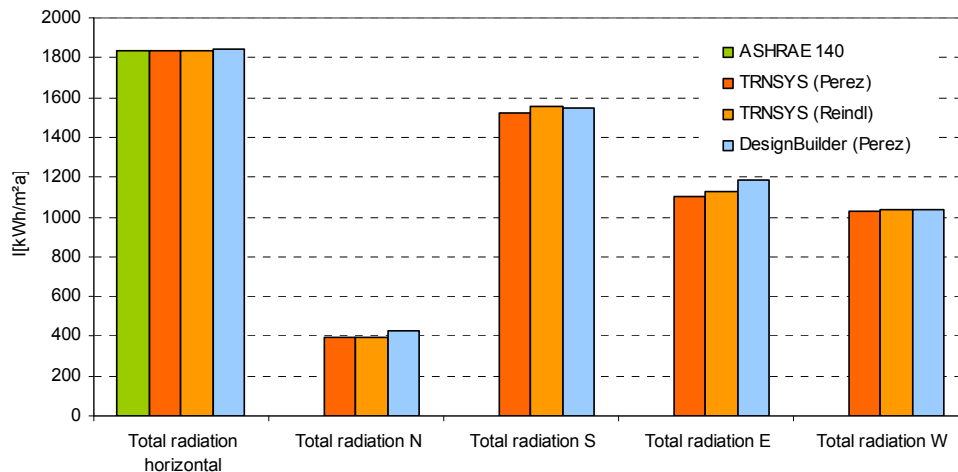
Figure 38: Annual total radiation on differently oriented surfaces, TRNSYS and DesignBuilder

3.2.7   Simplifying Case 600 (without windows)

In order to investigate the difference in the transmission gains (Figure 31), Case 600 has been simplified by removing the windows, setting internal gains to zero and neglecting infiltration gains and losses. Thus the only way to exchange energy with the environment is via transmission.

To eliminate the influence of the differing solar radiation on the heat transmission through the building envelope, both simulations have been run with exactly the same values. Diffuse radiation on all surfaces was calculated with DesignBuilder and saved as a plain text file. This file was imported to TRNSYS with the data reader Type9a. In Type 56 the imported diffuse radiation data have been used, instead of the values calculated with the radiation processor.

The transmission gains in this simplified version of Case 600 are still significantly different. The cause of these differences can be easily identified by means of Figure 39. The lowermost figure shows transmission gains in the south facing wall over a period of eight days in January. Significant differences in transmission occur only at the daytime and are strongly correlated to the total radiation on the surface. The second figure from the top shows the outside surface temperatures, which essentially exhibit the same behavior as the transmission gains. Since the solar irradiation and the external shortwave radiation properties of the surface are identical (2.4.7), the temperature difference can only be caused by surface convection. The uppermost figure confirms this assumption. The external convection coefficient in DesignBuilder is always much smaller than the convection coefficient in TRNSYS. Thus DesignBuilder displays a higher surface temperature during periods of solar irradiation. Because of the thin insulation and the low thermal mass of the wall, this has a significant effect on the conduction gains in the zone.
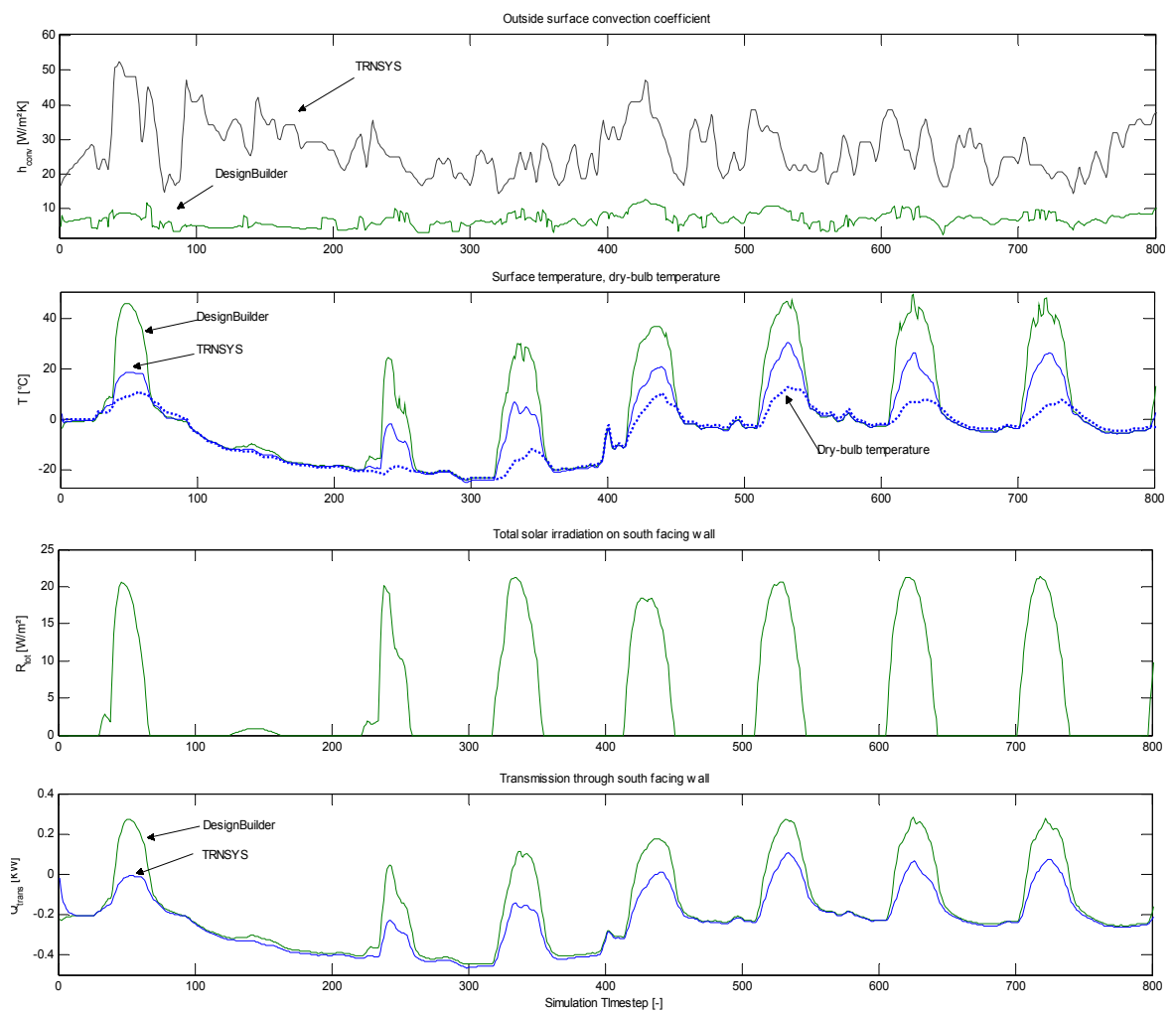
Figure 39: Transmission through building envelope, Case 600 (without windows)

The external convection coefficient in TRNSYS is calculated as a function of windspeed (3.2.1), according to the ASHRAE 140 standard. The external convection coefficient in DesignBuilder is calculated with the detailed convection model, which splits convection into a wind speed dependent forced convection term (equation(1.69)) and a natural convection term (equation(1.70)) which depends on the temperature difference between the surface and the surrounding air. The coefficient proposed by ASHRAE 140 shows a quadratic dependence on windspeed while the coefficient used in DesignBuilder shows a square root dependence, which explains the big differences between the coefficients in Figure 39. Figure 40 shows the external convection coefficients for the south facing wall of case 600 used in TRNSYS and DesignBuilder. Since the coefficient in DesignBuilder also depends on the temperature difference between the surface and the surrounding air, it is pictured for temperature differences of 1, 10 and 20 K.
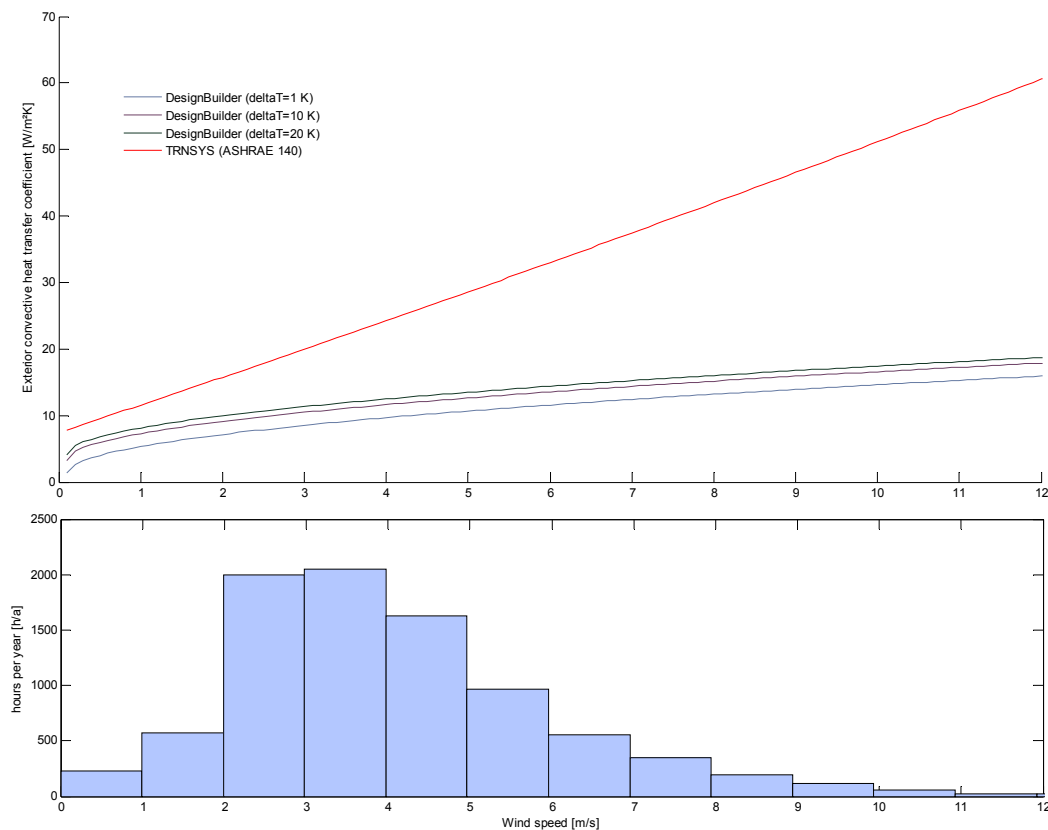
Figure 40: External convection coefficient as a function of wind speed, wind speed histogram

Calculation of forced convection on external building surfaces is a very complex subject, since the local windspeed at a particular surface strongly depends on the geometrical configuration and surrounding objects and is only loosely correlated to the "undisturbed" wind speed. Thus a variety of different correlations between wind speed and the external convection coefficient can be found in the literature (Davies, 2004, Loveday, Taki, 1995, Loveday, Taki, 1996, Sparrow et. al, 1979). Most authors propose some kind of power law relationship. Measurements on real buildings (Loveday, Taki, 1995) show a big variance in the data, thus the proposed correlations can only be seen as a rough approximation.

The correlation for forced convection used in DesignBuilder (LBNL, 2007) is based on a correlation by Sparrow et. al. (1979). Compared to other published correlations, this one leads to remarkably small values for the convection coefficient. One reason for that difference might be that in the case of Sparrow et. al. (1979), the correlations are based on wind tunnel experiments on inclined rectangular plates, while the correlations published by Loveday and Taki are based on measurements performed on real buildings.

Emmel and Mendes (2005) used a CFD program to predict external convection coefficients for the ASHRAE 140 model building. They considered different values of air

velocity (5m/s, 10m/s and 15m/s) and temperature difference (0K, 10K and 20K) and calculated the steady state velocity field. They found a very linear dependence between the convection coefficient and the airflow velocity (16W/m²K, 32 W/m²K and 47W/m²K). The temperature difference effects on the convection coefficients have been found to be very small.

To eliminate the influence of the differing convection models, the convection coefficients, calculated with DesignBuilder were used as an input in TRNSYS. The results now are very similar (Figure 41, Figure 42).

	Gains	Losses
◩ Diff	171	173
■ Qcool	0	229
■ Qheat	4098	0
□ Qgint	0	0
□ Qinfiltr	0	0
■ Qsolgain	0	0
■ Qtrans_op	1474	5343

	Gains	Losses
◩ Diff	416	395
■ Qcool	0	244
■ Qheat	3739	0
□ Qgint	0	0
□ Qinfiltr	0	0
■ Qsolgain	0	0
■ Qtrans_op	1512	5012
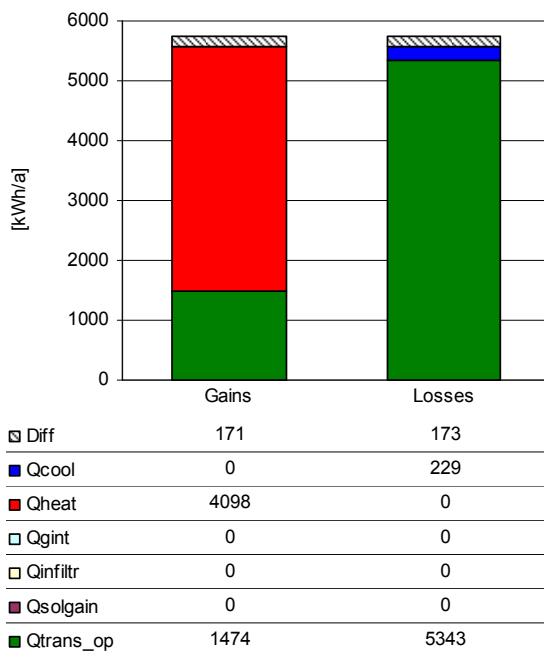
Figure 41: Energy balance, TRNSYS, Case600 (without windows, modified h_{conv})
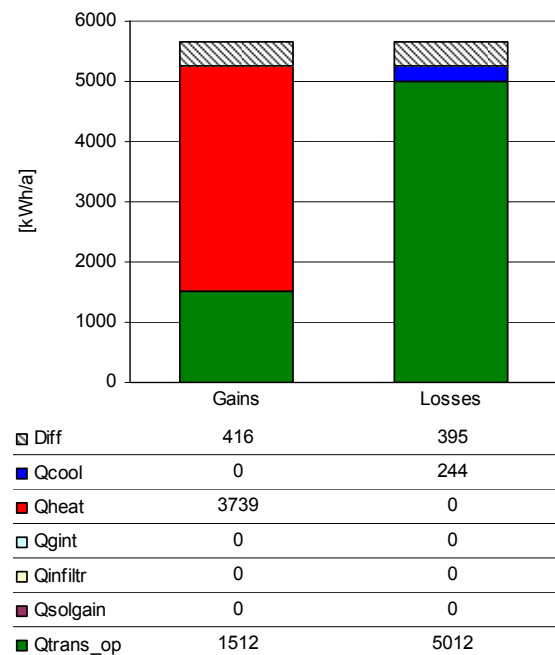
Figure 42: Energy balance, DesignBuilder, Case 600 (without windows)

3.3 Case 610 – south shading

Case 610 is exactly the same as Case 600, except that a 1m horizontal overhang for south facing windows is added (Figure 45). The goal is to investigate the different models used for shading calculations.

3.3.1 Modeling notes – TRNSYS

In TRNSYS overhang and wingwall shading can be simulated with Type 34 (2.4.7). Shaded beam radiation on the receiver surface is calculated based on the fraction of the receiver surface irradiated by beam radiation. Diffuse radiation is calculated based on view factors

to ground and sky (equation (1.77)). The receiver surface can be defined in various ways. Hiller (2006) suggests to define only the windows as the receiver surfaces, whereas Bradley (2004b) suggests to consider the shading effects on both, windows and walls.

Three different definitions of receiver surfaces have been compared: "Wall" considers the whole wall as the receiver surface, "Windows" considers only the windows and "Wall and Windows" considers both as separate receiver surfaces (Figure 43).

„Wall"

„Windows"

„Wall and Windows"
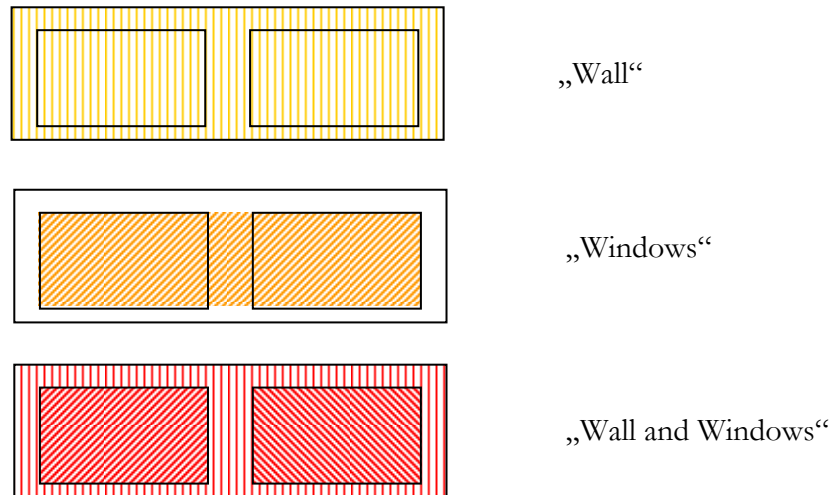
Figure 43: Modeling alternatives for shading in TRNSYS ("receiver" definition Type 34)

Figure 44 shows the monthly solar gains and heating and cooling energy demand for the three modelling alternatives. The receiver definition has a significant influence on the solar gains and the cooling energy demand. The "Wall" alternative shows significantly lower solar gains during the winter time. This happens because a fraction of the receiver surface is always being shaded and thus the irradiation on the window is reduced although in fact the window is not being shaded (Figure 45). In the other alternatives the receiver surfaces for windows have been defined separately, thus the solar gains are calculated more correctly during periods of a low solar incidence angle. During the summer period the difference between the alternatives is not so big because the fractions of the receiver surface irradiated by beam radiation are similar (Figure 46).

The "Wall and Windows" alternative is the most correct but also the most time consuming method, because separate receiver surfaces have to be defined and calculated for each wall and each window. In this case, the results between the "Windows" and the "Windows and Wall" alternative are very similar.

The results for Case 610 presented in the subsequent sections have been calculated using the "Windows and Wall" alternative.
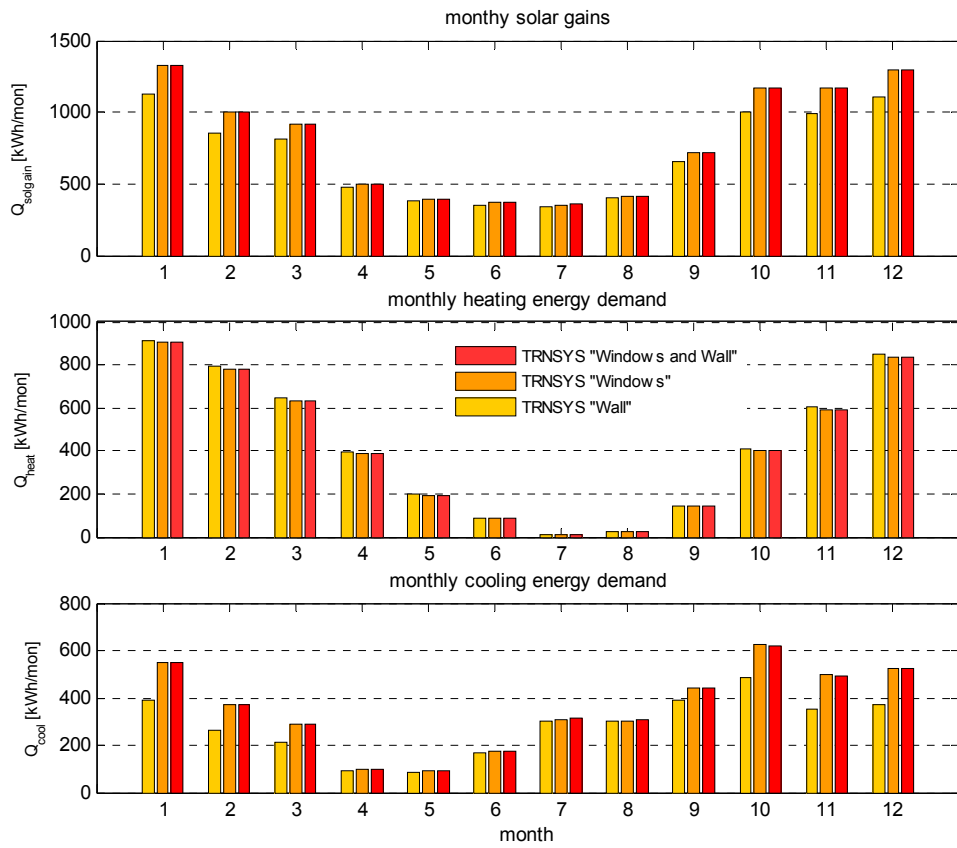
Figure 44: Modeling alternatives for shading (Case 610) in TRNSYS

Figure 45: Shading 01.01. 14:00
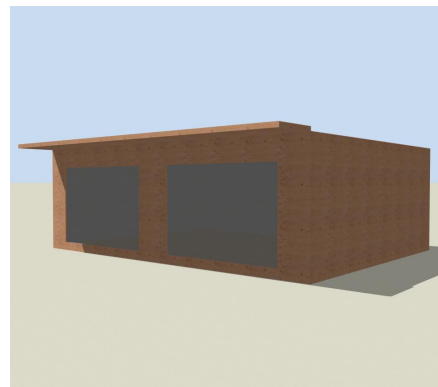
Figure 46: Shading 01.08. 14:00

3.3.2 Modeling notes – DesignBuilder

The overhang which is required by Case 610 specifications is modeled in DesignBuilder by an opaque component block. The surface radiation properties of the block are chosen equal to the properties of the building surface.

3.3.3 Comparison with published results

The simulation results for Case 610 have been compared to published results. The TRNSYS results agree with the results of other versions and are virtually identical to the results of Hiller (2006) which used the same TRNSYS version. All results are within the range of variation of published ASHRAE 140 results. The DesignBuilder results agree with published results of older versions and also lie within the range of variation of published ASHRAE 140 results. The associated figures can be found in appendix A.

	Annual Heating	Annual Cooling
	[kWh/a]	[kWh/a]
ASHRAE 140 MIN	4355	3915
TRNSYS 16.1	5006	4273
DesignBuilder1.4.0	4515	4859
ASHRAE 140 MAX	5786	5778
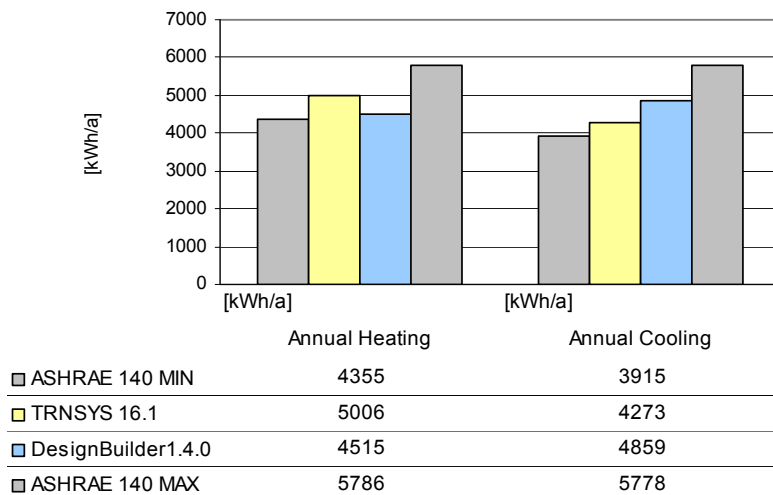
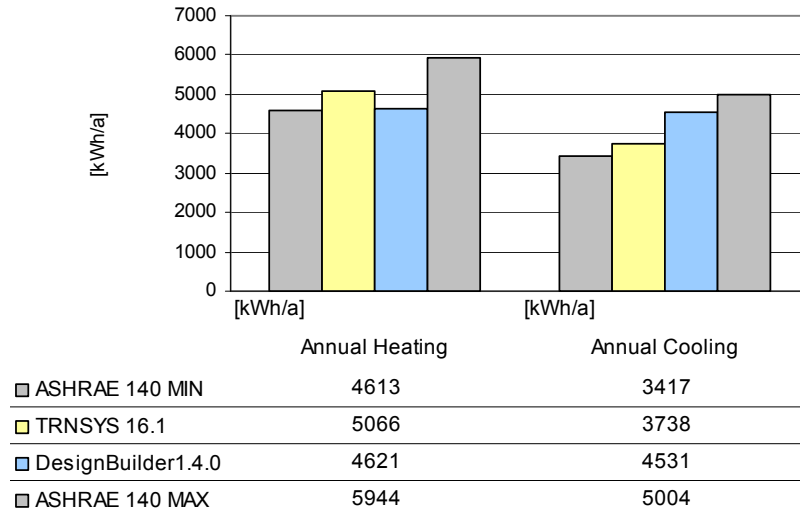Figure 47: Comparison of annual heating and cooling energy, Case 610

Comparing the annual heating and cooling energy of TRNSYS and DesignBuilder, they show a similar behavior than in Case 600. The heating energy of TRNSYS is higher (+11%) and the cooling energy is lower (-12%) than the energy calculated with Design-Builder. The calculated peak loads for heating and cooling in Figure 48 again show the expected tendency.

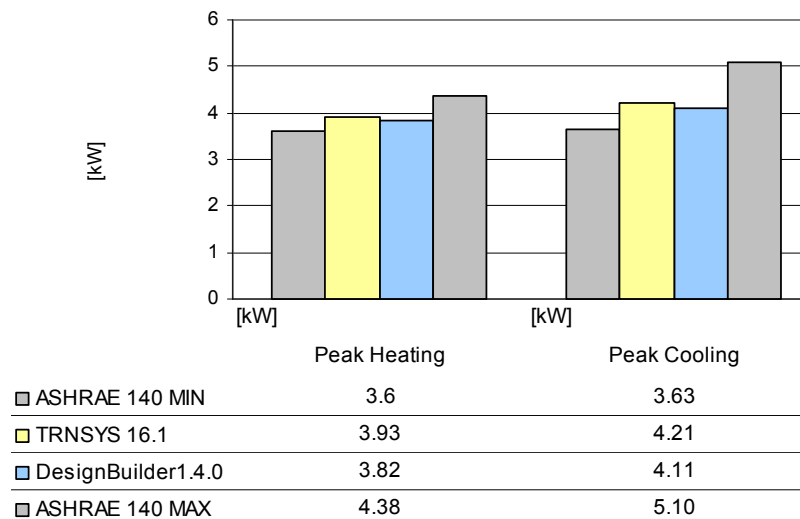|	Peak Heating	Peak Cooling
☐ ASHRAE 140 MIN	3.44	5.67
☐ TRNSYS 16.1	3.93	6.02
☐ DesignBuilder1.4.0	3.81	6.19
☐ ASHRAE 140 MAX	4.35	6.37
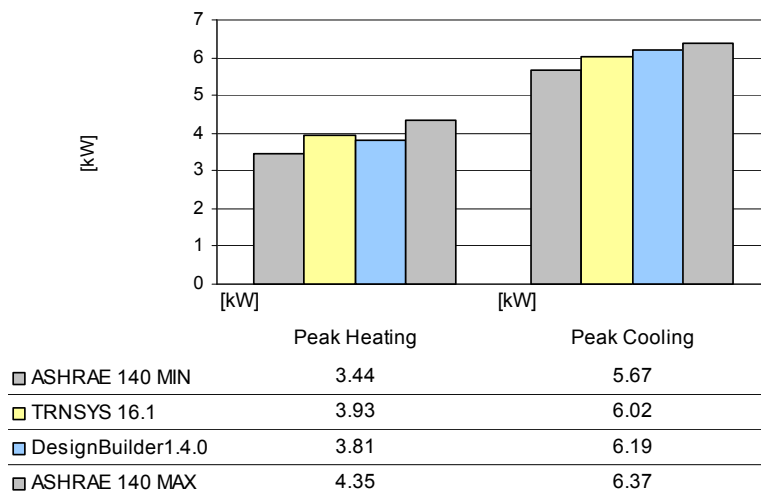
Figure 48: Comparison of peak heating and cooling load, Case 610

3.3.4 Comparing detailed energy balance

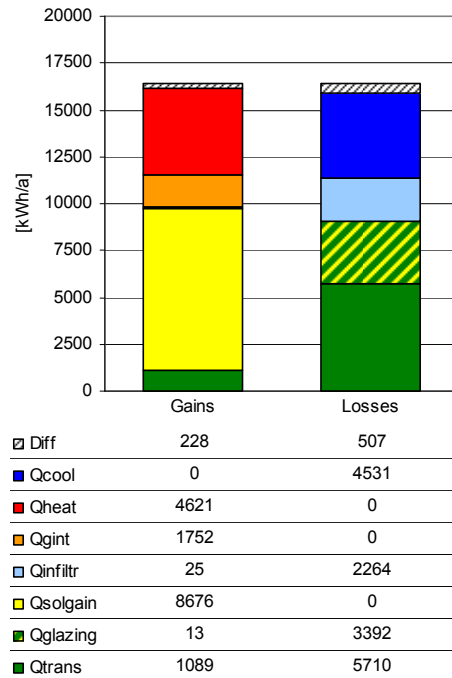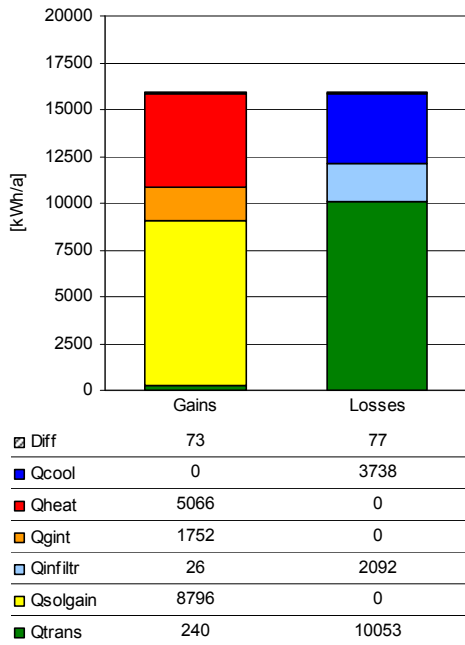Figure 49 and Figure 50 show the annual energy balance for Case 610, calculated with TRNSYS and DesignBuilder.

	Gains	Losses
☐ Diff	83	83
■ Qcool	0	4273
■ Qheat	5006	0
■ Qgint	1752	0
☐ Qinfiltr	26	2101
☐ Qsolgain	9625	0
■ Qtrans	178	10213

	Gains	Losses
☐ Diff	257	386
■ Qcool	0	4859
■ Qheat	4515	0
■ Qgint	1752	0
☐ Qinfiltr	25	2268
☐ Qsolgain	9124	0
☐ Qglazing	8	3322
■ Qtrans	1057	5904
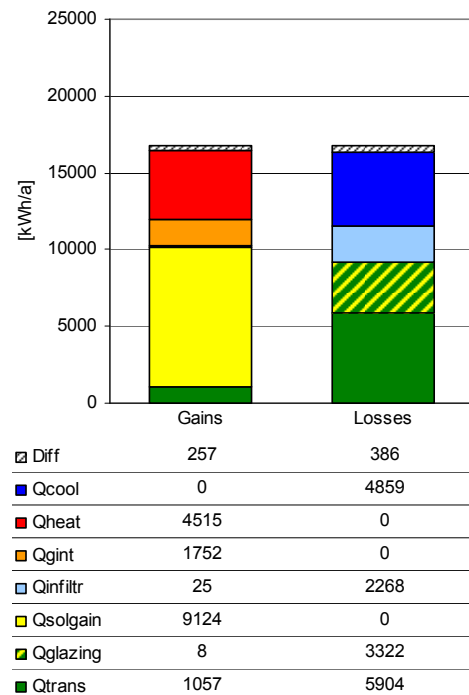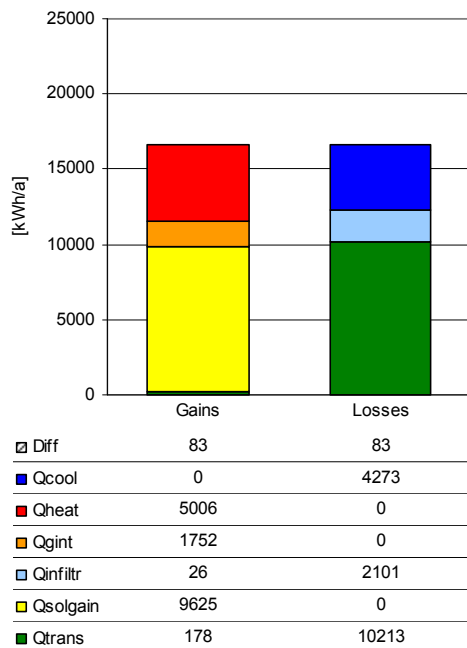
Figure 49: Energy balance, TRNSYS, Case610   Figure 50: Energy balance, DesignBuilder, Case 610

Due to the different modelling assumptions of both programs it is better to compare the differences between the cases, instead of the absolute values.
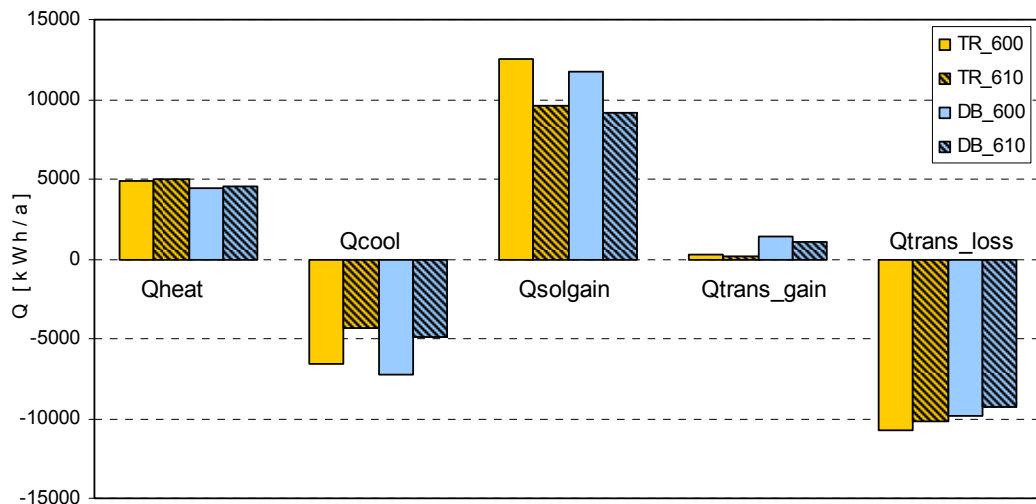
Figure 51: Comparison of balance components Case 600 and Case 610, TRNSYS, DesignBuilder

Both programs show the expected effect of an increased heating energy (TRNSYS +3%, DesignBuilder +1%) and a decreased cooling energy (TRNSYS -35%, DesignBuilder -33%), caused by overhang shading (Figure 51).

The solar gains were reduced by 2950 kWh/a (-23.4%) in TRNSYS and by 2660 kWh/a (-22.5%) in DesignBuilder. Figure 52 shows the relative reduction of solar gains due to overhang shading at each month. One can see that, as expected, the reduction in both programs is small in the winter months and large in the summer months. Comparing both programs, one can see that from March to September DesignBuilder has more reduction in the solar gains than TRNSYS. Since a large part of the solar radiation on a vertical south façade in summer is diffuse radiation (~60%), the diffuse radiation model plays a crucial role in predicting the effect of shading. The main difference between the shading models of the two programs is that TRNSYS uses the isotropic sky model, whereas DesignBuilder uses the anisotropic Perez model (2.4.7). The anisotropic model assumes that a part of the diffuse radiation comes from the direction of the sun (circumsolar brightening). Since the sun has a high incidence angle in the summer months, this component is screened by the overhang and does not contribute to the solar gains. In winter the sun has a low incidence angle, which means that the circumsolar component can't be screened by the overhang. This might explain the higher reduction of the solar gains in summer and the lower reduction in winter, using an anisotropic model for shading calculations.
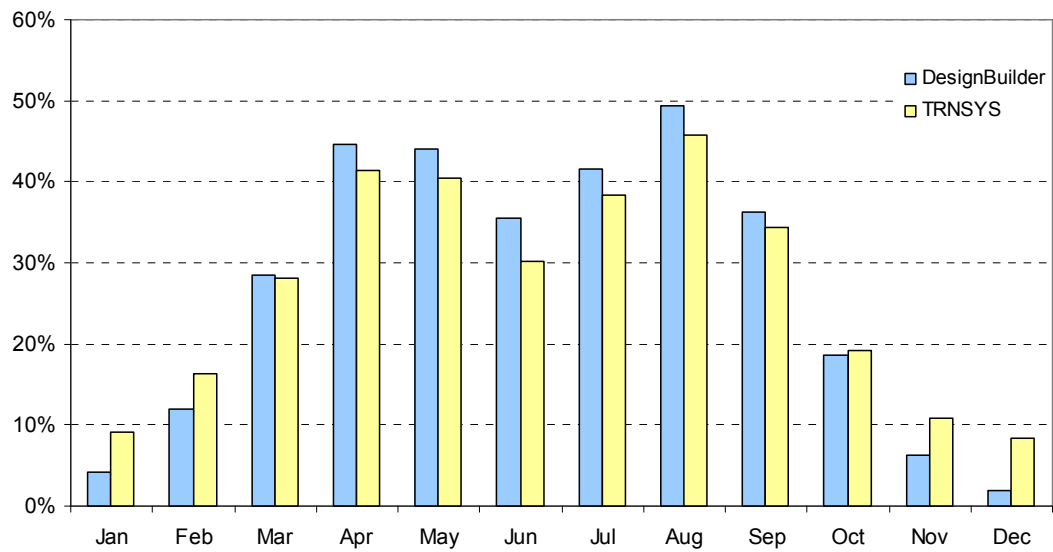
Figure 52: Reduction of solar gains between Case600 and Case610, TRNSYS, DesignBuilder

3.4 Case 620 – east and west window

Case 620 is exactly the same as Case 600, except that the window orientation has changed. The windows have been removed from the south façade and are now on the east and the west façade. The window size and construction remain unchanged.
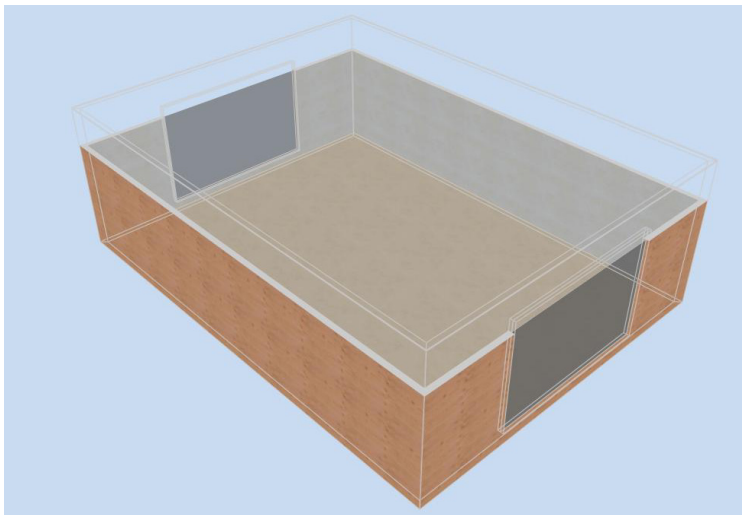
Figure 53: Case 620 – East and West Window

3.4.1 Comparison with published results

The simulation results for Case 620 have been compared to published results. The TRNSYS results agree with the results of other versions and are virtually identical to the results of Hiller (2006) which used the same TRNSYS version. All results are within the

range of variation of published ASHRAE 140 results. The DesignBuilder results agree with published results of older versions and also lie within the range of variation of published ASHRAE 140 results (see Figure 54 and 55). The associated figures can be found in appendix A.

	Annual Heating	Annual Cooling
	[kWh/a]	[kWh/a]
☐ ASHRAE 140 MIN	4613	3417
☐ TRNSYS 16.1	5066	3738
☐ DesignBuilder1.4.0	4621	4531
☐ ASHRAE 140 MAX	5944	5004

Figure 54: Comparison of annual heating and cooling energy, Case 620

Comparing the annual heating and cooling energies of TRNSYS and DesignBuilder, they show a similar behavior than the previous cases. The heating energy of TRNSYS is higher (+10%) and the cooling energy is lower (-18%) than the energies calculated with DesignBuilder.

	Peak Heating	Peak Cooling
	[kW]	[kW]
☐ ASHRAE 140 MIN	3.6	3.63
☐ TRNSYS 16.1	3.93	4.21
☐ DesignBuilder1.4.0	3.82	4.11
☐ ASHRAE 140 MAX	4.38	5.10

Figure 55: Comparison of peak heating and cooling load, Case 620

3.4.2 Comparing detailed energy balance

Figure 56 and Figure 57 show the annual energy balance for Case 620, calculated with TRNSYS and DesignBuilder.

	Gains	Losses
▨ Diff	73	77
■ Qcool	0	3738
■ Qheat	5066	0
■ Qgint	1752	0
□ Qinfiltr	26	2092
□ Qsolgain	8796	0
■ Qtrans	240	10053

	Gains	Losses
▨ Diff	228	507
■ Qcool	0	4531
■ Qheat	4621	0
■ Qgint	1752	0
□ Qinfiltr	25	2264
□ Qsolgain	8676	0
■ Qglazing	13	3392
■ Qtrans	1089	5710

Figure 56: Energy balance, TRNSYS, Case620   Figure 57: Energy balance, DesignBuilder, Case 620
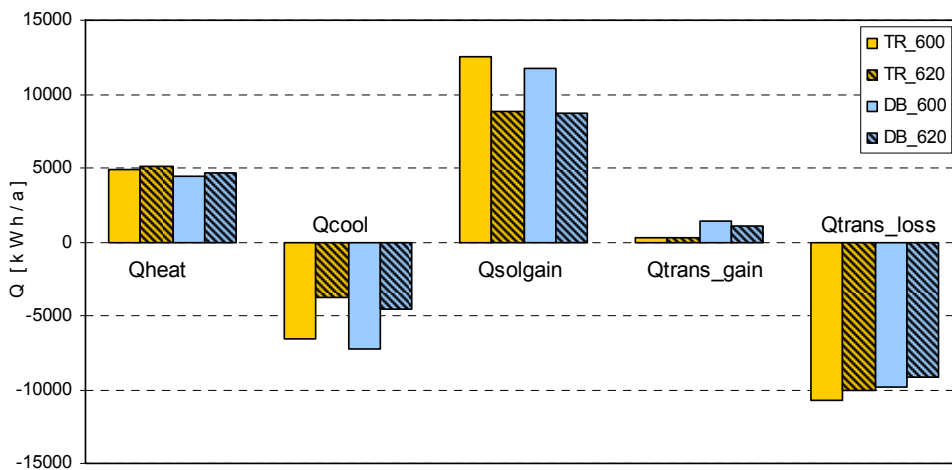
Figure 58: Comparison of balance components Case 600 and Case 620, TRNSYS, DesignBuilder

Both programs show a slightly increased heating energy (TRNSYS +4%, DesignBuilder +3%) and a massively reduced cooling energy (TRNSYS -43%, DesignBuilder -37%). This can be explained with the reduced solar gains (TRNSYS -30%, DesignBuilder -26%). Figure 59 shows monthly sums of solar gains and cooling energy for Case 600 and Case 620. Due to the modified window orientation, the solar gains have their maximum in the summer months, where the sun has a high incidence angle on the east (morning) and west (evening) façade. The cooling energy shows a similar distribution over the year. The cooling energy in summer is higher in DesignBuilder, although the solar gains are equal. This can be explained with the higher transmission gains (Figure 58) due to the different models for the external convection coefficient (3.2.7). The peak cooling load of Case 620 is also much smaller (TRNSYS -37%, DesignBuilder -39%, Figure 29 and Figure 48) than in Case 600. The east- and west orientated windows produce two smaller peaks (morning and evening) in the cooling load instead of one large peak at noon.
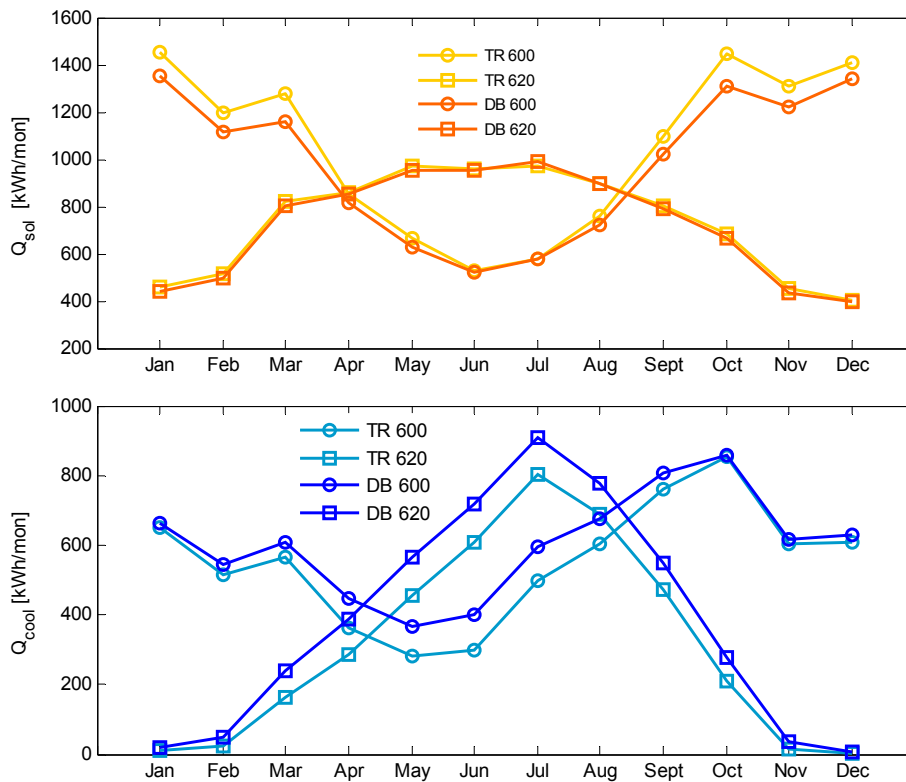
Figure 59: Monthly sums of solar gains and cooling energy for Case 600 and 620, TR, DB

4 Conclusion

The models of the two building simulation environments TRNSYS and DesignBuilder have been compared in section 2.4 and section 2.5. Table 6 gives a summarizing comparison of the models used in both programs.

Selected cases of the ASHRAE 140 code have been simulated. The results have been compared in section 3. In all simulated cases, TRNSYS showed a higher heating energy demand and a lower cooling energy demand. The differences in the annual results are in the order of ±10%. The main reasons for the differences can be found in the model for the external convection coefficient and in differing models and routines for solar radiation processing.

The model for the external convection coefficient used in TRNSYS shows a quadratic dependence on windspeed, whereas the model used in DesignBuilder shows a square root dependence (section 3.2.7). The higher convection coefficient in TRNSYS causes a lower outside surface temperature and lower conduction gains in periods of solar irradiation. The lower conduction gains partly explain the higher heating and the lower cooling energy demand.

Models for external convection are a considerable source of uncertainty in thermal building simulations. Many different models are proposed in the literature and are used in different programs. Especially for wind induced forced convection they lead to significantly different coefficients (section 3.2.7, section 3.3.4 and section 3.4.2). In case of buildings with a high thermal transmittance, this can lead to substantial differences in the conduction gains and losses through the envelope.

Different routines for radiation interpolation and different diffuse sky models lead to differences in the solar irradiation on the building surface (section 3.2.6).

The shading model in TRNSYS uses the isotropic sky model, DesignBuilder uses the anisotropic Perez model. For a south facing overhang, the anisotropic shading model shows a higher shading effect in summer and a lower shading effect in winter, compared to the isotropic shading model.

Solar radiation processing has a significant impact on the simulation results. Especially the diffuse sky model, which is utilized to calculate the diffuse irradiation on inclined surfaces, and the shading model, which is utilized to calculate the diffuse radiation shaded by an obstruction, are sources of predictive differences between simulation programs (3.2.6).

The main difference in the building models is that DesignBuilder uses a three-dimensional geometrical building model, whereas TRNSYS does not have explicit information about the building geometry. Due to the three-dimensional building representation, DesignBuilder is able to provide more sophisticated models for solar and longwave radiation calculations.

From a practitioner's perspective DesignBuilder is convenient and timesaving, because many radiation and shading calculations are performed automatically based on the three-dimensional building model. Examples are the calculation of solar irradiation on inclined surfaces, calculation of specular and diffuse reflections on external surfaces like a reflective glass façade or a water surface area, internal and external longwave and shortwave view factors, self shading of the building, shading by remote obstructions and overhangs, the distribution of solar radiation in the room and daylighting calculations.

On the other hand TRNSYS allows a much more flexible handling of the information flow in the program (e.g user defined input data, user defined equations, user defined connection of simulation modules).

An option which provides both, a comfortable interface and flexible modeling options, is to use both programs, DesignBuilder and EnergyPlus. DesignBuilder is used to define the model geometry and the basic settings. Then the IDF file is exported, modified in the IDF editor and simulated in EnergyPlus.

Finally it can be concluded, that both programs have their specific strengths and weaknesses. The three-dimensional building representation of EnergyPlus combined with the comfortable user interface of DesignBuilder, provides many advantages for thermal building modeling and simulations. It should be mentioned that this thesis only compares and evaluates the modeling capabilities for thermal building simulations and not for HVAC and energy systems simulations.

Table 6: Comparison of the models used in TRNSYS and DesignBuilder

	TRNSYS	DesignBuilder
Thermal zone model	• Star Network Method	• Convection and LW radiation separately
Conduction	• CTF (Laplace Method)	• CTF (State Space Method) • EnergyPlus: Finite Difference Method (implicit, Gauss-Seidel iteration)
Internal convection	• User defined: h =const. • Internally calculated: h=f(ΔT)	• Detailed: h=f(ΔT) • Simple: h =const. • CIBSE: h =const • Ceiling diffuser:: h=f(ACH) • Cavity: h=f(Nu, Ra)
External convection	• User defined: h =const.	• Detailed: $h_{nat} = f(\Delta T), h_{forced} = f(v)$ • Simple: h=f(v) • BLAST: (equal to Detailed) • TARP: (equal to Detailed) • MoWiTT: $h_{nat} = f(\Delta T), h_{forced} = f(v)$ • DOE-2: $h_{nat} = f(\Delta T), h_{forced} = f(v)$
Internal LW radiation	• Black body radiation • Constant average surface temperature (LTI) • ViewFactor= f(Area ratio)	• Grey, diffuse radiation model (Lambert) • Actual surface temperature values • ViewFactor= f(Area ratio, constraints)
External LW radiation	• Grey, diffuse radiation model (Lambert) • Tsky, Tair	• Grey, diffuse radiation model (Lambert) • Tsky, Tair • LW Shading
Diffuse sky model:	• Isotropic Sky • Hay and Davies • Reindl • Perez	• Perez
SW radiaton external distribution	• Shading types (Isotropic)	• Minimal: no external shading • Full exterior (Anisotropic) • Full exterior with reflections (Anisotropic)
SW radiaton, internal distribution	• Beam: user defined factors (geosurf) • Diffuse: absorptance weighed area ratio	• Minimal: Beam: on floor, Diffuse: absorptance weighed area ratio • Full interior: Beam: calculated, Diffuse: absorptance weighed area ratio
Zone air temperature	• Uniform temperature	• Uniform temperature • Dynamic gradient model
Infiltration, natural Ventilation	• User defined ACH • TRNFLOW: COMIS model	• User defined ACH • EnergyPlus AirflowNetwork model: based on COMIS model
Ground modeling	• User defined: Tsurf • "dummy" zones + undisturbed ground temperature • Ground modeling types (Tess Library): 3d-Finite-difference method	• User defined: Tsurf • Ground material layer + deep ground temperature • EnergyPlus slab/basement program: 3d- Finite-difference method

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Notation and Abbreviations

ASCII   American Standard Code for Information Interchange

ASHRAE   American Society of Heating, Refrigerating and Air-Conditioning Engineers

BLAST   Building Loads Analysis and Systems Thermodynamics

CFD   Computational Fluid Dynamics

CIBSE   Chartered Institution of Building Services Engineers

CTF   Conduction Transfer Function

CRTF   Comprehensive Room Transfer Function

DHW   Domestic Hot Water

DLL   Dynamic Link Library

DOE   US Department of Energy

EPW   EnergyPlus Weather File Format

FEM   Finite Element Method

HVAC   Heating Ventilation and Air-Conditioning

IDF   EnergyPlus Input Data File

LBNL   Ernest Orlando Lawrence Berkeley National Laboratory

SEL   Solar Energy Laboratory

SMOT   Standard Method of Test

TMY   Typical Meteorological Year Data Format

TESS   Thermal Energy Systems Specialists

TRNSYS   Transient Systems Simulation Program

UC   University of California

UI   University of Illinois

UWM   University of Wisconsin-Madison

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Appendix A

	Annual Heating	Annual Cooling
	[kWh]	[kWh]
☐ ASHRAE 140 MIN	4355	3915
☐ TRNSYS 16.1 (Karitnig)	5006	4273
☐ TRNSYS 16.1 (Hiller)	5000	4300
☐ TRNSYS 15.3 (Bradley)	5300	4250
☐ TRNSYS 13.1 (ASHRAE 140)	4970	4601
☐ ASHRAE 140 MAX	5786	5778

Figure A1: Annual heating and cooling energy, TRNSYS, Case 610

	Peak Heating	Peak Cooling
	[kW]	[kW]
☐ ASHRAE 140 MIN	3.44	5.67
☐ TRNSYS 16.1 (Karitnig)	3.93	6.02
☐ TRNSYS 16.1 (Hiller)	3.90	6.00
☐ TRNSYS 15.3 (Bradley)	3.90	5.80
☐ TRNSYS 13.1 (ASHRAE 140)	3.92	5.68
☐ ASHRAE 140 MAX	4.35	6.37

Figure A2: Peak heating and cooling load, TRNSYS, Case 610

	Annual Heating	Annual Cooling
ASHRAE 140 MIN	4355	3915
DesignBuilder1.2.0	4530	4900
DesignBuilder1.4.0 (Karitnig)	4515	4859
ASHRAE 140 MAX	5786	5778

Figure A3: Annual heating and cooling energy, DesignBuilder, Case 610

	Peak Heating	Peak Cooling
ASHRAE 140 MIN	3.44	5.67
DesignBuilder1.2.0	3.82	6.27
DesignBuilder1.4.0 (Karitnig)	3.81	6.19
ASHRAE 140 MAX	4.35	6.37

Figure A4: Peak heating and cooling load, DesignBuilder, Case 610

	Annual Heating	Annual Cooling
	[kWh]	[kWh]
☐ ASHRAE 140 MIN	4613	3417
☐ TRNSYS 16.1 (Karitnig)	5066	3738
☐ TRNSYS 16.1 (Hiller)	5100	3700
☐ TRNSYS 15.3 (Bradley)	5500	3670
☐ TRNSYS 13.1 (ASHRAE 140)	5073	3901
☐ ASHRAE 140 MAX	5944	5004

Figure A5: Annual heating and cooling energy, TRNSYS, Case 620

	Peak Heating	Peak Cooling
	[kW]	[kW]
☐ ASHRAE 140 MIN	3.60	3.63
☐ TRNSYS 16.1 (Karitnig)	3.93	4.21
☐ TRNSYS 16.1 (Hiller)	3.90	4.20
☐ TRNSYS 15.3 (Bradley)	3.90	4.10
☐ TRNSYS 13.1 (ASHRAE 140)	3.92	4.28
☐ ASHRAE 140 MAX	4.38	5.10

Figure A6: Peak heating and cooling load, TRNSYS, Case 620

	Annual Heating	Annual Cooling
	[kWh/a]	[kWh/a]
■ ASHRAE 140 MIN	4613	3417
□ DesignBuilder1.2.0	4651	4351
▨ DesignBuilder1.4.0 (Karitnig)	4621	4531
■ ASHRAE 140 MAX	5944	5004

Figure A7: Annual heating and cooling energy, DesignBuilder, Case 620

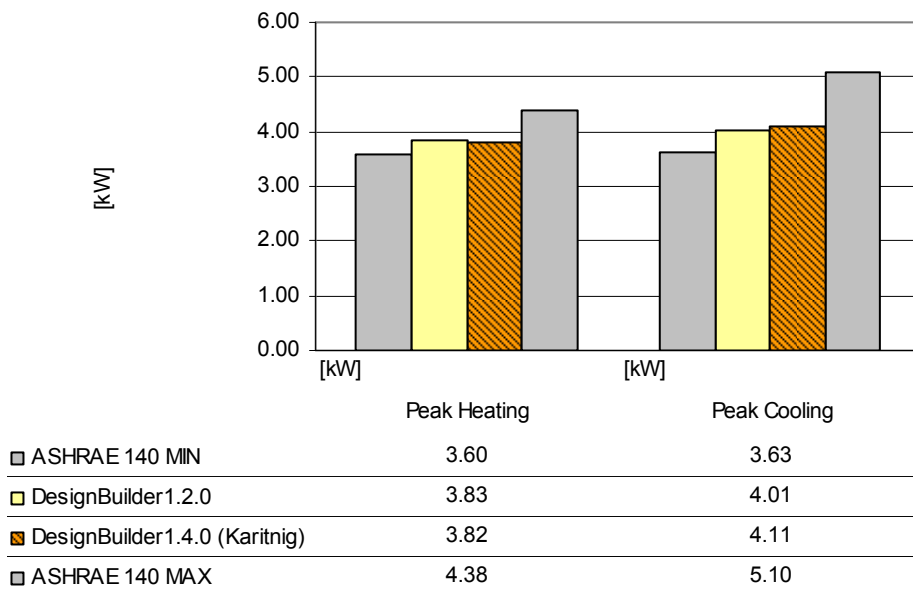|	Peak Heating	Peak Cooling
	[kW]	[kW]
■ ASHRAE 140 MIN	3.60	3.63
□ DesignBuilder1.2.0	3.83	4.01
▨ DesignBuilder1.4.0 (Karitnig)	3.82	4.11
■ ASHRAE 140 MAX	4.38	5.10

Figure A8: Peak heating and cooling load, DesignBuilder, Case 620