Report

Software for modelling and simulation of ground source heating and cooling systems
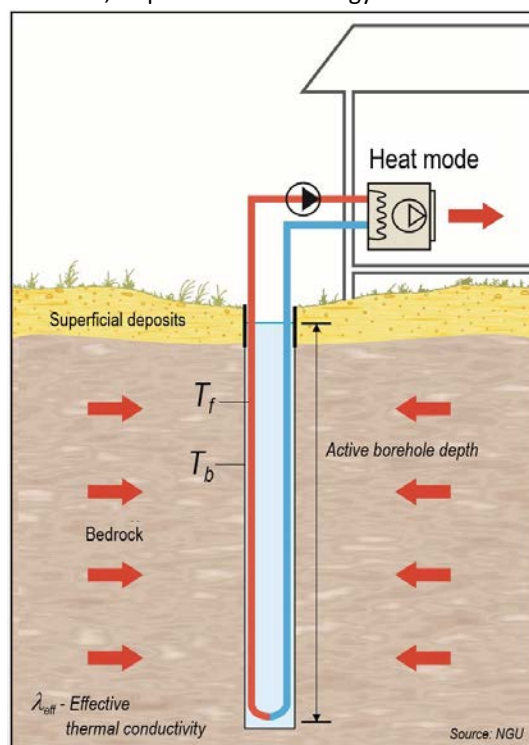
WP2 INTERACT

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Report

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Software for modelling and simulation of ground source heating and cooling systems

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ABSTRACT
The aim of this survey is to explore different simulation software for designing of ground source heating systems. Models to simulate borehole storages, heat pumps, and system components like water storages, hydraulics and building loads are explored. This study is based on a literature survey of software and models for simulation of geothermal heating and cooling systems with focus on vertical ground heat exchangers. The study focus on the software used by the authors, which are EED, TRNSYS, Polysun, Modelica, IDA ICE, and Matlab/Simulink+Carnot. The scopes and limitations of the software and models are evaluated and the advantages and disadvantages with the software are addressed. It was found that the user-friendliness is strongly linked to the level of flexibility in the models. Higher flexibility usually means less user-friendliness and more time to learn the tool. EED, Polysun and IDA are considered to be the more user friendly softwares, while Modelica, TRNSYS and Matlab/Simulink+Carnot are considered to be the more flexible softwares. The models covering most of the aspects of borehole simulations are the TRNSBM-model in TRNSYS and the "INTERACT 2016" model for Modelica.

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1 Introduction

Ground source heat pump systems (GSHP) are becoming more and more popular, especially in the Nordic countries. When these systems are implemented in larger buildings with both heating and cooling loads and the borehole heat exchangers placed together forming a ground heat storage, the complexity increases and the challenge to size such systems are more demanding and requires more advanced simulation software. The challenges for such models are that they have to handle both the cooling and heating demand in the building correctly, as well as the performance of the system and the borehole storage.

Ground source heat pump systems (GSHPs) can be divided in different categories depending on the design and heat source. Lake water, ground surface or ground water (aquifer storages) can be used as heat source as well as vertical boreholes with heat exchangers, which the latter is the scope of this study. The borehole storage can be designed solely for extraction of heat from the ground or for both charging and discharging of heat during the year. The borehole geometry can be dense when designed as a storage or spaced when the main purpose is heat exchange with the ground.

1.1 Objective

The aim of this survey is to explore different simulation software for designing of ground source heating systems. The focus is on the component models for borehole thermal energy storages (BTES), but also brine to fluid heat pumps and other components included in heating and cooling systems are discussed. Models to simulate borehole storages, heat pumps, and system components like water storages, hydraulics and building loads are explored. Properties of the borehole models and benefits and shortcomings of the different models are analysed. The focus of the evaluation is to describe the level of detail in the software and models for simulating and their potentials and limitations. In addition, advantages and disadvantages of these programs are studied considering their use by consultant companies and not only researchers.

1.2 Limitations and scope of the report

Available models and software for the simulation and sizing of vertical borehole heat exchangers and brine to water heat pump systems are explored. The study focus on the software used by the authors, which are EED, TRNSYS, Polysun, Modelica, IDA ICE, and Matlab/Simulink+Carnot. Other models and software for borehole storages found during the study are also mentioned synoptically in section 3, but they are not explored in detail. The current study does not give a full review of all existing models for ground source heat pump systems. The study on heat pump models is limited to those models suitable to simulate brine to water heat pumps.

1.3 Method

This study is based on a literature survey of software and models for simulation of geothermal heating and cooling systems with focus on vertical ground heat exchangers. Literature on validation of the borehole models are addressed. The scopes and limitations of the software and models are evaluated and the advantages and disadvantages with the software are addressed.

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2 Ground heat exchangers

There are several possibilities to extract heat or cold from the ground. U-tubes inserted in boreholes are a common method for the heat exchange from the rock to a heat pump through a brine circuit (figure 2.1). The borehole can be filled with ground water (common in Norway and Sweden) or a grouting material that support heat exchange between the tubes and the borehole wall.

2.1 Energy and thermal capacity

Energy and thermal capacity are two fundamental definitions within ground source heat pump technology and they are both essential for sizing conditions. Energy can be described as the ability to perform a mechanical work or to produce heat. Pursuant to the first law of thermodynamics, "energy can be transformed from one form to another, but cannot be created or destroyed". For ground source heat pump systems, the form of energy concerned is heat. Heat flows from a place with higher temperature towards a place with lower temperature by conduction, convection or radiation. The common unit for measurement of energy is joule (SI), calories or kilowatt-hours (kWh). Concerning ground source heat pump systems, the unit kWh is commonly used.

The thermal capacity is the work performed within a unit of time and is measured in watts (W) or kilowatts (kW). I W = 1 Joule per second. Thermal capacity is an instantaneous value for heat output, while energy expresses the use, the need or the production throughout a period of time.

2.2 Thermal response tests

Thermal response tests with mobile measurement devises were introduced in Sweden and USA in mid-1990 (Gehlin, 2002). The borehole and the surrounding bedrock is heated or cooled at a constant rate, and the temperatures of the in- and outflowing collector fluid is measured during the test. Thus, the ability of the bedrock to absorb heat or cold is measured. The minimum test duration is 50 hours, and recommended test duration is 60-72 hours (Gehlin, 2015). The three parameters measured in, and prior to (undisturbed temperature in the ground) a thermal response test are:

- Effective thermal conductivity (λ_{eff}) for the energy well is the sum of the thermal conductivity of the bedrock and an eventual contribution from groundwater movement, and is represented by heat conduction (in solids) and convection (fluid flows transporting energy).

- Thermal borehole resistance (R_b) describes the heat transfer in the borehole and how effective the closed loop collector works as a borehole heat exchanger. Low thermal borehole resistance means good heat transfer, and low temperature difference between the borehole wall and the collector fluid. Equation 2.1 describes the relation between the temperature in the ground collector fluid (T_f) and the borehole wall (T_b) and the thermal borehole resistance (R_b) at a certain specific heat rate (q) [W/m]. See also figure 2.1 and a more detailed description of thermal borehole resistance in Gehlin (1998) and Gehlin (2002).

$$T_f - T_b = R_b \cdot q \qquad\qquad (2.1)$$

- The undisturbed temperature is the average temperature in the borehole below the groundwater level and to the bottom of the borehole, i.e. the water filled part of the borehole which is called the active borehole depth, see figure 2.2.
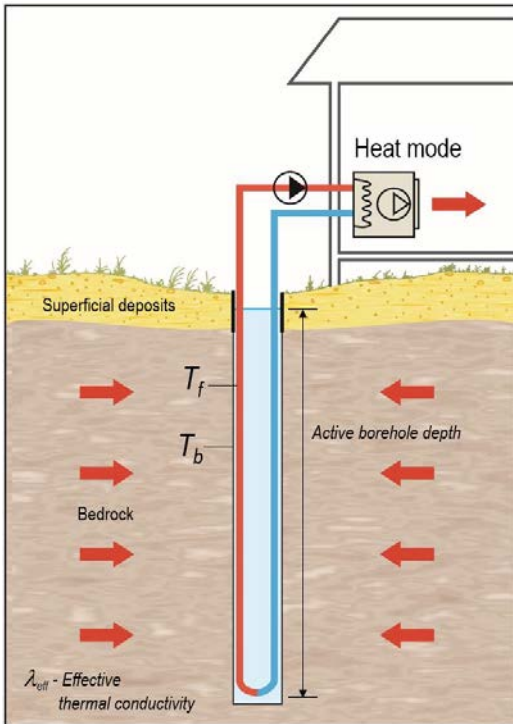
Figure 2.1. Principle drawing of an energy well with a closed loop collector. The indication of the active borehole depth, effective thermal conductivity (λ_{eff}), temperature in the collector fluid (T_f) and the borehole wall (T_b), respectively. Modified after NGU (www.ngu.no).
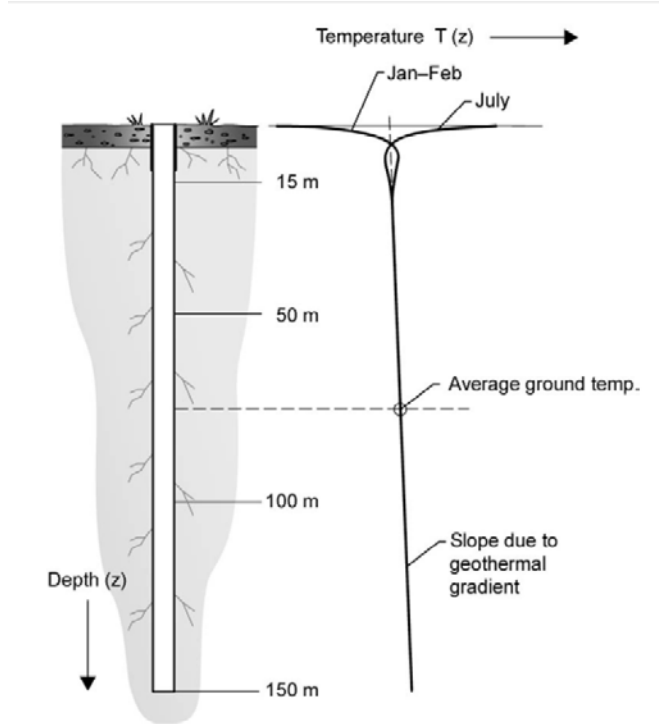
Figure 2.2. Principle drawing of a theoretical temperature profile. Seasonal temperature variations reach down to approximately 15 meters depth after Ericsson (1985) in Gehlin (2002). Undisturbed temperature in the ground is the average temperature in the borehole below the groundwater level and to the bottom of the borehole, i.e. the water filled part of the borehole, which is called the active borehole depth.

2.3 Sizing criteria

The core of all dimensioning of a ground source heat pump system is to achieve an optimal relation between the number of energy wells, the total active borehole depth, and the well configuration on one side, and the temperature of the heat source on the other side. For the energy wells, the temperature in the circulating collector fluid represents the temperature of the heat source.

A borehole system volume and geometry has to be sized in a way that the energy load can be charged or discharged from the storage on long term (20-50 years) without the storage being too cold or too hot. At the same time the heat exchanger surface have to be sized for thermal capacity of the evaporator without the instant fluid temperatures becoming too low.

The temperature in the collector fluid from the energy wells to the evaporator of the heat pump must harmonize with the performance and characteristics of the heat pump in such a way that the heat pump achieves good operating conditions. If the temperature in the collector fluid from the energy wells deviates from the preferred temperature ranges for the heat pump, the result will be poor operating conditions with reduced performance of the heat pump system and in the worst case a faster breakdown of the compressor. It must be emphasized

that to achieve the highest possible efficiency, or the chosen efficiency for the whole system, proper sizing of the ground storage is crucial.

Simply said, more energy wells will give a higher and more uniform temperature in the collector fluid and thus better operating conditions for the heat pump. The relation between the number of wells, well configuration, total active borehole length and temperature in the collector fluid and the belonging influencing factors are explained schematically in figure 2.3.
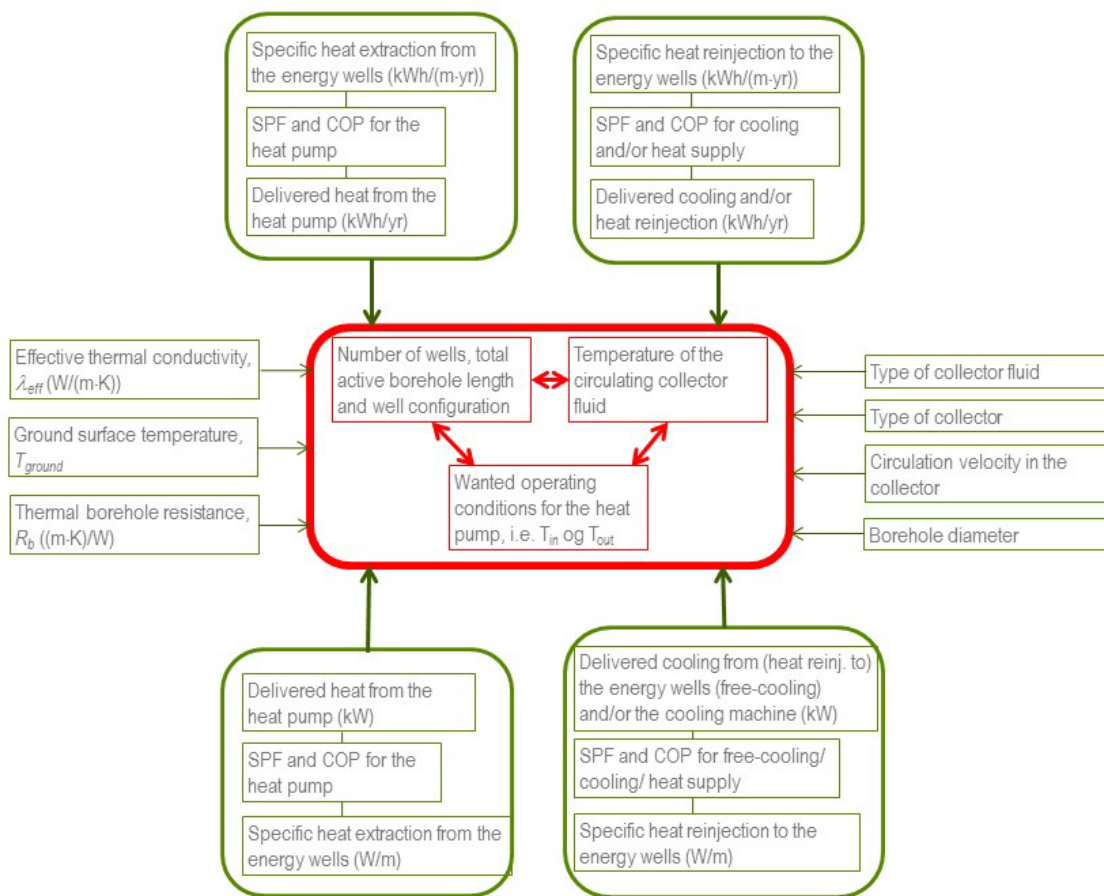
Figure 2.3. The core of all dimensioning of a ground source heat pump system is to achieve an optimal relation between the number of energy wells, the total active borehole depth, and the well configuration that gives the temperature wanted and needed in the collector fluid to achieve the operating conditions wanted for the heat pump.

2.4 Heating and cooling loads (kW vs kWh)

One of the most important factors for sizing is the yearly heat extraction from the energy wells and/or the reinjection of heat to the energy wells in terms of free-cooling, cooling or "charging". Extracted and reinjected heat (kWh) affects the required total active borehole length and the temperature in the collector fluid. The annual heat extraction from the energy wells can either be expressed for all the energy wells at kWh/year or as the specific heat extraction per meter active borehole length, i.e. kWh/(m·year). The specific heat extraction

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per meter active borehole length is practical to use to compare the performance and the loads between different ground source heat pump systems. *Specific heat reinjection* can be used the same way as specific heat extraction.

The terms *active borehole length* or *active borehole depth* means the part of the energy wells that exchange energy with the surroundings, i.e. with the groundwater and the surrounding bedrock (figure 2.1). The effective thermal conductivity λ_{eff} (W/(m·K)), the ground surface temperature T_{ground}, and the thermal borehole resistance R_b ((m·K)/W) are the most important factors regarding geology, climate and the technical properties of the borehole heat exchanger (see section 2.2 at page 8).

The specific extraction and reinjection capacity in terms of watt per meter active borehole length (W/m) influence the temperature drop between the circulating collector fluid and the surrounding ground. Higher borehole resistance and higher heat output will increase the temperature drop.

The key to profitability for ground source heat pump systems is to extract as much of heat and cooling (kWh) per borehole meter as possible. It is therefore important to size the total active borehole length based on produced kWh. The size of the heat pump (kW) should be in accordance with the heating and cooling demand (kWh). There are at least two main factors that will lead to increased total borehole length:

- If the specific heat extraction/-reinjection (kW) are too high compared to the energy deliverance (kWh)
- If the temperature of the collector fluid is affected in such a way that the heat pump, the cooling machine or the free cooling gets too high temperature drops and/or temperature lifts.

In these cases, the thermal capacity of the heat pump is the dimensioning factor for the system. This is not optimal since the cost effectiveness of ground source heat pump systems rely on saved expenses for heating and cooling (kWh/yr). The factors listed to the right in figure 2.3 (the kind of collector fluid, collector type, circulation velocity and borehole diameter) are less important than the other factors mentioned in the figure.

2.5 Time step and dynamics of a simulation

A borehole thermal storage (BTES) consists of boreholes drilled in a specific pattern with a specific distance in-between. Usually the heat exchange takes place by U-tubes inserted in the boreholes. When simulating such storages with heat pumps evaluating the system performance, it is important, that the dynamic response is realistic in both short time steps (minutes) as well as for the daily and annual perspective of gradually decreasing borehole temperatures. In short time, the temperature response due to instantaneous peaks from a sudden change in discharge rate has to be realistic as the performance of the heat pump is dependent on the temperature level of the circulated fluid.

Models that are intended for system simulation and evaluation of annual system performance therefore need to take into account the far field as well as the heat capacity of the borehole filling and pipes. The heat capacity of the fluid and the borehole itself has been shown to be of high importance when simulating the dynamic behaviour of a heat pump (Pärisch *et al.*, 2015). During the first hours of operation, the energy stored in the borehole is utilized and this delays the temperature drop due to heat extraction. Since the grout material (borehole filling) is usually just ground water in Norway, the heat transfer between the tubes and the borehole wall also contain a convective term. If there is groundwater flow (advection) or thermally induced convection in a water-filled hole the heat transfer increases (Javed *et al.*, 2009).

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2.6 Heat transfer modelling in boreholes

The thermal processes in the storage region are complex and deals with at least two separate problems: the global heat flow problem and the local heat flow problem (Lazzarotto, 2014). The global heat flow problem relates to the interaction between the boreholes and the storage volume and the surrounding ground and is important for the long-term changes in the temperature levels. The local thermal problem presents the thermal process around the individual ducts (the boreholes) and proper calculations are vital for the temperature levels in the fluid supplied to the heat pump on a short time step. The steady-flux problem explains heat pulses around a pipe for a constant injection or extraction rate and this part is important for the fluid temperatures at medium time frame. Pärisch *et al.* (2015) show the importance of the local thermal problem for proper evaluation of the transient conditions and peak performance periods. Heat transfer characteristics in the borehole and the properties of the borehole filling are important parameters here.

Numerical models

Numerical models of borehole thermal energy storages (BTES) are solving all the physical domain using two or three-dimensional discretization by means of finite volume (FVM) or finite elements methods (FEM). FVM and FEM are able to handle a high level of detail if the mesh grid is small enough, however their drawback is that they require large computational time and are therefore not well suited for annual simulations with short time steps.

Analytical models

Analytical models means different levels of simplifications and means that the disadvantages using analytical calculations compared to numerical models are that a number of assumptions have to be done to simplify the calculations, which may influence the reliability of the result and requires validation by measurements (Holmberg, 2009).

g-functions

Using g-functions proposed by Eskilson (1987) for calculation of ground temperature response around boreholes is a common approach applied by several simulation software (EED, Polysun, GLHEPRO). This makes it possible to determine the temperature at a given distance of the borehole with a certain load, after a certain time for a given borehole geometry. The g-functions are defined as the non-dimensional thermal response factors of the borehole field. They can be derived from analytical solutions or from numerical simulations using discretization methods of the differential heat conduction equation. An more comprehensive description of the theory behind modelling of boreholes are given by Ochs *et al.* (2013)

One of the main uncertainties in the modelling of ground heat exchangers (GHX) is the knowledge of the ground and grout properties, ground water flow and building loads. In order to achieve high accuracy from the model the input parameters have to be properly set, so that the heat transfer is properly modelled. A thermal response test as described in section 2.2 is used to measure the properties of the ground. Using numerical models also the meshing is important. To be able to properly take into account short term response, the mesh have to be fine enough close to the borehole and to take into account long term effects, the meshing has to reach out to the undisturbed ground.

The global heat flow problem

Different models were developed for the calculation of the thermal interference from the surrounding boreholes in borehole storages (BTES). A commonly used method proposed by Eskilson (1986) and Eskilson (1987) is to calculate dimensionless temperature response factors for the specific BTES configuration, commonly known as g-functions. The g-functions are calculated by a numerical calculation, for a specific geometry and these g-functions are later used in the analytical simulation model. Implementing this method in simulation software implies that a selection of numerically calculated g-functions plotted for different borehole

configurations have to be stored as a database in the simulation software. The g-functions can be calculated using separate programmes like the EWS-programme by Huber and Pahud (1999). Development of analytical g-functions for higher flexibility and usability in simulation software have been addressed by Lamarche and Beauchamp (2007a) with better match to the numerical calculations, than the analytical approaches by Zeng *et al.* (2002).

The local heat flow problem

One of the first to analyse the short-term response of a ground heat exchanger was Yavuzturk (1999) and Yavuzturk and Spitler (1999) who implemented short-term g-functions that was applicable for simulation times in between 2.5 min and 200 hours. The model accounted for pipe, grout and flow-related convective resistances but the method has the disadvantage of numerically obtained solutions. Young (2001) developed an expression to model the influence from borehole diameter, fluid pipe and grout thermal capacity based on the theory of the heating of a buried electrical cable. Lamarche and Beauchamp (2007b) developed analytical expressions assuming the U-pipes are one cylinder inside the cylindrical grout for the assumptions of constant flux and for convective heat transfer with a constant fluid temperature. Bandyopadhyay *et al.* (2008) developed a model that also takes the thermal capacity of the circulating fluid into account and calculate both average fluid temperature and borehole boundary temperature.

3 Overview of borehole models

The borehole models and software investigated in sections 4 to 9 are presented in table 3.1 and their abilities and limitations are evaluated and compared. The authors judged user-friendliness associated with operating the software and the model has been graded in three steps.

3.1 Investigated simulation software

In the TRNSYS simulation software there are two models available for multiple borehole systems; Type 281 by Pahud (2012) and Type 557 from the TESS library. The Type 451 model can only simulate single boreholes. In Type 557 the boreholes are assumed to be placed to form a cylindrical storage. The Type 281 is also called TRNSBM and is based on the Superposition borehole model by Eskilson (1986). In Polysun, the EWS model from Huber and Pahud (1999) have been implemented. IDA ICE has one model for simulation of boreholes which can be used both for single and multiple boreholes simulation. In Modelica there are two user defined models presented in table 3.1 and another four models presented briefly in section 6.3. The Matlab/Simulink+Carnot program has a model for boreholes based on the EWS model by Ochs (2012). The Earth Energy Designer (EED) software is one of the most common PC-software for the dimensioning of energy wells in a ground source heat pump system and the calculations for different geometries are based on g-functions from a table (Blomberg *et al.*, 2015).

3.2 Other simulation software

Other software being developed for the simulation of bore hole heat exchangers are GLHEPRO, EnergyPlus and eQuest with the simulation engine DOE-2. Spitler (2000) developed a model for the program GLHEPRO (GLHEPro 4.1, 2014) based on the *g-functions* developed by Eskilson (1987). A validated model for EnergyPlus was developed by Fisher et al. (2006). Enhancements in the borehole heat exchanger model for eQuest/DOE-2 were implemented by Liu and Hellstrom (2006) with a library of 308 different GHX configurations available.

Recent studies contributing to the development on thermal modelling of borehole heat storage systems is the thesis by Lazzarotto (2015) who developed a network-based methodology for mathematical description of the topology of the borehole heat exchanger network and borehole fields with arbitrary oriented boreholes. He further developed a method to calculate g-functions for non-vertical boreholes based on a new methodology for the generation of thermal response factors of geothermal bore fields using the concept of *g*-functions developed by Cimmino and Bernier (2014).

A new analytical solution to model the short-time response of the borehole system and a finite-length line-source solution to determine the long-term response of the borehole system has been developed (Claesson and Javed, 2011; Javed, 2012). The thesis by Javed also further contributed to the knowledge of thermal response testing of groundwater-filled boreholes. Thus several new publications on borehole modelling, none of it so far seemed to be implemented in software or other available models.

3.3 Advantages and disadvantages of the models

Selecting suitable software and a model for simulation and sizing of borehole heat exchangers requires attention to the possibilities and limitations in the borehole model and the additional models like building loads, heat pumps and hydraulics. The aspects of the different software collected in table 3.1 are discussed

under respectively headline below. The software and related hydraulic models are described further in sections 4 to 9.

Estimating the size and geometry of a borehole storage based on monthly heat loads and peak capacity of the heat pump is often possible using the simpler user-friendly software like EED, but the influence from system design cannot be studied. However if the performance of the entire system or building is going to be calculated along with the borehole storage, more advanced software may be required. Special borehole geometries, heat exchanger configurations or charge patterns may require a certain model (table 3.1).

The type of system and level of details to be simulated are the main parameters for selecting the type of software to use. TRNSYS, Polysun, IDA ICE, Carnot/Matlab are software suitable to study the influence on the performance from system design, but building the system in the flexible software like TRNSYS, Modelica and Carnot may require too much time for design purpose and are more suitable for research purpose or complicated design cases.

In order to provide good simulations of multiple boreholes IDA ICE needs the user to buy extensions and Carnot/Matlab requires an expensive license. Using Polysun for sizing of heat exchangers also requires the purchase of the EWS-program to be able to investigate different geometries more freely.

User aspects

The user-friendliness is linked to the level of flexibility in the simulation software and the models. Higher flexibility usually means less user-friendliness. With flexibility we mean the range in what types of systems and components that can be modelled and the possibility to modify the code for your specific purpose. The evaluation of user-friendliness was based on the estimated learning time to use the program, and the time to set up a simulation.

The EED model is limited to simulation of the borehole and the ground with an hourly time step and is considered to be an easy to use software. Also IDA ICE and Polysun are relatively easy to use compared to Matlab, Modelica and TRNSYS, but with more limitations in the system design even though the component models in some cases have more details, as is the case with the IDA ICE-model allowing sloped boreholes.

IDA ICE has a good size community and it is easy to get support. When it comes to Carnot the community is small and most of the available documentation is in German. TRNSYS, Type 281 and Modelica offers the opportunity to simulate multiple boreholes in any configuration you like, and at a detailed and complex level, but are not very user-friendly. Modelica is depending on a licence for a simulation platform like Dymola. Full flexibility to modify and create models in TRNSYS requires a Visual FORTRAN compiler and programming knowledge.

In IDA ICE it is relatively simple to mount a simulation case as many of the "boxes" are available and only need little information from the user. Also in Polysun a system can be relatively easy to set up, but learning how to set up controllers and storage tanks etc. will take some time. Modifying one of the many templates is usually easier than creating a new system from start.

Setting up simulations in IDA ICE and Polysun is relatively quick for an experienced user and one can test many different things in short time. Carnot on the contrary is very complex and users can introduce a big level of detail, however, it also request a big share of information from the user and mounting a simulation case takes time. The same applies to TRNSYS, even though some of the models are quite straight forward, there are plenty of work to set up the system and checking the correctness of the simulation and energy balance. For Modelica there exist some libraries containing components that can be used to simulate boreholes, heat pumps and the hydraulics (Section 6.3). The user-friendliness is linked to how detailed the models should be, but in

general it is necessary with some knowledge if the components should be custom made and detailed and complex systems should be simulated.

Table 3.1. Overview of evaluated borehole models. For a description for the different criteria, see section 3.3.

Plattform	Borehole models	User friendly	Level of flexibility (open source code)	Time step down to 60s	Preconditioning	Input of measured borehole resistance Rb from response test	Multiple vertical nodes (layered ground)	Undisturbed temperature in the ground (adjustable)	Ground water movement	Grouting heat capacity	Grouting thermal conductivity	Borehole diameter	Single U-collector	Double U-collector	Coaxial collector	Smooth or rough inner shape	Time dependent mass flow rate	Multiple boreholes	Non-uniform spacing of boreholes	Boreholes charged in series	Boreholes charged in parallel	Sloping boreholes	Variable load for boreholes/ independent operation of boreholes	Documentation
TRNSYS	Type 281 (TRNSBM)	N	Y	Y	Y	Y	Y	Y	N[3]	N[1]	Y	Y	Y	N[11]	Y	N[11]	Y	Y	Y	Y	Y	Y	Y	Pahud (2012) Pahud *et al.* (1996b) Eskilson (1986)
	Type 557 (TRNVDST)	Mid	Y	Y	Y	N	Y	Y	N	N[1]	Y	Y	Y	Y	N	N	Y	Y[10]	N	Y	Y	N	N	Pahud et al. (1996a) Mazzarella (1993) Hellström (1989)
	Type 451 (EWS)	Mid	Y	Y	Y	N	Y	Y	N	Y	Y	Y	Y	N	N	N	Y	N	N	N	N	N	N	Wetter and Huber (1997)
Polysun	EWS	Y	N	Y	Y	N	Y	N[7]	N	Y	Y	Y	Y	Y	N	Y	Y	Y	Y[9]	N	Y	N	N	Huber and Schuler (1997b) Huber and Pahud (1999)
IDA ICE	GHX	Y	N[2]	Y	N	Y	N	Y	N	Y	Y	Y	Y	N	N	Y	Y	Y	N	N	Y	Y	N	EQUA Simulation AB (2013)
Modelica	INTERACT 2015	N	Y	Y	N	N	Y	Y	N	Y	Y	Y	Y	Y	N	N	Y	N	Y	Y	N	N		Holstad (2015)
	INTERACT 2016	N	Y	Y	N	N[8]	Y	Y	N	Y	Y	Y	Y	Y	N	N	Y	Y	Y	Y	Y	N	Y	Developed in project INTERACT 2016
Matlab/Simu-link+Carnot		Mid	Y	Y	Y	Y	N[4]	Y[5]	N	Y[6]	Y	Y	Y	N	N	Y	Y	N	N	Y	N	N		Ochs (2012)
EED		Y	N	N	N[12]	Y	N	Y	N	N	Y	Y	Y	Y	Y	N	N	Y	N	Y	Y	N	N	Hellström and Sanner (2000) Blomberg *et al.* (2015)

1) The heat capacity of the grout and pipe can be taken into account by adding a pipe with heat capacity (Pärisch et al., 2015).
2) Source code is open but cannot be modified
3) There is another version of the model (Type 280) to simulate energy piles with ground water flow (Pahud et al., 1996)
4) Layering of the ground is not implemented in Carnot but is supported by the EWS algorithm
5) Connected by g-function (g-function create the boundary conditions for the near pipe area)
6) Pipe heat capacity not included
7) Undisturbed ground temperature given by the selected location
8) Would be a very simple addition to the model
9) Requires also the EWS-programme by Huber and Pahud (1999)
10) Only cylindrical borehole storages
11) Could be taken into account using R_b from thermal response test and externally calculated pipe to pipe resistance R_a
12) Not required due to the fast calculation and that the model cannot be implemented in a system

Geometry of borehole storage

The existing model having the highest flexibility regarding the borehole geometries is the TRNSYS model Type 281 (TRNSBM). The IDA ICE model allowing *sloped boreholes* and the custom made model for the INTERACT project in Modelica allowing different sections of the borehole storage to be charged individually.

Time step

When simulating borehole storage systems one must reflect if the transient conditions involved in heat pump cycling should be taken into account or not. During the initial period of heat pump operation, heat is extracted mainly from the grout material causing smaller temperature drop in the heat exchanger. Thus detailed system simulations require borehole models that take into account the heat capacity of the heat exchanger pipes and the grout.

The TRNSYS components can be simulated using time steps defined by the user, but to make use of small time steps in the borehole models, the grouting heat capacity needs to be taken into account (see section 4.2 on page 22). The Polysun simulation software will vary the time step during the simulation depending on the current load condition. During peak load, the time step is shorter; however the heat pump model does not take into account the start-up dynamics, thus this have to be included in the simulated average COP (coefficient of performance, for a heat pump). Models written with the Modelica language can take heat capacity of the grouting material into account and the time step is based on seconds. EED time step is based on hours, where the peak load is given as a certain capacity for a certain number of hours. Carnot simulation software has a good level of resolution of the ground. The authors have not used IDA ICE extended version and cannot comment on that.

Another aspect of the time step is that the time to reach relatively steady conditions in the surrounding ground of the boreholes may take 20 years or more, meaning that the simulation time becomes substantial for complete system simulations. To simulate the long-term degradation of the ground temperature when the complete system is included, a pre-simulation of only the borehole model with a certain annual withdraw of energy can be performed in for example Polysun to reduce total simulation time. In TRNSYS, the final ground temperature of a n-year simulation can be stored in a file and later used as start conditions when simulating n+1 years. After the simulation, the user must check that the borehole energy balance of the finally simulated year is similar to the predefined load and that the borehole temperature is similar at the start and the end of the simulated year. Such features are labelled *preconditioning* in table 3.1 and can be applied in TRNSYS, Polysun, Modelica and Matlab/Simulink.

Borehole and ground properties

All models can be adapted to the ground and borehole properties like diameter, ground heat transfer and the vertical temperature gradients; however the ground water movements cannot be handled by any of the models. Heat capacity in the grouting can be handled by most of the models, but the TRNSYS models need a workaround to take into account the heat capacity of the pipe and the grout. Using a pipe component in series with the borehole model can give good agreement on short time steps according to Pärisch *et al.* (2015). EED does not take into account the grouting heat capacity, however as the time step is one hour, it has smaller importance.

Ground water movement cannot be simulated specifically by any of the models, just taken into account by adjusting the grouting thermal conductivity. The undisturbed temperature in the ground can be adjusted for all models, but in Polysun, it is given by the location and cannot be adjusted further. All models except in IDA ICE and EED can simulate *several layers in the ground* with different properties. Possibilities of using results from a *response test* as boundary conditions and for input of borehole thermal resistance is possible in IDA ICE models, Matlab/Simulink+Carnot and EED.

Type of borehole heat exchanger

All models can simulate *single U tube* configurations and handle *time dependent mass flow rates* (not EED), but for *double U-tubes* and *coaxial collectors* there are differences between the models. Only the IDA ICE models has a function to take into account variable *pipe roughness* on the inside of the tubes.

Simulation results

Using a software for sizing of borehole heating and cooling systems requires that the key parameters like the peak temperatures and average temperatures of the brine and borehole can be observed for the relevant time span. Using EED the important outputs are predefined and presented in a perspicuous and easily accessible layout (figure 9.4 and figure 9.5 on page 53). Also Polysun have easily accessible output results (figure 5.2 and figure 5.3 on pages 27-28). In TRNSYS the desired output results must be made available by connecting the output producing components simulation summaries, printers and online plotters (figure 4.2 on page 22). When using Modelica it is possible to select which simulation results that should be showed after the model has been simulated. However, to decrease the simulation time, it is possible to choose to not include all results for the different components. The results are showed in graphs in Dymola, but could also be exported to Excel. In IDA ICE it is possible to access the most important variables in the user interface as well as a 3D visualization of the temperature field. In the advanced interface, all the variables of the model are available.

For Carnot, which is based on Simulink, all the variables are exported from the component block (outlet temperature and ground/grout temperature) but no 3D visualization is available.

4 The TRNSYS simulation software

TRNSYS (TRNSYS 17, 2012b) have several component models available which are key components in geothermal systems like borehole storages and heat pumps. TRNSYS is initially developed for transient simulation of solar heating systems and include component models for solar collectors and thermal storages.

4.1 General description

TRNSYS 17 (2012b) is a dynamic simulation environment for transient simulation of systems, including multi-zone buildings, solar collectors, storage tanks, etc. The user builds the system by connecting the inputs and outputs of the component models (called *Types*) in the graphical interface *Simulation Studio* (figure 4.1) and adjusting the parameters of the components. Equations can be used to achieve the desired functionality. The time step of the simulation is set by the user depending of the time constant of the modelled components and the control system. The multizone building is also a good feature to study building energetic performance by itself or integrated in a system providing heating and cooling loads.

TRNSYS is based on a modular structure, where the source code of the kernel (calculation engine) and the component models is open and delivered to the end users. This makes it possible to modify components or create new components that fit the needs of the user by a FORTRAN compiler. This means that there are both standard components included when purchasing the program package as well components sold from different institutes, like the TESS libraries (TESS, 2012a). There are also nonstandard components that are shared or sold between the users. For very detailed studies of systems the components included in the package may not have the required level of details, therefore there are several nonstandard components developed by different users.

TRNSYS consists of separate programs operating together: The TRNSYS Simulation Studio (figure 4.1) is the graphical interface where the component models are connected to systems. This feature makes it possible to build systems out of the components by connecting the components inputs and outputs. Before starting a simulation the TRNSYS dck-file (text-file) which is used to run the simulation is produced from the Simulation Studio. Errors in the dck- file or problems in the iteration and conversion process are reported in a lst-file which is created during the simulation.

The simulation engine is programmed in FORTRAN and compiled into a dll-file. TRNSYS can be connected to many other applications, for pre- or post-processing or through interactive calls during the simulation (e.g. Microsoft Excel, Matlab, COMIS, etc.). This means for example that external components from Matlab can be used in the TRNSYS simulation.

In order to describe boundary conditions and heat loads there are hourly weather data available for more than 1200 locations in the world (TRNSYS 17, 2012a). Climate data for further locations can be generated by interpolation using the separate program METEOTEST (1999) A solar radiation processor calculates solar radiation for each time step to any desired direction. Heat loads can be created using building models integrated in the system or by using load files with information of flow rates and temperatures.

The standard components included handle the fluid mass flow rates but not the pressure drops related to the flow. In most cases the heat capacities and densities, are assumed to be constant. In this sense, TRNSYS is rather simplified. Most components take into account the thermal mass and the time step can be adjusted in relation to the time constant of the components. An important part of the system is the control functions that can be implemented using components of ON-OFF controllers, equations or PID-controllers (Proportional-Integral-Derivative).
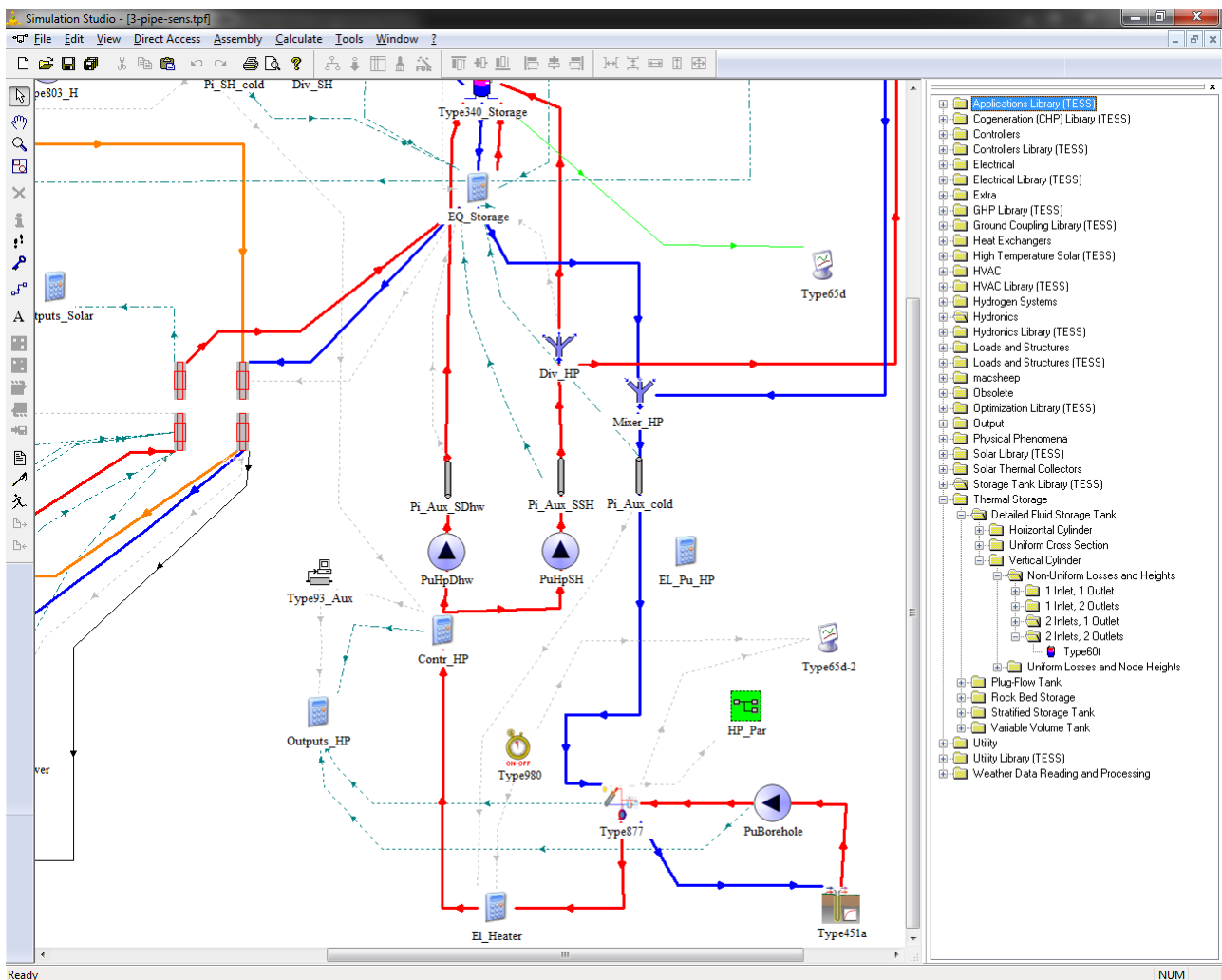
Figure 4.1. The graphical interface of TRNSYS is the Simulation Studio where the component models are connected to systems. Components can be inserted from the direct access toolbar in the right of the figure or copied from other system drawings (screenshot from program).

The TRNSYS program itself does not check that the energy balances of the system is correct. Energy can easily "disappear" or be "invented" by a mistake in the setup of the system. Thus checking the correctness of the system through evaluation of temperatures and energy balances and by making parametric studies is fully the responsibility of the user and is very time consuming. For checking of the correctness of the simulation, output producing components are useful. The output producing components have to be implemented in the TRNSYS studio and connected by the user in the same manner as the other component models. The online plotter Type 65 (figure 4.2) is used to show any value along with the simulation. The simulation can be paused at any time to check the results. There are also printer components (Type 25) that prints a simulated value for a desired time step to a text file and the "printegrator" (Type 46) that first integrate the values over a desired period and then prints the result to a text file.

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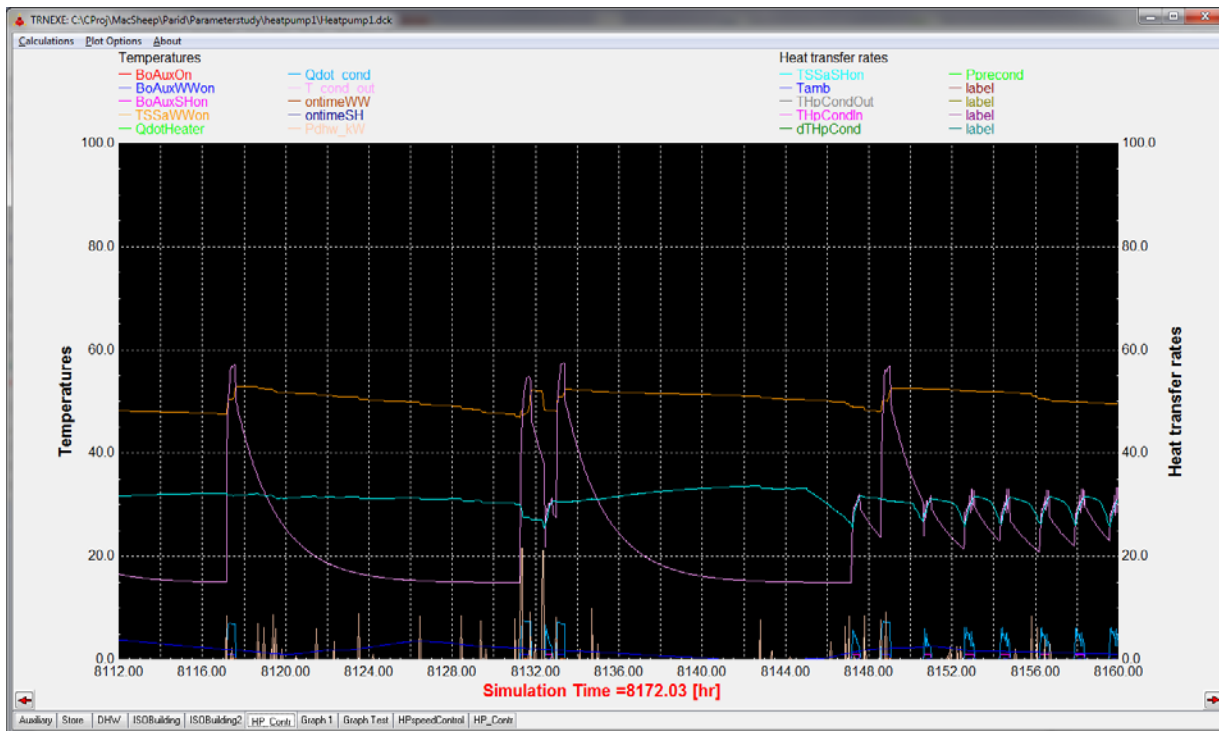REPORT NO.
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Figure 4.2. The online window from TRNSYS Type 65 makes it possible to show any value (Temperature, flow rate, heat rate, etc.) in the simulated system (screenshot from program).

Climatic data

There are Weather data files for more than 1200 specific locations included in the TRNSYS 17 package. There are US-TMY2 data sets from NREL for 237 locations in the US Alaska and Hawaii and More than 1000 selected locations worldwide from Meteonorm; however there are only three locations from Norway. The weather and radiation data from Meteonorm is based on monthly measured values that Meteonorm generates stochastically to hourly values.

To be able to create hourly data for further locations, Meteonorm has to be purchased (METEOTEST, 1999) which gives the possibility to create further locations by interpolating data and providing height above the sea level. As the data are based on measured monthly averages the high temperature variations over the day that may occur in the Nordic countries will not be properly modelled in this data. Other measured climatic data of temperatures and irradiation can also be used in the simulation and recalculated to other orientations.

4.2 Geothermal storages

The borehole model Type 557 (TRNVDST)

Hellström (1989), (1991), Pahud *et al.* (1996a) and Pahud *et al.* (1996c) developed the duct storage model (DST) which is now widely used in different applications and is also the basis for the TRNSYS Type 557 included in the TESS component library (TESS, 2012a; 2012b). The DST model from Hellström was implemented in TRNSYS by Mazzarella (1993) and there have been several modifications and updates since then by different authors. There is another version of this model (Type 280) allowing to simulate energy piles with ground water flow (Pahud *et al.*, 1996a).

The Type 557 from the TESS library models single or multiple vertical borehole heat exchangers (formed as a cylindrical duct) that interacts thermally with the ground. It can model both U-tube and tube-in-tube heat exchanger configurations (table 3.1 on page 16). A heat carrier fluid circulates through the ground heat exchanger and either rejects heat to, or absorbs heat from the ground depending on the temperatures of the heat carrier fluid and the ground. There is convective heat transfer modelled within the pipes, and conductive heat transfer to the storage volume.

A limitation is that the boreholes are assumed to be densely packed with a shape of a cylindrical heat storage. Another limitation is that the model neglects the thermal capacity of the borehole filling and pipes which causes an error when changing flow rate and inlet temperature. However implementation of an extra pipe component with heat capacity according to Pärisch *et al.* (2015) can compensate for this limitation. Another limitation is that maximum one model per simulation can be used.

The superposition borehole model Type 281 (TRNSBM)

The superposition borehole model (SBM), was originally developed by Eskilson (1986) and implemented to TRNSYS as Type 281 by Pahud *et al.* (1996b) and updated in 2012 by Pahud (2012). The model calculates the there-dimensional temperature field in the ground for arbitrary located boreholes using the superposition technique. The boreholes can be connected in up to five separate hydraulic systems and the boreholes in each of them can have independent loading conditions and boreholes can be coupled in series or in parallel (table 3.1). The model have been validated against measurements of a borehole thermal storage of 60 000 m³ by Nußbicker *et al.* (2009) showing good agreement for energy balance. The model have also been validated regarding the short term response of a single bore hole by Pärisch *et al.* (2015). The model neglect the thermal capacity of the borehole. In order to have realistic dynamic response on short term, a pipe model with heat capacity corresponding to the grouting material should be put before the inlet of the borehole model (Pärisch *et al.*, 2015). A circulation loop should be applied that continuously circulates the water through the boreholes and the capacitive pipe when there is no external flow rate.

The borehole model Type 451 (EWS)

Single boreholes can be simulated using the nonstandard borehole model Type 451 from TRANSSOLAR written by Wetter *et al.* (1997). This model takes into account the thermal capacity of the borehole, but it cannot be used for multiple boreholes interacting with each other (table 3.1).

4.3 Hot water storages

There are several standard models for hot water stores in TRNSYS. Type 4 and Type 60 are constant volume stores where stratification can be modelled using up to 100 nodes. Type 60 has the possibility of using up to three heat exchangers (TRNSYS 17, 2011a; b), but there are a maximum of two pairs of direct connections to the store (double ports).

There are also several fluid storage models from TESS (2012b). The Type 531 is a stratified store model having a capacity of up to 10 double ports and 5 heat exchangers. The Type 1237 can be used to model a store with a wraparound coil heat exchanger.

Despite the standard package of TRNSYS including several useful storage models, the nonstandard Type 340 Multiport Storage Model (Drück, 2006) with a maximum of 4 heat exchangers and 10 double ports is commonly used due to its flexibility. Several publications dealing with measurements, parameter identification and validation giving a broad basis for the validity of the model (Drück, 1994; Drück and Hahne, 1996; 1998; Bales, 2000; 2002a; b; 2003; Bales and Persson, 2003; Drück and Bachmann, 2003). Besides modelling

different kinds of heat exchangers, this type can also model stratified inlets or immersed heat exchangers with stratifiers. In general the agreement with the model has shown good results, however modelling complex stores using capsulated immersed heat exchangers where buoyancy forces and friction influence the heat transfer, there are still limitations in the model (Persson, 2001).

4.4 Heat pumps

TESS heat pump model Type 927
The Type 927 heat pump model included in the TESS library (TESS, 2012b) is based on user-supplied data files containing catalogue data for the capacity and power demand based on the load and source temperatures. Type927 operates in either heating or cooling mode and have a temperature level control when the user defined control signal indicates that the unit should be ON, it operates at its capacity level until the control signal values changes. The model does not take into account heat losses or the dynamic effects during starting up of the heat pump. There is also another version called Type 1221 which models a two-stage water-to-water heat pump, meaning that it can switch between two separate user-supplied data files.

TRNSYS Heat pump model Type 877
This nonstandard TRNSYS model calculates the performance based on the refrigerant cycle and refrigerant properties and is more detailed than the other TRNSYS models. It was programmed at Institut für Solartechnik SPF and further developed in cooperation between the Institute of Thermal Engineering, Graz University of Technology and SPF (Heinz and Haller, 2012). The basis for the Type 877 is an EES-model, that has originally been developed at NTB Buchs by Bertsch (2009). The model is currently not available for sale, and can only be used in cooperation projects with SPF in Rapperswil, Switzerland.

4.5 Building load calculations

The most advanced model for calculating of heat and cooling load in TRNSYS is the multi zone building simulation model Type 56 (2011). The building component models multiple thermal zones with each wall, floor and ceiling built up as multilayer objects. The thermal capacitance effect of walls is taken into account using wall transfer functions. The radiation exchange between the surfaces of a zone assumes that all surfaces see each other and the radiation exchange is area weighted. Each zone is assumed to have a homogeny air temperature and the air node exchanges heat with the wall surfaces with a convection coefficient that can be constant or temperature dependent.

Solar radiation through the windows is taken into account depending on the orientation of the window. The building model can be linked to external geometrical window shading devices and internal airflow can be simulated by linking to the COMIS multizone airflow simulation software (COMIS, 2011) or by using the modified version of the multizone building model called TRNFlow (TRNFlow, 2011).

In order to use the building component, a separate pre-processing program must first be executed. The TRNBUILD program reads and processes files containing the building description and generates the files that will be used by the TYPE 56 component during a TRNSYS simulation.

In TRNSYS usually the building model is integrated with the system to model the interaction between the heating and cooling systems and the building. The model can also be used separately to create a heat load and cooling load text file that is later used for system simulations using a data reader component. Using heating

and cooling load profiles from other simulation software or measured data is also possible by reading a text data file.

4.6 Hydronic components

In the standard TRNSYS package (TRNSYS 17, 2011b) there are models of pumps (type 3), pipes (Type 31), valves, flow diverters (Type 11), etc. that can be used to build a system. The components model the fluid flow assuming constant heat capacity and density of the fluid. Heat losses from pipes are modelled using UA-values. Pressure drop is not considered in the models and TRNSYS components are not prepared to model the pressure drop as a measure to calculate flow rates. Three way diverter valves control the direction of the fluid streams.

4.7 Controllers

Simulating systems in TRNSYS requires implementation of a control system to control the components similar to what is the case in the real systems. There are models available to simulate controllers like the differential controller Type 2, or the PID controller Type 23 (TRNSYS 17, 2011b). Control functions can also be implemented using equations such as $LT(x,y)$ (Returns one if $x<y$, otherwise zero), $GT(x,y)$ (Returns one if $x>y$, otherwise zero), $MAX(x,y)$ (Maximum value of x or y) and many other basic functions are available. More advanced functions with conditions as is available in Microsoft Excel are not included in TRNSYS as they would reduce the stability of the simulation. Such functions can only be implemented when programmed in the component models.

5 The Polysun simulation software

Polysun allows performing very detailed system simulations. It is also relatively user-friendly and offers valuable support to design, analysis and calculation of installations in the field of renewable energies. The designer license makes it possible to build new unique systems using components from the Polysun library.

The first version of Polysun was released in 1992 by the SPF, Institut für Solartechnik, in Switzerland. Currently the company Vela Solaris develops and distributes the simulation software Polysun. The Polysun Simulation Software offers the possibility to size and calculate system performance and automatically produce sales reports.

5.1 General description

Polysun is a software that enables users to simulate solar-thermal, photovoltaic and geothermal systems. This section focus on the possibilities to simulate systems with heat pump and long term ground heat storages combined with solar thermal collectors.

Predefined systems:
Predefined systems allow making successful calculations of standard systems. The predefined systems are designed for a certain system size and the designer has to adapt components when changing system size or other conditions. As by adjusting heat transfer capacity in heat exchangers, water storage volume, heat pump capacity, etc.
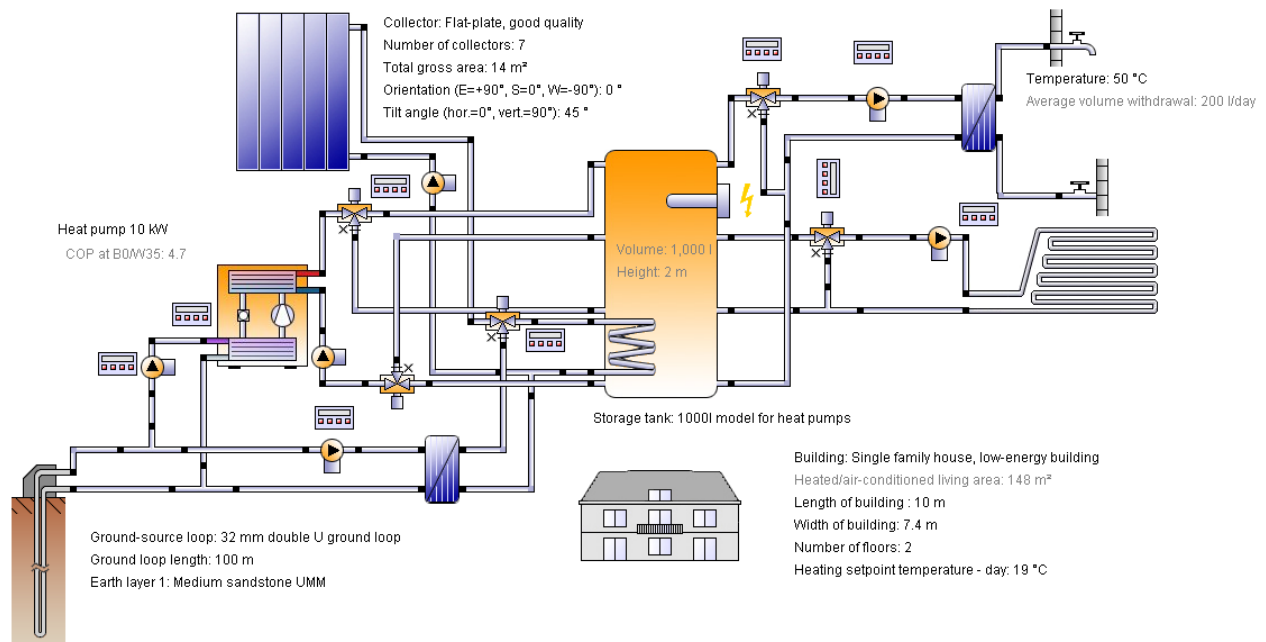

Figure 5.1. The graphical interface of Polysun showing an example of a system diagram with heat pump, ground source loop and solar thermal collector (screenshot from program).

Change predefined systems

Starting up with predefined systems and making changes systematically is usually easier than making advanced models from the start. For example if the user needs to change components or controllers, it is easier to modify a template similar to the system you want to study.

Making your own system with Polysun components

If there are no suitable templates similar to the system to simulate, Polysun gives the possibility to make own systems from the components available in Polysun.

New components or new templates in cooperation with Vela Solaris

Vela Solaris also develops templates for customers. These templates can include control strategies or certain components that are not available as free components as they are developed in cooperation with the customer. If there is a strong request on certain new components, Vela Solaris is able to develop and introduce new ore modified components in coming versions.
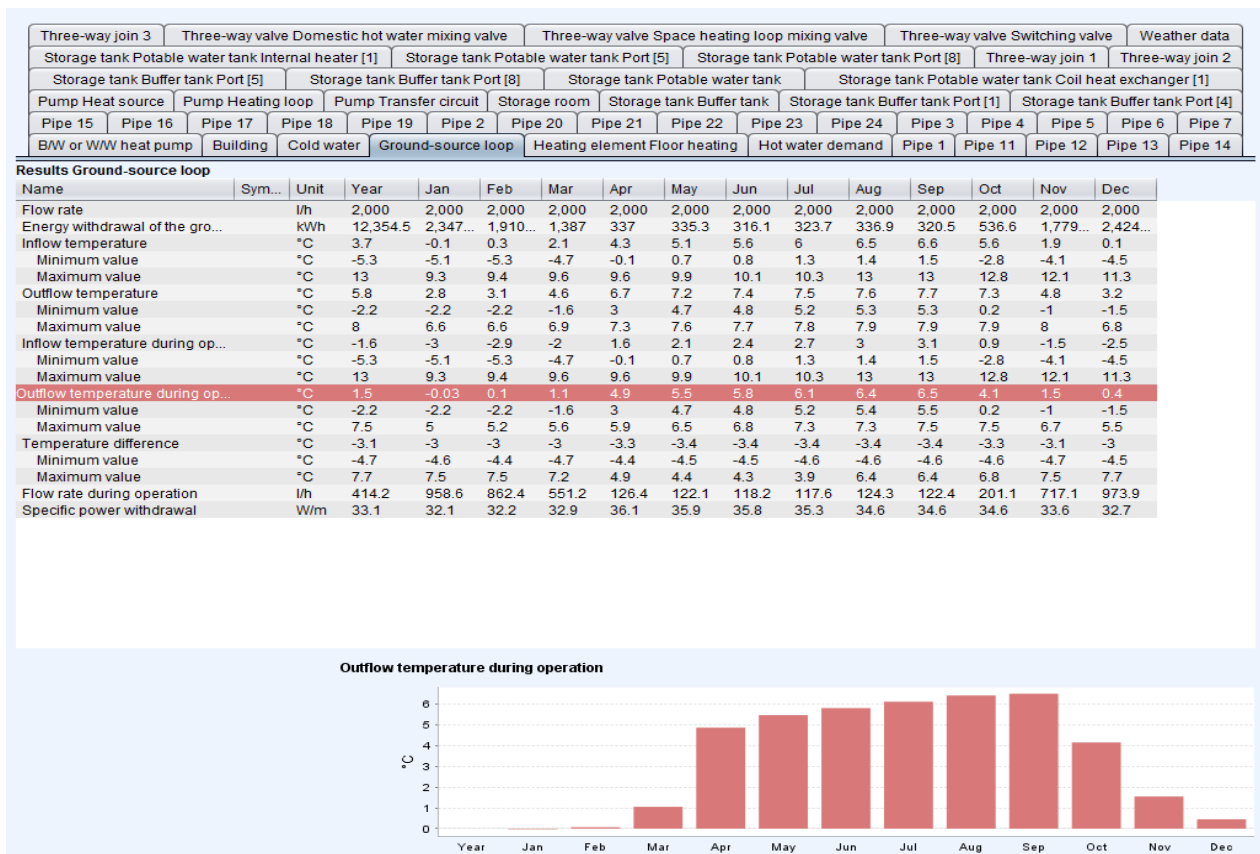

Name	Sym...	Unit	Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Results Ground-source loop															
Flow rate		l/h	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000
Energy withdrawal of the gro...		kWh	12,354.5	2,347...	1,910...	1,387	337	335.3	316.1	323.7	336.9	320.5	536.6	1,779...	2,424...
Inflow temperature		°C	3.7	-0.1	0.3	2.1	4.3	5.1	5.6	6	6.5	6.6	5.6	1.9	0.1
Minimum value		°C	-5.3	-5.1	-5.3	-4.7	-0.1	0.7	0.8	1.3	1.4	1.5	-2.8	-4.1	-4.5
Maximum value		°C	13	9.3	9.4	9.6	9.6	9.9	10.1	10.3	13	13	12.8	12.1	11.3
Outflow temperature		°C	5.8	2.8	3.1	4.6	6.7	7.2	7.4	7.5	7.6	7.7	7.3	4.8	3.2
Minimum value		°C	-2.2	-2.2	-2.2	-1.6	3	4.7	4.8	5.2	5.3	5.3	0.2	-1	-1.5
Maximum value		°C	8	6.6	6.6	6.9	7.3	7.6	7.7	7.8	7.9	7.9	7.9	8	6.8
Inflow temperature during op...		°C	-1.6	-3	-2.9	-2	1.6	2.1	2.4	2.7	3	3.1	0.9	-1.5	-2.5
Minimum value		°C	-5.3	-5.1	-5.3	-4.7	-0.1	0.7	0.8	1.3	1.4	1.5	-2.8	-4.1	-4.5
Maximum value		°C	13	9.3	9.4	9.6	9.6	9.9	10.1	10.3	13	13	12.8	12.1	11.3
Outflow temperature during op...		°C	1.5	-0.03	0.1	1.1	4.9	5.5	5.8	6.1	6.4	6.5	4.1	1.5	0.4
Minimum value		°C	-2.2	-2.2	-2.2	-1.6	3	4.7	4.8	5.2	5.4	5.5	0.2	-1	-1.5
Maximum value		°C	7.5	5	5.2	5.6	5.9	6.5	6.8	7.3	7.3	7.5	7.5	6.7	5.5
Temperature difference		°C	-3.1	-3	-3	-3	-3.3	-3.4	-3.4	-3.4	-3.4	-3.4	-3.3	-3.1	-3
Minimum value		°C	-4.7	-4.6	-4.4	-4.7	-4.4	-4.5	-4.5	-4.6	-4.6	-4.6	-4.6	-4.7	-4.5
Maximum value		°C	7.7	7.5	7.5	7.2	4.9	4.4	4.3	3.9	6.4	6.4	6.8	7.5	7.7
Flow rate during operation		l/h	414.2	958.6	862.4	551.2	126.4	122.1	118.2	117.6	124.3	122.4	201.1	717.1	973.9
Specific power withdrawal		W/m	33.1	32.1	32.2	32.9	36.1	35.9	35.8	35.3	34.6	34.6	34.6	33.6	32.7

Figure 5.2. Example of a component result, here the outflow temperature of the ground source loop (screenshot from program).

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Time steps in Polysun simulations:

In order to minimize the simulation time, Polysun uses variable time steps. When there are quick changes in loads (for example a DHW tap) Polysun simulates with smaller time steps down to 1 second when there are quick changes in the system like DHW-draw offs.

System templates

There are several hundred templates in Polysun. An example is shown in figure 5.1. This system is defined with a DHW consumption of 200 l/day and predefined size of the heat pump and space heating load. When changing the load, the component sizes must be changed manually to keep up the same system performance, as in a real system.
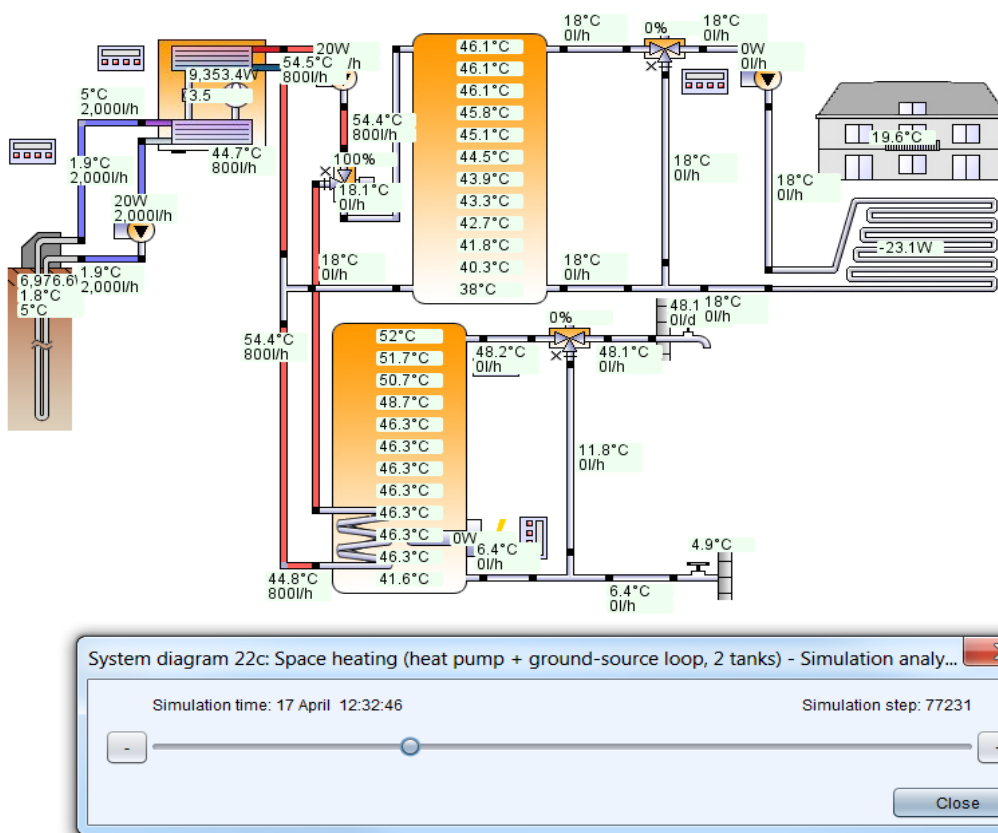
Figure 5.3. An example illustrating the simulation analysis tool. Here it is shown the simulation step 77231 for April 17th time 12:32:46. By pushing the "+" bottom the next simulation step is shown and the changes in each component (flows, temperatures, valve position and so on) is presented (screenshot from program).

Results output

Simulation results can be obtained on many different levels. The *Results overview* gives the main energy and temperature figures from a simulation. Figure 5.2 shows an example of *Component results* which gives monthly and annual averages of all components inputs, outputs and heat transfer. *Graphical analysis* plots simulated values as a function of time. Hourly values of all simulated components can be exported to Excel. The function *simulation analysis* makes it possible to follow the simulation systematically for all simulation time steps (figure 5.3). This feature is useful in fault-finding and in order to understand the system performance

for different situations. A predefined *professional report* can be printed out with a selection of information about key numbers and important results in tables and diagrams.

5.2 Geothermal storages

Geothermal storages can be simulated in Polysun, by using the model "ground source loop" (table 3.1). The model is based on the mathematical EWS model (Huber and Schuler, 1997). Interaction between boreholes for a certain geometry can be taken into account using the g-functions proposed by Eskilson (1987) (section 2.6). However the mathematical model to calculate these g-functions is not implemented in Polysun and there are a limited numbers of geometries available as templates. A wider range of ground-source loop configurations is available in a separate catalogue. Calculating the g-functions required for other geometries requires the EWS program (Huber and Schuler, 1997; Huber and Pahud, 1999). Three different types of ground source heat exchanger loops can be modelled: single-U; double U and coaxial. Polysun also allows simulation of ground water heat pump systems however; this is not further introduced here.

The borehole model admits a maximum of up to 10 different earth layers each of which will affect the calculation of the ground source loop as connected in series. Multiple temperature nodes will be calculated for each earth layer according to the detailed physical model. The model also takes into account a possible energy rear feed, for example, for regeneration or free cooling purposes.

To simulate the long-term degradation of the ground temperature when extracting heat the "annual withdraw energy" and "loop preload time" may be entered. The long-term behaviour of a ground source loop by can be calculated by choosing "preliminary simulation". It is for example possible to pre-simulate 9 years and then give the data for the 10th year as result. For a more detailed description of the ground source loop model, see reference (Huber and Schuler, 1997).

5.3 Hot water storages

Hot Water storages in Polysun are calculated in 12 layers (nodes). Internal heat exchangers, internal tanks, electric heaters and 10 tube connections can be defined and located anywhere in the storage. Stratifier devices may also be defined in Polysun. Figure 5.4 shows some possible configurations of the storages. It is possible to define a unique storage with heat exchangers and connections placed as desired. Also different insulation thickness and connection losses can be defined.

5.4 Heat pumps

A water to water or brine to water heat pump is a component with 4 hydraulic connections. The calculation of heating capacity and absorbed capacity are based on a so called "scattered data interpolation". Start-up losses are not considered. A realistic heat pump control can be reproduced by means of the minimum operation time and the minimum idle time. A catalogue for different heat pumps is provided in Polysun. A specific performance of a heat pump can be defined by copying one heat pump model and change the input data for the component. There are also air-to-water heat pumps available in Polysun.
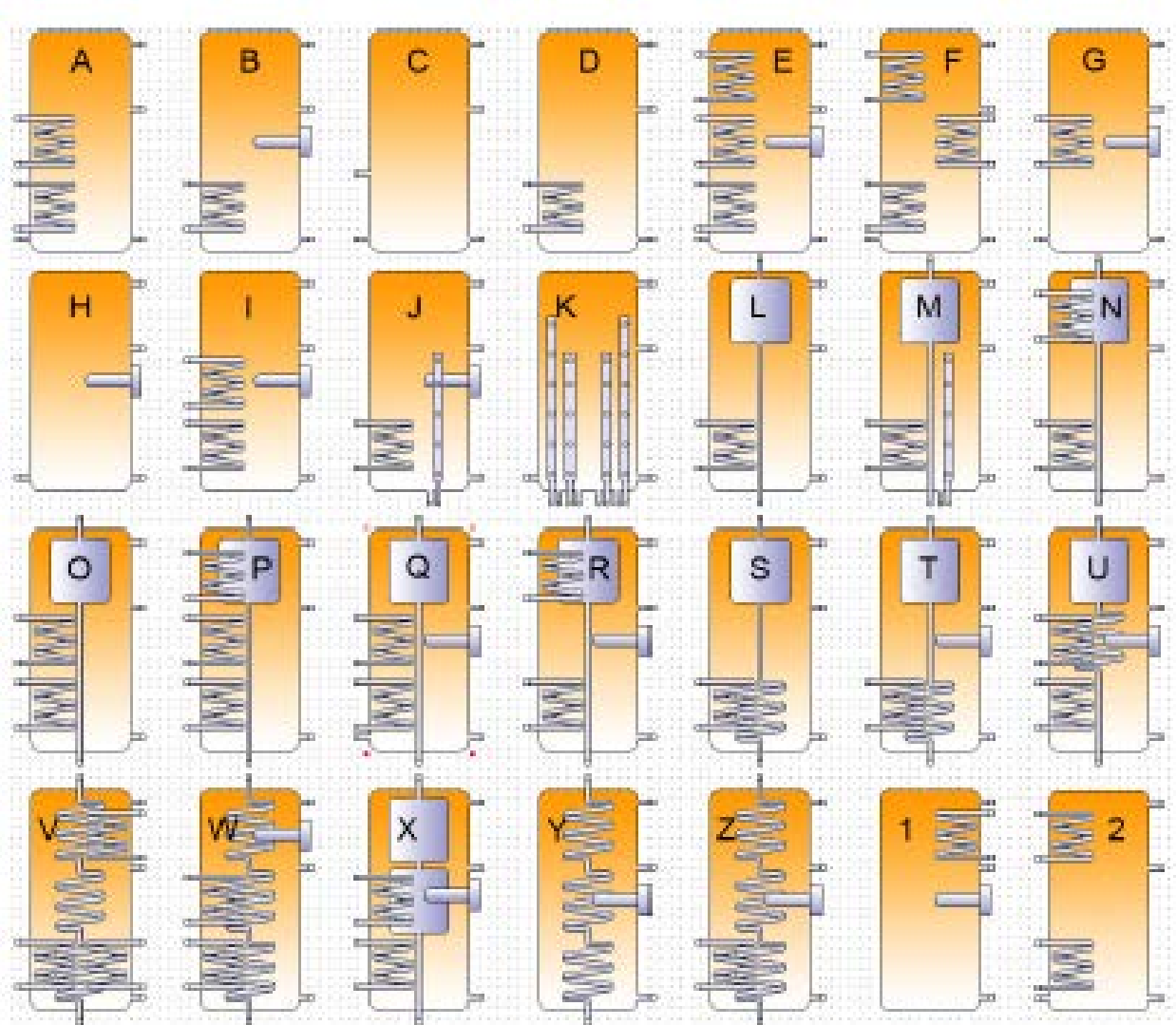
Figure 5.4. Different storage configurations in Polysun.

5.5 Solar collectors

Since Polysun is a *solar* simulation program there are nearly all solar collectors defined in a catalogue. Manufacturer, name, collector type and all test data for each solar collector is available in the collector catalogue. Other collectors can be simulated by changing the collector parameters into the catalogue and make the calculations with the new component. The size, orientation and tilt of the solar collector field can be changed in the dialog window.

5.6 Building load calculations

The two main loads in Polysun are domestic hot water load (DHW) and space-heating load (SH) cooling and shading are also included in the building model.

Building simulation

The building model is a simple model based on the heating/cooling energy balance equation with thermal heat capacity. Transmission, ventilation and infiltration are taken into account as well as passive solar gains and internal gains from persons. Both heating and cooling load can be supplied to the building. The building can be defined based on geometrical dimensions as well as by means of a variety of building types included in the catalogue. Alternatively, a building may be defined based on a known heating energy demand or the annual fuel consumption.

Another way to define both cooling and heating demand is by using the component "heat sink/source" that reads a csv-file with hourly values for heating and cooling. Measured data or simulated loads from another program can then be used by providing supply water temperature, return water temperature and heat rate. As the flow rate is calculated from the temperature difference and heat rate, the temperature difference should not be zero as this is causing an error in the calculation.

The hot water consumption dialogue box allows users to choose between "profiles" and consumption specific "monthly values". Different VDI 6002 profiles are available. DHW, withdraw start each hour at time 24:00 and flow rate and duration for each hourly withdraw can be individually adjusted. For example one withdraw can last 10 minutes at a volume flow rate of 45 l/min. Then there can be no withdraw up to the next hour. DHW profiles can also be defined in csv-files with hourly time step.

5.7 Hydronic components

Pumps

The pump model used in Polysun is based on the pump curve that regulates the flow rate foreseen in the circuit. When not in operation, the pump blocks the flow. The pump can be controlled according to one of the following options:

- *Circulation pressure drop*. The flow rate is calculated in correspondence to the pump curve that regulates the flow rate in the circuit. Valves have no pressure drop in Polysun, but pipes and heat exchangers have a "friction factor" that takes care for the pressure drop.
- *Fixed flow rate*: the flow rate in the circuit is regulated by a pre-established flow rate
- *Controlled flow rate*: a controller manages variable pump flow rate.

Piping:

The pipe components work as links between the components. Supply and return pipes are separately defined. Pipe material, pipe diameter, insulation thickness and length of the pipes can be defined. In the mode "circulation pressure drop" the turbulence of the flow is defined when defining the pressure drop.

Valves

Three way valves play a crucial role when it comes to the actuation of fluid loops. The position of the mixing valve is adjusted by a controller. The valves can be defined to split incoming flow in a fixed proportion or to merge 2 incoming flows.

Heat exchangers (external flat plate)

In Polysun there is a catalogue with several predefined heat exchangers. New heat exchangers can be defined by copying one and define new parameter values.

5.8 Controllers

Polysun on designer level allows integrating controllers individually within hydraulic schemes. There are many possibilities for implementing control functions and the following controllers are implemented in Polysun:

- Solar loop controller
- Variable speed pump controller
- Auxiliary heating controller
- Mixing valve controller
- Heating circuit controller
- Temperature controller with AND/OR Operation
- Flow rate controller
- Irradiance controller
- Programmable controller

All controllers except the programmable controllers are structured with an "input mask" where the values for the actual task are defined. Programmable controllers enable operating states to be freely defined. This makes the controller suitable for diverse applications. The control logic is defined by means of formulas that are comparable to the calculation formulas used in Excel.

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6 Modelica

6.1 General description

Modelica is an object orientated equation based programming language for modelling of complex physical systems, including mechanical, electrical, thermo-physical subcomponents etc. (Modelica Association). The object orientated structure allows reusing of developed components and therefore the possibility of easy modification and amplification of existing models. The component models could either be made from scratch or be taken from existing libraries.

There is a selection of Modelica compilers available. The Dymola (Dassault system) environment provides a graphic user interface for modelling, compilation, simulation, and results viewing. Dymola can be considered to also provide a lower threshold to get started, as the possibility to work on different levels is well handled. The codes and the developed components' properties as well as the characteristic equations can be written and displayed at the lowest level. Figure 6.1 shows the second level which is the graphical interface in Dymola where components could be connected to systems. In the example shown in figure 6.1, components from the TIL Library (Richter, 2008) are used to develop a simplified borehole model. Parameters of the components can also be changed in the second level.
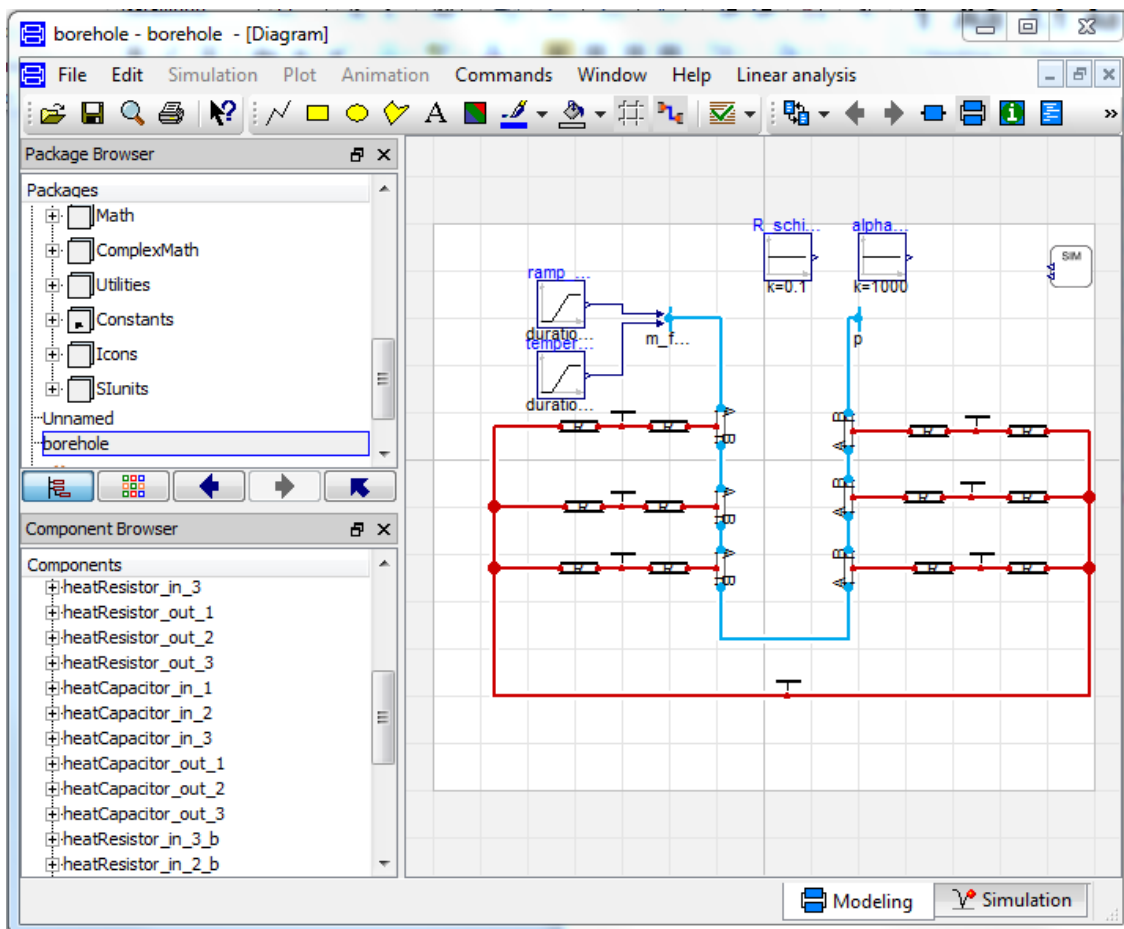

Figure 6.1. The graphical interface in Dymola where components can be connected to systems (screenshot from program).

6.2 Libraries

There are several available libraries containing ready-made components and component classes (templates). Some are freely available while other requires a license. Some of these libraries contain components that can be used directly to simulate geothermal storages, hot water storages and heat pumps, while other libraries contain more basic building blocks that can be assembled to construct similar components and systems.

An example is the TIL Library (Richter, 2008) which has several components designed for stationary and transient thermodynamic simulations, for instance heat exchangers, pipes, valves and compressors. Thereby it is possible to model thermodynamic systems with a high complexity, such as refrigeration or heat pump cycles. TIL Media is an associated material data library which provides physical and thermodynamic properties of fluids and solids. Both pure substances and mixtures are included and single-phase and two-phase states are represented. These libraries have been developed by the Institute of Thermodynamics at the Technical University of Braunschweig and the TLK-Thermo GmbH (Lüer, 2014). The TIL libraries do not include a model of boreholes, but the components could be used to develop a model of the entire system.

6.3 Geothermal storages

The open-source Modelica Buildings Library is the only freely available library which contains a U-tube single borehole model. A convective heat transfer coefficient which depends on the fluid velocity, the heat resistance between the two pipes, and the heat resistance between the pipes and the circumference of the borehole is used when computing the heat transfer in the borehole. The transient heat flux in the ground is solved by discretizing the surrounding ground in several cylindrical layers. The temperature in the outermost layer is calculated by using an approximation of the line-source theory together with superposition and is updated every week. The borehole and the surrounding ground are divided in vertical direction into several adiabatic horizontal layers. The model is not suited for multiple borehole simulation (Picard and Helsen, 2014; Modelica Buildings Library, 2015).

Lüer (2014) used the TIL libraries to develop a borehole model. The model includes the use of different types of grouting materials or ground water filled boreholes, and it contains both a single U-tube and a double U-tube heat exchanger. The model has been verified by comparing the simulation results with measured data from a borehole. The result showed a good match in both short term (35 hours) and long term (30 days). The model is not suited for multiple borehole simulation (Lüer, 2014).

Another borehole model for single U-tube and coaxial heat exchangers has been developed by the E.ON Energy Research Center in Germany (Picard and Helsen, 2014). This borehole model is connected to a cylindrical ground model which is discretized in vertical and horizontal direction, and the ground model uses a fixed temperature boundary condition. Multiple borehole simulation is not possible with this model.

Picard and Helsen (2014) proposed a new model, implemented in Modelica, which met the following requirements: (i) is able to simulate any arbitrary configuration of boreholes, (ii) allows coaxial, U-tube type or double U-tube type BHX, (iii) has short- and long-term accuracy for minute-based year-long simulations, and (iv), is numerically efficient.

To achieve both long-term and short-term accuracy, a long-term and a short-term response model is merged into one hybrid step-response-model. The long-term response model takes the interaction between the boreholes and the ground temperature evolution of the surrounding ground into account. They assumed uniform heat flux from all boreholes, which means that the accuracy for the model decreases for long simulation times for configurations with non-uniform heat fluxes, for instance a densely packed rectangular

grid. However, this can be solved by plugging a g-function in the model instead of the calculating of the temperature step response (Picard and Helsen, 2014).

The short-term response model was implemented to describe the transient heat flux in the BHX to the surrounding ground. The simulation periods for the calculations are typically less than 200 hours, and the interaction between the boreholes can be neglected for such small time periods. Single borehole models are therefore used. The main elements are the heat carrier fluid, the pipes, the grout, the surrounding ground and the undisturbed ground temperature. The structure of the model is shown in figure 6.2. The simulation time proves to be significantly shorter than for the borehole model from the Modelica Building library (Picard and Helsen, 2014).
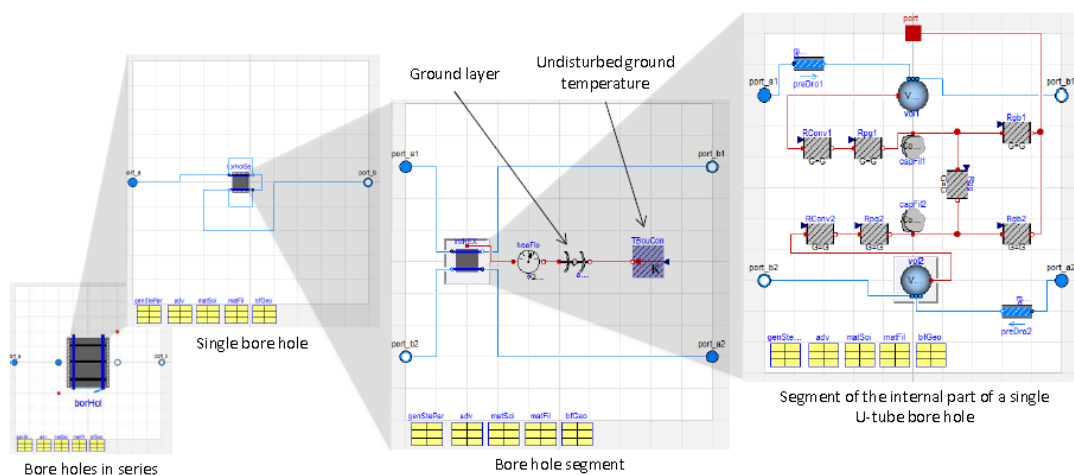

Figure 6.2. The model structure for a set of single-U-tube boreholes in series (Picard and Helsen, 2014)

Within the INTERACT project, a ground heat exchanger model has been developed using the Modelica language (table 3.1). The following information is taken from the report about this work (Holstad, 2015). First, a complex model consisting of three types of entities where made:

- Building blocks: The basic units that are used to construct larger components.
- Components: These are more complex entities that are constructed from building blocks.
- Testers: These are codes that simulate the components interacting together and set up the overall environment for a simulation.

The most basic building block in the model is the borehole segments. These are transverse intersections of the borehole itself. The borehole segment is circular and there are two smaller circular pipes inside of it. The borehole is filled with water, while the pipes are filled with an aqueous solution of 20 volume percent ethanol.

In order to represent the entire borehole, several borehole segment building blocks are connected together in the borehole component. The pipes in each segment are connected with the pipes in the next element. In the lowest segment the pipes are connected together to close the U-pipe. A similar method was used to represent the ground.

Testers where made for validating of the model. The test results were compared with previous studies and showed that the model gives a good approximation for the response of a borehole heat exchanger to a

distributed thermal response test (Holstad, 2015). The model can be used to set up any rectangular grid of boreholes and simulate their behaviour and interaction with each other.

After validating the results from the complex model, a simplified model was made to decrease the computation time. One simplification was that the pipe was modelled as one pipe instead of two, and did not consist of several borehole segments, only one. This was compensated for by increasing the thermal mass, reducing the resistance and using LMTD. The simplified model seems to give fairly similar responses as the complex model. The simplified model can also be incorporated into a larger system without giving a too long computation time for the large system.

6.4 Heat pumps

Heat pump models can be built using the Modelica language based on for instance the TIL Library (Richter, 2008). It is possible to model the heat pump as a complex system with heat exchangers, compressors and valves and many different working fluids are available. The efficiency of such a heat pump system is calculated based on many different parameters such as temperature level, pressure ratio, heat transfer coefficient and heat transfer surface etc. A heat pump model can also be built as a simple system without the subcomponents where the efficiency is calculated based on only the temperature level.

6.5 Building load calculations and climate

A building model can be made by using the Modelica language to calculate the building loads taking different parameters such as location, climate, insulation materials etc. into account. An alternative is to calculate the building loads externally and use them as input values in the Modelica model.

6.6 Controllers

The controllers can be made as advanced as necessary when using the Modelica language. The elements in the model, such as compressors, valves, pumps etc., can be controlled using PID-controllers. The controllers are used to minimize the difference between a given set point and a measured process variable over time. The set points can also be changed over time.

7 IDA ICE

7.1 General description

Ida Indoor Climate and Energy (IDA ICE) developed by EQUA Simulation AB, is a dynamic multi-zone simulation application for the precise simulation of the indoor air quality of individual zones (simulated as points) as well as the energy consumption of an entire building.

It is possible to use IDA ICE in different levels of detail, giving users freedom to develop models according to their needs and wishes. IDA ICE also offers the opportunity to study various passive techniques.

IDA ICE can be used at three levels;

1. *Wizard.* This version using some default models for heating system, cooling system, default boreholes, ventilation system, domestic hot water, etc. In addition see Figure 7.1 and default models for insulation, occupation as shown in figure 7.2 can be defined. See IDA ICE's user manual (EQUA Simulation AB, 2013b).

2. *Standard.* This version allows going into some additional details such as insulation indoors and outdoors, more advanced control system for heat pumps and boreholes. In addition one should use this level when the goal is to simulate different configurations of buildings or interaction between several buildings.

3. *Advanced.* One will use the advanced level when interested at introducing all the possible details such as heat transfer variation of the boreholes with time and heat extraction, more advanced controls or further detail in interactions among buildings. See figure 7.3 as an example of the detail when using the advanced level.
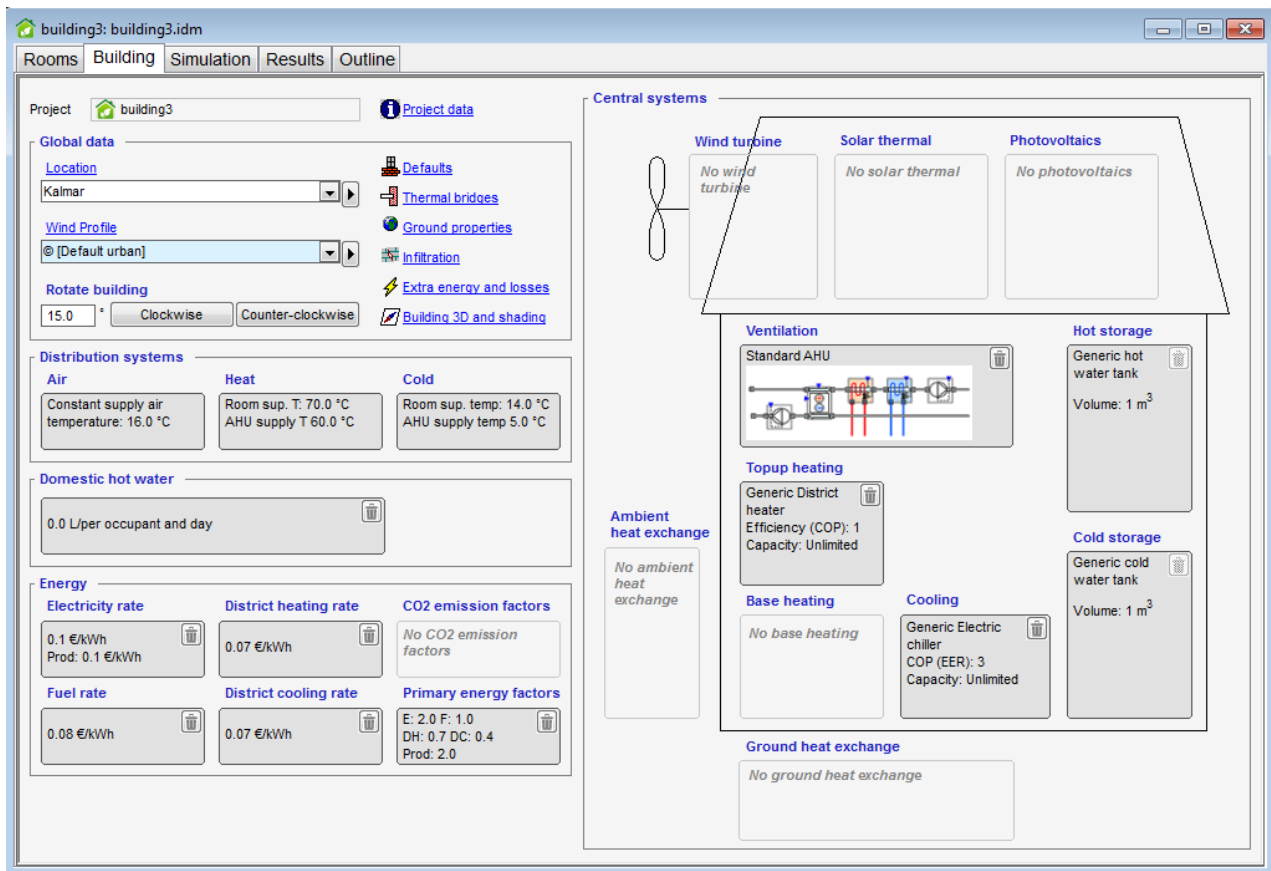
Figure 7.1. Detail of a Wizard plant where one introduces type of heating, cooling, ventilation and production of electricity and storage when available (screenshot from program).
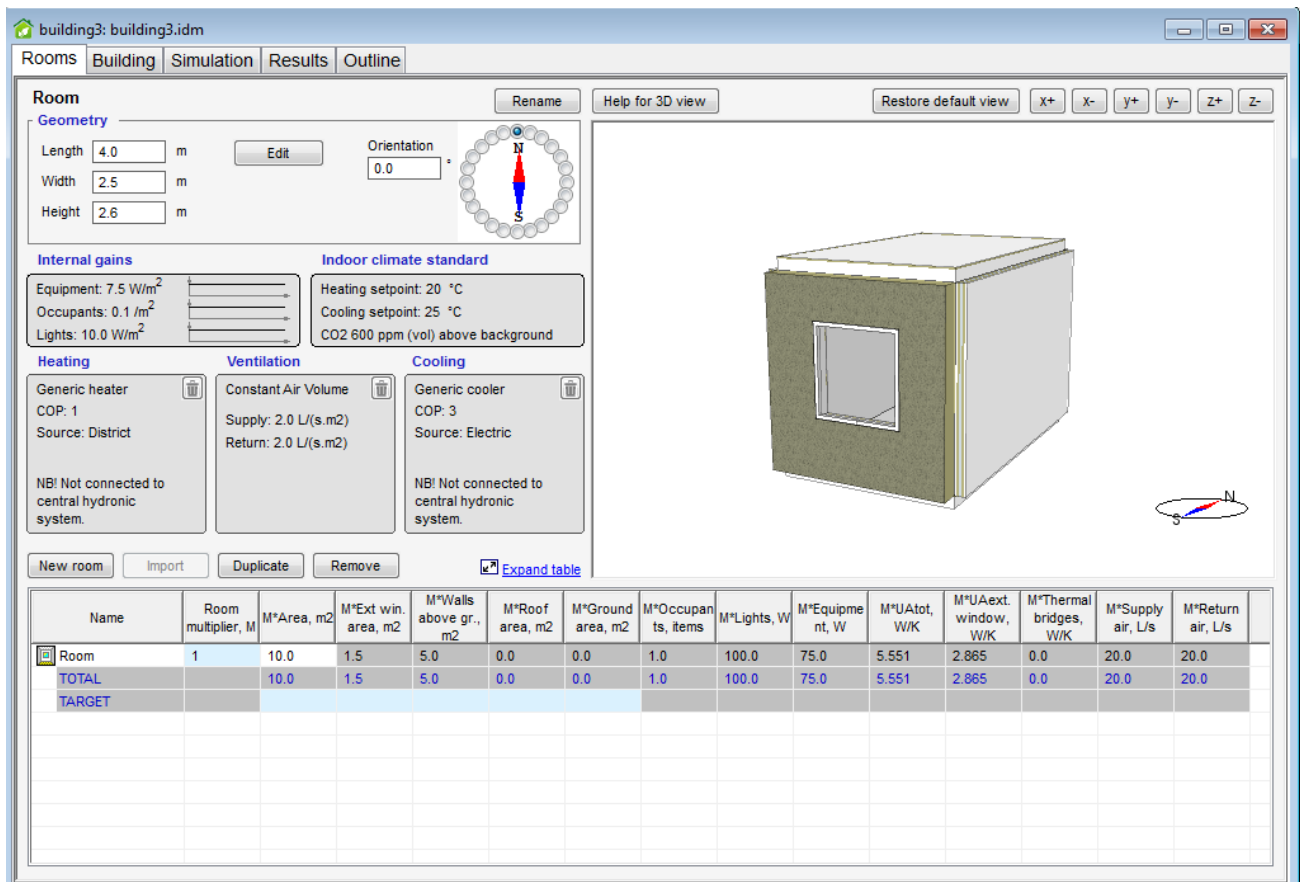
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Figure 7.2. Detail of wizard level when introducing information regarding building, climate and others (screenshot from program).

In the mathematical level (Advanced) a model is built up by inserting objects then connecting some of them. Objects mostly appear as boxes with explanatory pictures and connections as lines between pictures. A typical object is created with NMF (Neutral Model Format) or Modelica which are languages for describing mathematical models. One has the possibility to modify the elements on Dymola for example and import them into IDA ICE; however some collaboration with EQUA Simulation AB is needed to implement new models. One can also create models from scratch such as the detailed models available in house at SINTEF Energy Research regarding CO_2 heat pumps. Other objects work as boundary conditions. At this level it is possible to view and edit the code, giving the user a direct control over the mathematics behind.
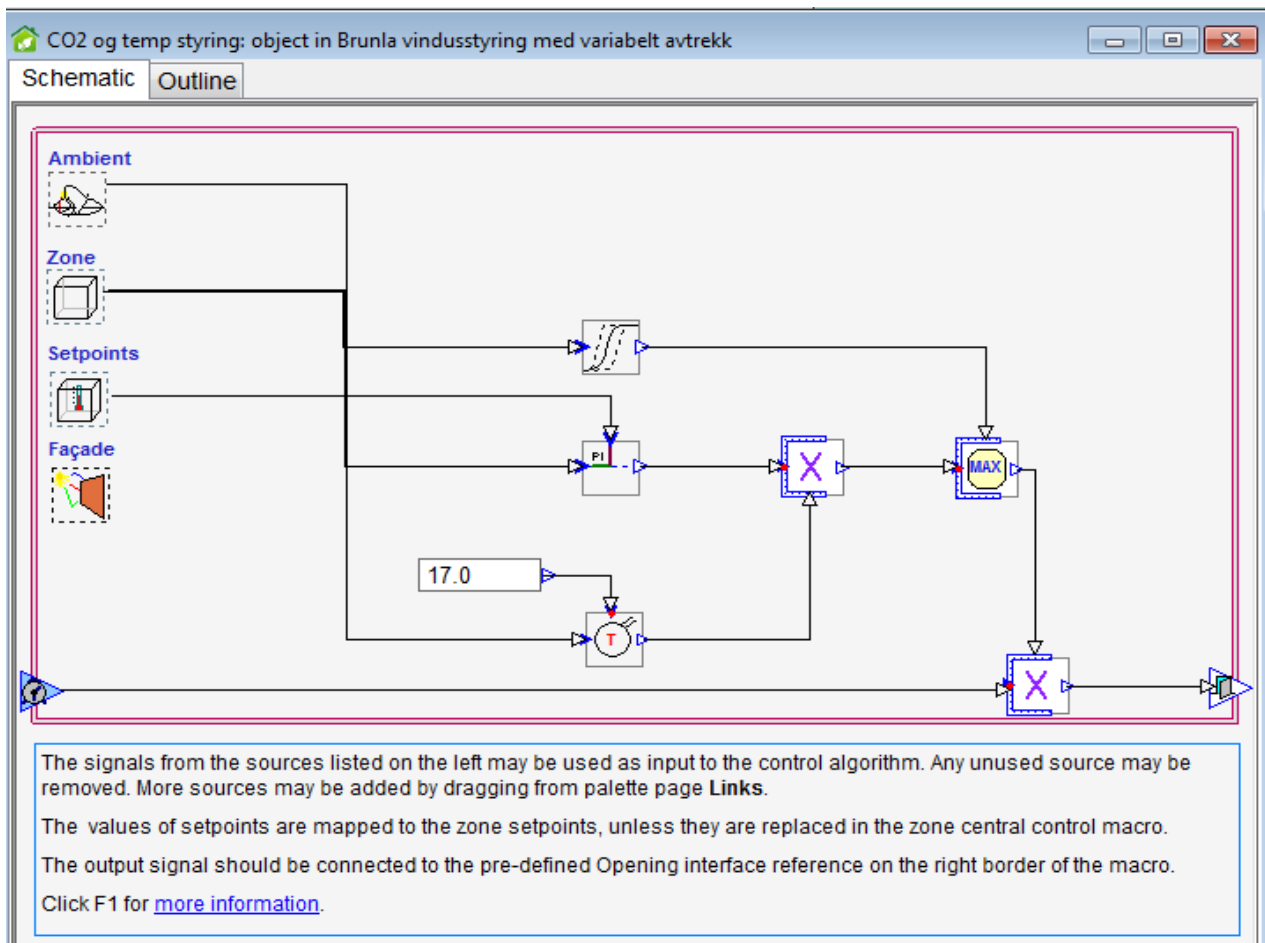
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Figure 7.3. Advanced definition of a control system based on CO_2 concentrations and temperature (screenshot from program).

7.2 Geothermal storages

IDA ICE version 4.6 includes new models for heat pumps, solar collectors, storage tanks, boreholes, CHP, wind turbines, PV, and other renewable energy sources.

The GHX model (EQUA Simulation AB, 2013a) is a 3D model for an arbitrary combination of boreholes (vertical or leaning) of equal length. The model can be used in different variations like; single borehole version of borehole model- GHX_S (Nord *et al.*, 2016) and GHX_SLIN (Fadejev and Kurnitski, 2015) (with the difference of having variable mass flow in homogenous ground and only limited variability respectively) and multiple borehole version GHX_MIR (Nord *et al.*), GHX_MIRLIN (Fadejev and Kurnitski, 2015), with the same variations as before but for multiple boreholes.

The model is based on superposition of cylindrical 2D fields around each borehole and a 1D vertical field for the undisturbed ground temperature including geothermal temperature. The restrictions in the model are:

- The ground can only have one layer,
- All holes have the same length,
- Only U-pipes as heat exchanger,
- Constant Borehole Resistance.

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Regarding geometrical parameters the user supplies the radius, and active length, for the borehole(s) and the radius for the U-pipe; the number of U-pipe in the hole, and the thickness of the pipe wall (figure 7.4).
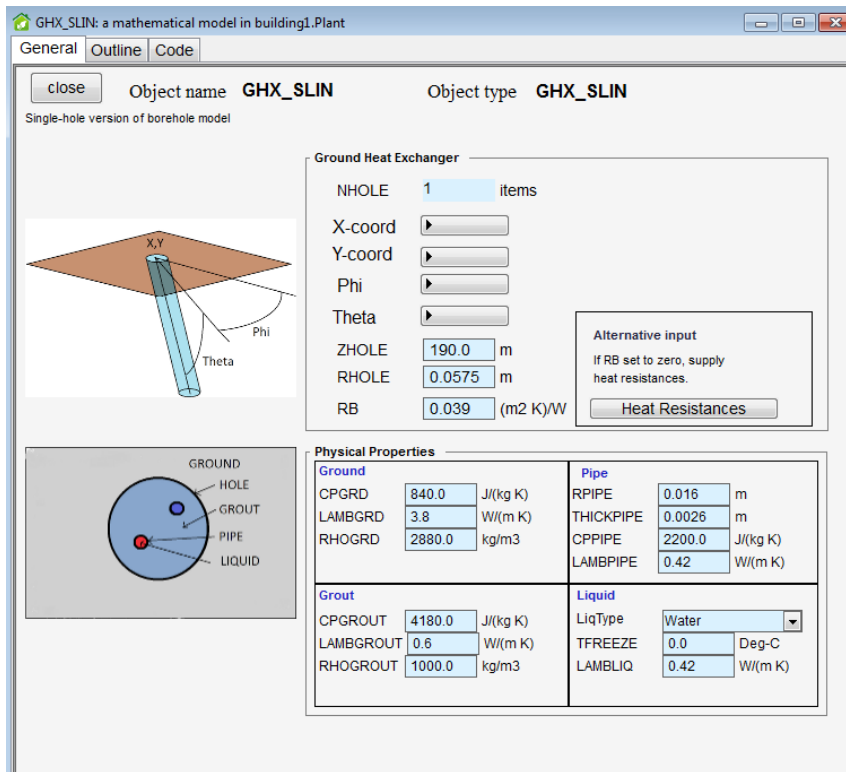

Figure 7.4. Simple borehole definition (Screenshot from program).

The boreholes are all straight but can have different inclination. The borehole pattern can be arbitrary with the exception that the boreholes are not allowed to overlap or intersect. The pattern is given as x-and y-coordinates and as angels for each borehole. One has to specify the angel between the borehole and the x-axis on the ground surface, and the angel between the borehole and the vertical z-axis.

Then one should also define physical properties of the ground, the filling material (grout) and the liquid in the pipes. For the ground and the grout there are basically the same parameters to supply, the heat capacity, the heat conductivity λ and the density ρ. The user also must give the annual mean temperature in the ground. For the liquid, the user chooses between a predefined set of brines including non-mixed water. The user gives the freezing point of the brine, and the heat conductivity, for the brine, all other properties for the liquid are calculated as temperature dependent properties. The borehole resistances can be supplied as data from a thermal response test (section 2.2) or as detailed resistances (Fadejev and Kurnitski, 2015).

7.3 Hot water storages

Regarding hot water storages, the default version of storage tanks available simulates an ideal tank and other default tanks are for cold storage and brine tank without stratification. Many models of storage tanks are available in Modelica and can be directly used in the simulation with some help from the developers. In order

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to introduce PCM in the storage, many authors have already solved the simulation challenges (Ruschenburg *et al.*, 2010), also many Modelica models are available and all the properties of the tank can be changed.

7.4 Heat pumps

Default models for air to water, brine to brine and air to air chiller and heat pumps are available. In addition to this, SINTEF Energy Research has models for heat pumps using CO_2 as refrigerant that can be directly introduced into IDA ICE with help from program developers. In addition working pressures for the heat pump, dependence of the heat pump on outdoors temperature, etc. can be modified in order to simulate the same unit as the one needed for the simulation.

As IDA ICE is making yearly simulations it would be easy to calculate SCOP and the term of bivalent temperature could be calculated by programming it. Other types of heating systems can be easily implemented in case of being interested in the comparison of different effects of different heating solutions and indicators such as PEF or CO_2 emissions can be calculated.

7.5 Building load calculations

IDA ICE 4 is validated against NS-EN 15265 (Norsk standard, 2007) which is required for all simulation programs used for documenting the energy performance of a building in Norway. The loads are calculated based on a detailed description of the location of the building and the climate, description of the insulation materials both external and internal, thermal bridges, percentage of recoverable losses, ground properties, infiltration, pressure coefficients, extra energy and losses and then, defined per room, the occupancy, appliances and lights. Further information regarding shading, sun irradiation etc. can be introduced in the calculation of loads. In addition the loads can be calculated yearly or by seasons.

7.6 Hydronic components

Regarding the hydronic, one could introduce information about the heating curve given distribution through water or air. The user should define supply and return temperature (outdoors correction curve) and this would be taken into account when calculating the efficiency of the heat pump. The author must define as well the share of recoverable and non-recoverable losses affecting in the total demands for heating.

7.7 Controllers

Regarding the controllers with IDA ICE the author can make them as advanced as one would need. Figure 7.3 for example shows how a ventilation system is controlled by CO_2 and temperature in one room. In addition one has "if, or, xor, and..." elements available for the control of every heating, ventilation and cooling system. In addition given the possibility to model controls using Modelica, controls that are not yet developed or available, can also be programmed.

8 MatLab/Simulink+ Carnot

The information of this section is taken form the project thesis of Ytterhus (2014) unless otherwise stated.

Simulink/Matlab has the advantage of being flexible in system design. Its disadvantage regarding heat pumps is that the Carnot library is highly simplified and as this report will show, there are significant challenges related to the borehole model implemented. The main advantages and disadvantages are summarized here:

+ Various emission-, distribution-, boiler - systems
+ Detailed tank models
+ Pressure drop and heat lost in the components and the pipes possible
+ Library is available free of charge
+ Coupling with / executing from Matlab without problems
 - No advanced HP model (just on/off HP)

8.1 The Carnot Library

The Carnot toolbox is developed as an extension to the Simulink/Matlab at the Solar Institute Jülich in Germany. Carnot is available for free from the University of Applied Sciences Düsseldorf. The Carnot library has no guidance and does not offer any guaranty of its utility for any particular application.

The toolbox consists of blocks in which the different physical models are implemented. Inside the block there are either Simulink blocks or S-functions used to reproduce physics. The S-functions refers to an m-file including the code. In this way, it is easy to change or modify the blocks. The different sub libraries and the main blocks available are listed in the table below.

Table 8.1. Overview "Carnot toolbox"

Sub library	Components
Basic	Material Properties, Hydraulics, Pressure drop, Thermal models, Weather and sun
Control	Sensors, Controller, Energy meters
Hydraulics	Valves, Mixers, Diverters, Pumps, Pipes
Load	Electric, General, Houses, Hot water tapping
Outputs	THB-, THV-, Weather-selectors
Storage	Ground storage, Water storage
Source	Boiler, Chiller, Heat pump, Heat exchanger, Solar thermal, Electric generator
Toolbox	System functions, Utility blocks
Weather	Weather blocks, Collector positioning

Carnot uses a Thermo-Hydraulic Bus (THB) to describe the different properties and the state of the fluid circulating in the system. The THB consists of a total of 12 different parameters, including temperature, mass flow rate, pressure, and fluid type/fluid mix. From the parameters in the THB, other fluid properties such as heat capacity and flow characteristics such as the Reynolds number can be calculated by other blocks that are implemented in the library.

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8.2 The Carnot EWS Model for double U-tube collectors with grouted boreholes

The CARNOT EWS model is a transient model for dynamic simulation of vertical boreholes in the simulation environment Matlab/Simulink. The model is based on the equations described by Huber and Schuler (1997) and implemented into Matlab/Simulink by (Bianchi, 2006). It is developed for double U-tube collectors with grouted boreholes. This sub-chapter is based on the documentation of the Carnot EWS model by Ochs (2012), Ochs *et al.* (2013) and own investigations of the actual model (Carnot Version 6.0, 2014).

Changes of the mass flow during operation/simulation could not be considered in the original model, but an update made it possible to turn the mass flow on and off during the simulation. (Ochs *et al.*, 2013). It is not possible to vary the mass flow rate during simulation. The model is mainly intended for single boreholes, as there are only a limited number of borehole configurations implemented (section 8.3) and there are no validation performed for multiple borehole configurations.

The Carnot EWS model is implemented in the "Ground Source Heat Exchanger" block (CGSHEB), (figure 8.1). By double clicking on the CGSHEB, a list of in total 17 different parameters can be selected. It is not possible to choose different ground properties at different depths in the CGSHEB. Geometry parameters define borehole and borehole field geometries. Finally, calculation parameters define the calculation grid, which affects the accuracy and computational time of the simulation. In addition to the parameters described above, a large number of parameters are also defined and calculated in an initialization Matlab-script in the CGSHEB. Fluid properties are calculated based on an average temperature and are constant during a simulation.

The number of ground temperature nodes calculated depends on the number of radial and axial calculation nodes set by the user. By default, 45 ground temperatures (nine in radial direction, five in axial) are reported. For each vertical layer there are two brine calculation nodes, one on the downward flowing liquid and one on the upward flowing liquid. The outer radius temperature is calculated by the response factor (g-function) approach and used as a boundary for the other calculation nodes.

Upward and downward flowing fluid temperatures are calculated based on thermal conductance values calculated in the initialization script. Input parameters used to calculate fluid temperatures depends on whether there is a liquid flow rate or not. The upward flowing liquid temperature at the last node gives the outlet temperature in the THBout. The one dimensional heat equation is solved by a state space model included in Matlab/Simulink (yellow circle in figure 8.1). An extended description of the implementation of the EWS model including how the thermal resistances are calculated can be found in Ochs (2012).
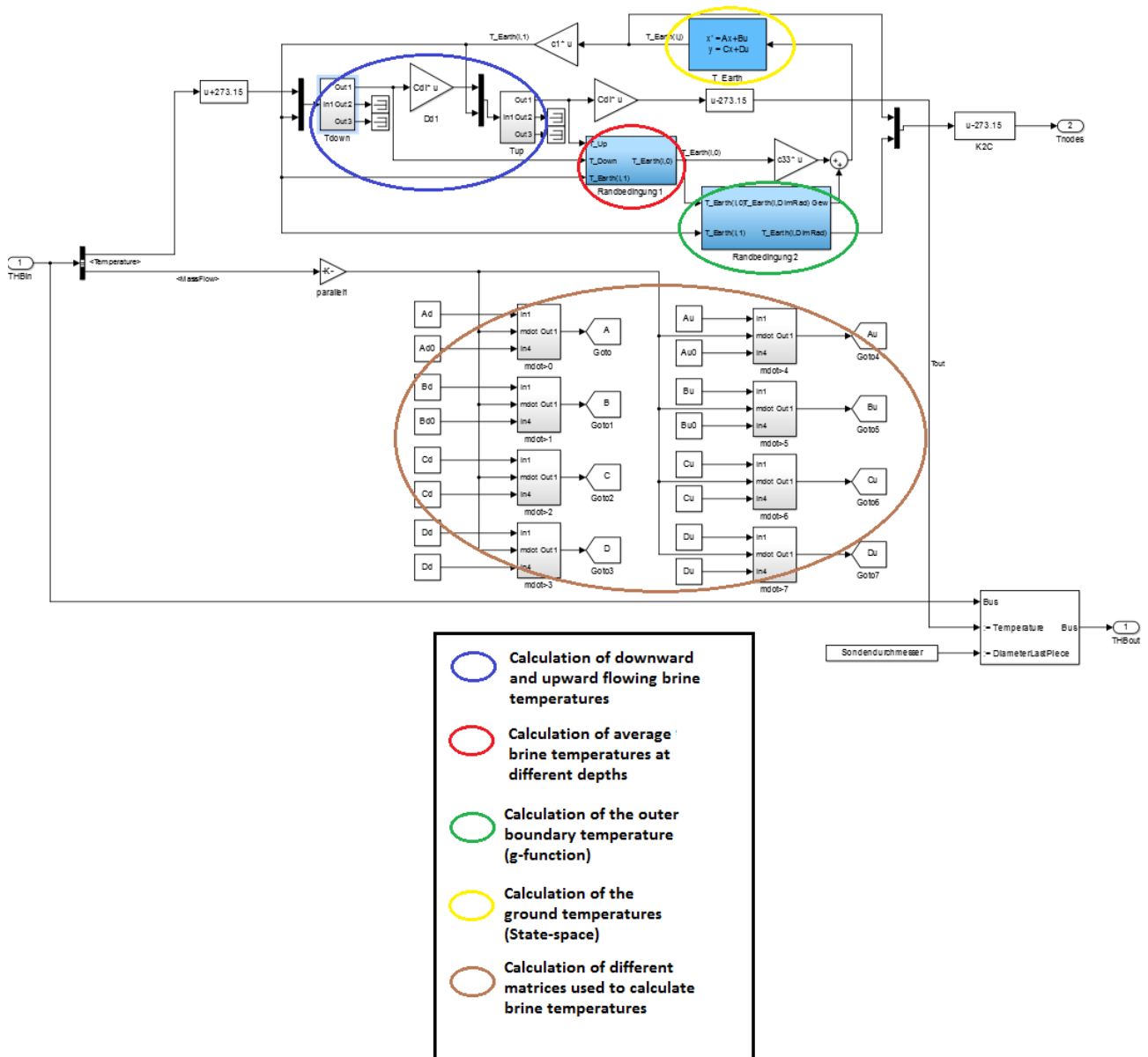
Figure 8.1. Under the mask of the CGSHEB (Carnot Version 6.0, 2014). *Additional explanation of the different parts of the model has been added (screenshot from program).

8.3 Implementation of Eskilsons g-functions

g-functions from Eskilson (1987) for a total number of five different borehole configurations have been implemented (1 probe; 2 probes B/H=0,1; 2 probes B/H=0,05; 3x6probes B/H=0,1 5x10, B/H=0,1). B/H is the borehole distance to borehole depth ratio. Thus the model is only valid for one single borehole heat exchanger or a field of 2, 18 or 50 BHEs. For two boreholes, two different boreholes distance to borehole depth ratios have been implemented. All other configurations have given a borehole distance to borehole depth ratio of 0.1. All g-functions are based on a borehole radius to borehole depth ratio of 0.0005. The g-functions are generated in the initialization script based on some imported Eskilson g-function values. The values are equal to those

found in He (2012). Matlab functions (polynomial fitting) in the script are used to generate weekly g-values based on the given Eskilson g-function values.

In the Simulink model, the g-function values are given in a lookup-table. g-functions are given from 1 to 20 meter radius with time steps of one week up to a total of 5000 weeks. Interpolations between g-functions are performed during simulation in the Simulink model. The initial time (t_start) and heat extraction (Qdot0) are defined in the initialization script.

8.4 Validation of the Carnot EWS model

Ochs (2012) and Ochs *et al.* (2013) performed three validation cases of the Carnot EWS model. The two first validation cases investigate short-term behavior, while the third case looks at the long-term behavior. For the first validation, the simulation results are compared data from a thermal response test, while case 2 and 3 are validated against other borehole models. The long-term comparison is done over a one year period against results of simulations done with EED and EWS. The maximum deviation between EED and Carnot is 2K. This is, according to Ochs, due to a more realistic modelling by the Carnot EWS model than EED. The validation cases are conducted for one single borehole heat exchanger and there is no available documentation of how the Carnot EWS model performs for a field of boreholes.

8.5 Heat pumps

The "Carnot toolbox" just includes an on/off model of the HP. This is a linearized HP model which uses measured data according to EN14511 as input. The dynamic behavior of the heat pump is calculated using an empirical model (Schwamberger, 1991). The model is based on the static characteristics of the heat pump according to the German standard DIN 8900. In the two-dimensional diagram the heat capacity is given for different temperatures in the primary and secondary cycle. The model also includes thermal and hydraulic losses. The block requires temperature vectors, power matrices and the thermal and hydraulic coefficient as input. The temperature vectors and the power matrices can be found in characteristic curves for the heat pumps.

8.6 Hot water storages

The tank model divides the tank into nodes on both fluid sides; the heat transfer side and the outer wall. The energy balance for every node is solved using the differential equation. The model allows the user to modify the size of the tank or the position of the inlet, and outlet. It is also possible to change the heat exchangers implemented in the tank. This model gives the possibility to investigate different tank layouts and sizes. All these settings which were investigated during this thesis are listed below.

8.7 Building loads

A simplified model of the building following the shoe box approach is available in Carnot. It is also possible to use externally calculated load such as Murer (2015) has done is his master thesis. He used the output file from the SIMIEN software including information about the capacity requirement, the outdoor temperature and the indoor temperature. The time step of the data is one hour. These values were read in by Matlab and then imported to the Simulink model as an imported signal.

8.8 Heat and cooling distribution system and control

This system represents the interface between the heating system and the building. It includes the radiators or floor heating as well as the DHW-consumption. There are serval sensors which control the tank temperatures and the mass flow through the radiators. The emission system temperatures are based on heat balance and it can be as accurate as required. As Carnot is based on SIMULINK, one could introduce very advanced control systems, but this increases the difficulty of using the program.

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9 EED

9.1 General description

This chapter gives an overview of the features in the software Earth Energy Designer (EED). The software is described in the two manuals; Hellström and Sanner (2000) and Blomberg *et al.* (2015).

Earth Energy Design (EED) is one of the most common PC-software for the dimensioning of energy wells in a ground source heat pump system. The software is easy to use, have a quick learning curve and is restricted to the sizing of borehole heat exchanger systems based on heat and cooling loads (figure 9.1). Different from the other simulation software described in this report, the EED-software consider the borehole system only and not the entire heating system or building and heating system. The heat pump performance can be taken into account by a seasonal performance factor. With EED the highest possible efficiency or the chosen efficiency for the system can be optimized by varying borehole length and/or heat pump size. The size of the heat pump is an input parameter together with seasonal performance factor.
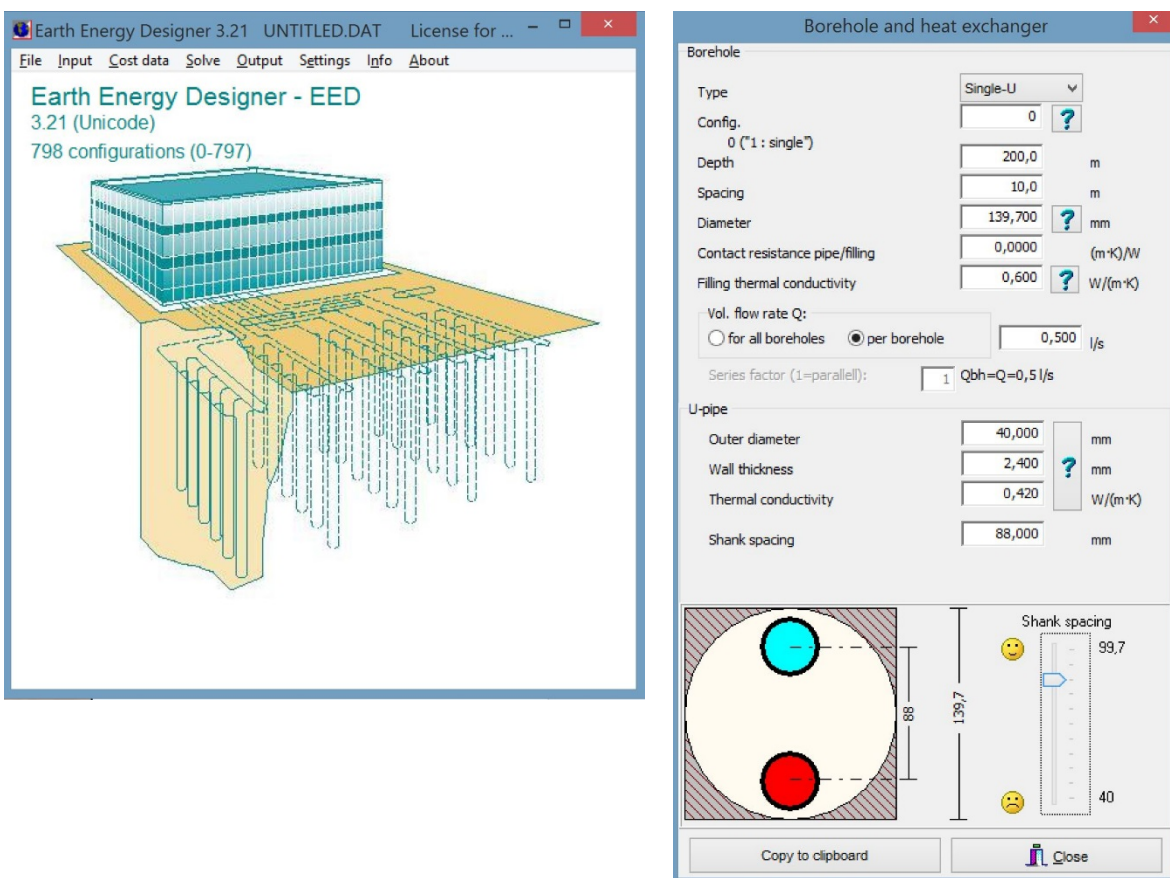

Figure 9.1. The EED front page (left) and input details for the borehole heat exchanger (right). Screenshots from the program.

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9.2 Borehole storage

EED is based on parameter studies with the numerical simulation model by Eskilson (1986) resulting in analytical solutions of the heat flow with several combinations for the borehole pattern and geometry (g-functions). These precalculated g-functions are stored in a data file and used as input by EED to take into account the borehole geometry. In the latest version of EED (v3.2) there are 798 different borehole configurations available. The borehole spacing is given as an input parameter and is the same for all the boreholes in the configuration.

The properties of the ground is given by four parameters (figure 9.2a). The borehole thermal resistance can either be calculated by EED or a measured value from a thermal response test can be applied as a constant value (figure 9.2b).
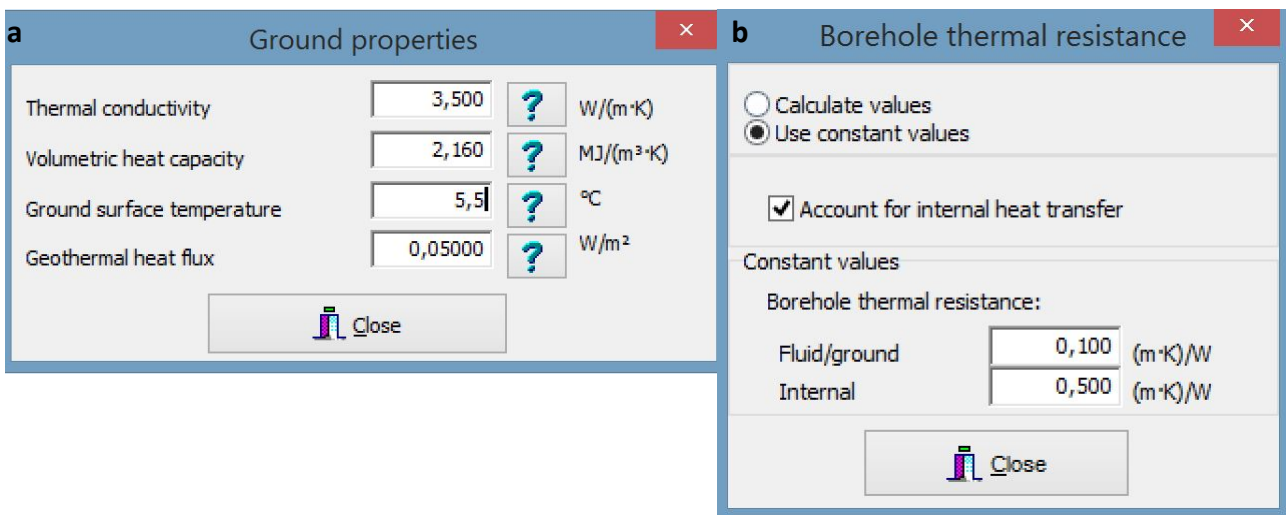

Figure 9.2. Input data of ground properties (a) where the thermal conductivity and the ground surface temperature are the most important. The borehole thermal resistance, R_b (b) can either be calculated by EED or the measured value from the thermal response test can be applied (screenshots from the program).

9.3 Loads

The loads are described as both base loads and peak loads. Base load are provided as monthly values of heat and cool with a seasonal performance factor (SPF) given for the heat pump. Domestic hot water load can be described separately as an annual load with a separate SPF. Peak heating loads and peak cooling loads are provided as maximum capacity and duration for each month. The results are always displayed as average fluid temperatures ($T_{average}$) at different operating conditions and for different periods. The results are used for the evaluation of the performance of the energy wells and the heat pump installation.

9.4 Output results

The principle drawing in figure 9.3a shows $T_{average}$, and the temperatures of the collector fluid, T_{in} and T_{out}, to and from the evaporator (E) in the heat pump, respectively. $T_{average} = (T_{in} + T_{out}/2)$. The letter "C" symbolizes

the condenser in the heat pump. The condenser exchanges heat with the heating system in the building. Figure 9.3b shows the percent and assumed distribution of delivered heat form the heat pump per month. The distribution of delivered heat per month affects the temperature of the collector fluid in the same way as extracted and reinjected heat from/to the energy wells (figure 2.3).
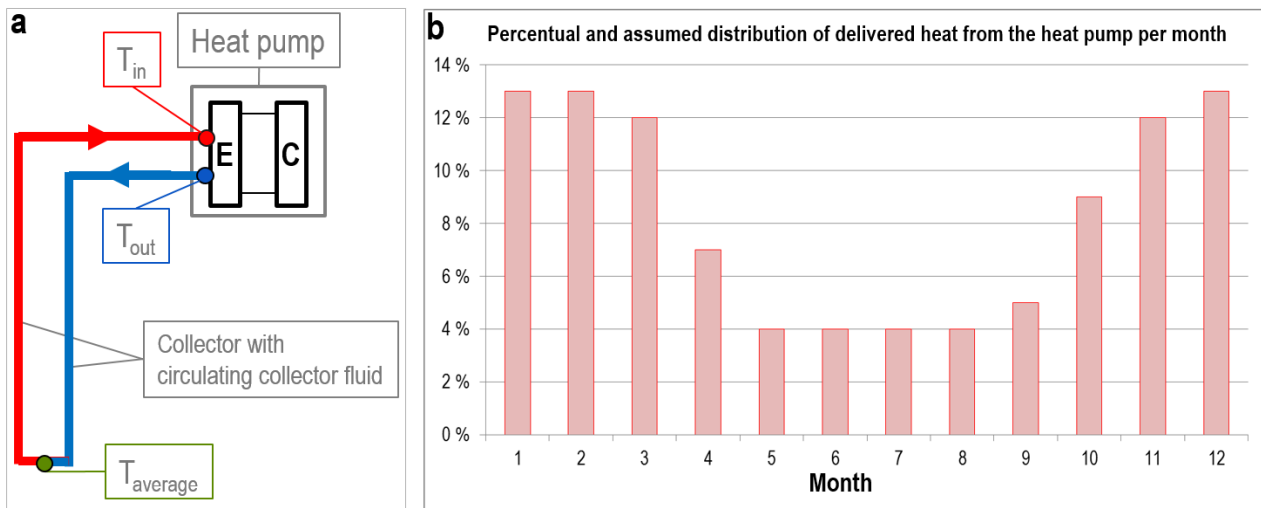

Figure 9.3. Sketch (a) shows the circulating collector fluid and T_average which is always presented in the EED-results. In diagram (b) the percent and assumed distribution of delivered heat from the heat pump per month is shown.

The temperature development for the collector fluid is commonly shown for the period of operation that is calculated by EED, e.g. for the year 1-25 of operation (figure 9.4), and the variations in temperatures in the last year of operation, e.g. in the 25th year (figure 9.5). All the curves in these figures shows the average collector fluid temperature, $T_{average}$. This means that if ΔT is 3 degrees, the temperature from and to the energy wells are 1,5 degrees higher and lower, respectively than what the curves in figure 9.4 and figure 9.5 shows.

The temperature levels (curves) in figure 9.5 represent the minimum and maximum values for the different operating conditions at different periods of the year. The red curve shows the minimum temperature of the collector fluid during the heating season at continuous and maximum heat output from the heat pump. The blue curve shows the corresponding maximum temperatures at maximum deliverance of cooling output. The minimum and maximum temperatures in the 25th year of operation can be found in August and January, respectively in figure 9.4.

The two black curves in figure 9.4 show $T_{average}$ of the fluid, when the heat pump and the cooling are at the lowest possible level of part load. The part load value is theoretically due to the calculation from the given heat deliverance that month (figure 9.3b) divided by the total hours in that month (722 or 744 at 30 and 31 days in the month, respectively). In figure 9.4 the black and unbroken line represents the minimum temperature for the part load situation during the heating season, while the black line with dots shows the equivalent maximum temperatures during the summer in cooling mode. The minimum and maximum temperatures for the part load situation in the 25th year of operation can be seen on the black unbroken line in figure 9.5 in January and August, respectively.
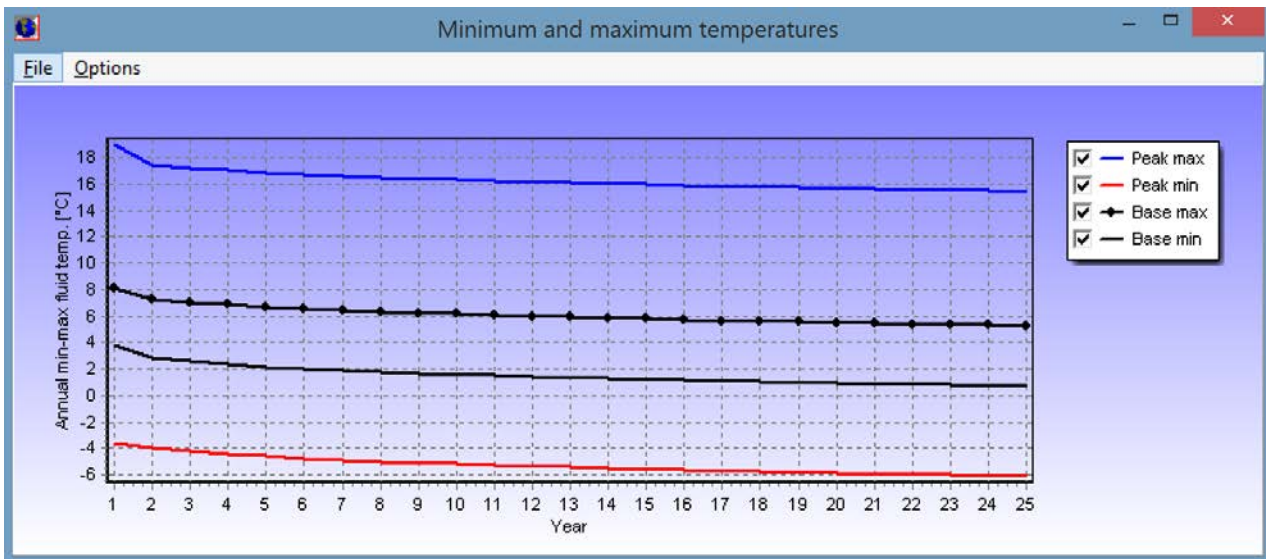
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Figure 9.4. The results in EED shown as the average collector fluid temperature, T_average for year 1-25 of operation.
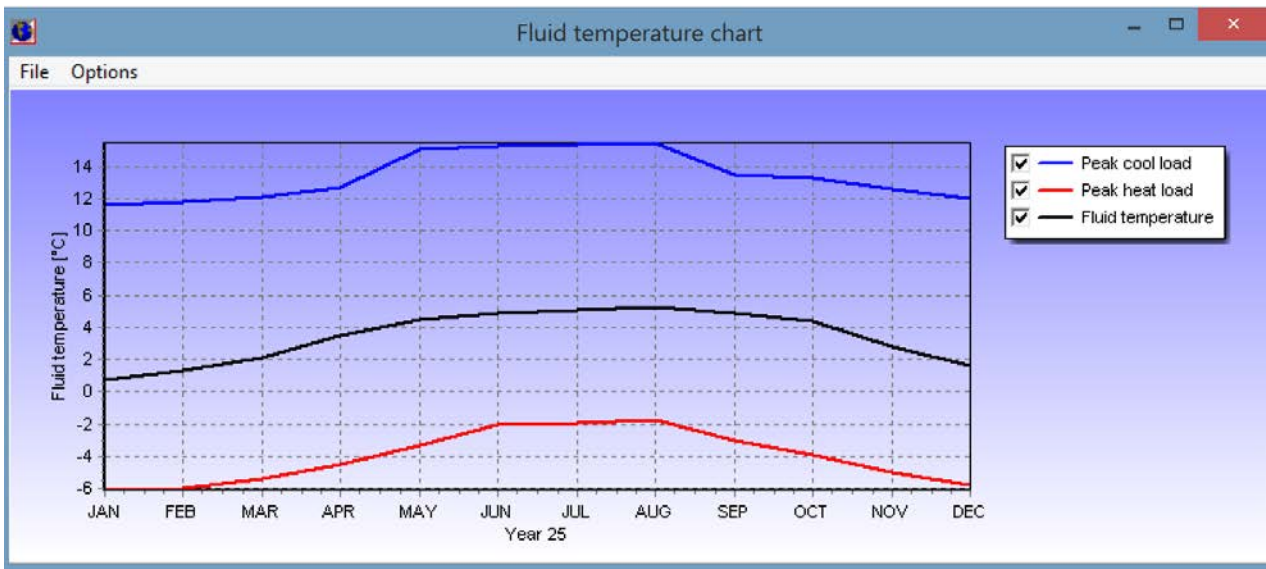

Figure 9.5. The results in EED shown as the average collector fluid temperature, T_average for different operating conditions per month in the 25th year of operation.

9.5 Uncertainties in EED-calculations

There are several circumstances and uncertainties in the EED-calculations which can make the ground source heat pump system perform better or worse in reality compared with the results from the calculations. These circumstances and uncertainties can be listed as follows:

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- The heating/cooling consumption (kWh) and required heating/cooling capacity (kW) of the building is higher or lower than originally stated.
- The estimated heating and cooling delivery and the distribution of the heating and cooling delivery per month deviates. If the real heating and cooling delivery is higher or lower than assumed, or has a different distribution, this influences the temperature of the collector fluid.
- The thermal properties of the bedrock are often based on one thermal response test. However, the bedrock geology can differ within small distances and for neighboring boreholes. Variations in the thermal conductivity influence the performance of the energy well to some extent.
- The ground water flow can affect the heat transfer and is not considered in the model. However, the thermal response test takes this effect into account.

The intention with this listing of uncertainties and circumstances to the prerequisites for EED-calculations is to emphasize the importance of a detailed follow up of the performance of the energy wells and the heat pump throughout the whole operating period. If one or more of the prerequisites making the basis for the EED-calculation deviates, this will influence the performance of the system either positively or negatively. The only way to discover deviations and following actions to correct the deviations, are good follow up, tuning, optimized and profitable operation.

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10 Discussion and conclusions

The software described in this study provides different levels of details and flexibility (table 3.1). The flexibility is slightly varied, but different tools have different limitations. With flexibility we mean the limitations in what types of systems and components that can be modelled and the possibility to adapt or modify the model after specific requirements. None of the models cover all of the features mentioned in table 3.1, but due to the flexibility of the TRNSYS model Type 281 (TRNSBM) most of the aspects can be addressed using additional models or workarounds. The Model developed in INTERACT project 2016 can also handle most of the aspects.

Among the software presented in table 3.1, the most user-friendly software is considered to be EED, followed by Polysun and IDA ICE. There is in most cases a trade-off between user-friendliness and flexibility. In general, for a higher level of flexibility the software is less user-friendly. However also the more user-friendly software IDA ICE provides some of the most detailed and flexible borehole models, as is the case with IDA ICE borehole models that support modelling of sloping boreholes. On the other hand the source code is not open and the models cannot be modified. Thus the criteria for flexibility are somewhat contractionary.

Geometry

The geometrical limitation for the borehole models differ between the different models (table 3.1). Limiting criteria for selecting software could be the available geometries for borehole storages. Complex borehole geometries or independent charge patterns cannot be handled by all software. The same applies to more complex heat exchanger configurations. Regarding full geometrical freedom in placing boreholes, only TRNSYS Type 281 can handle all the aspects.

Interaction between borehole storage, system and building

When selecting a software for a task one has to decide if the interaction between the borehole storage, the system and the building have to be included in the simulation model. Designing the borehole storage solely based on a known heating and cooling load can be performed with all the software in table 3.1. However for complex systems the building and system design may be a part of the task for the optimization.

For example, if shading devices are mounted on the building they will reduce the cooling demand and thus the heat being put into the ground. Changing the number of boreholes will change the temperature level of the borehole, which in turn will change the COP of the heat pump and thereby the amount of heat removed and put into the storage. For optimization of the complete system, the simulation of the building and the system is required. In order to calculate the performance on long term with reasonable calculation time, it is very convenient if the borehole storage alone can be simulated with a predefined load before simulating the whole system. This feature is labelled "preconditioning" in table 3.1, and is possible in the models from TRNSYS, Polysun and Matlab/Simulink.

Studying the interaction between the borehole storage, the system and the building cannot be performed using EED and requires one of the other softwares that can simulate systems. Only IDA ICE and TRNSYS offer a detailed multi-zone building model.

Validation

The most important criteria when selecting software would be that the model can simulate the current case with reasonable accuracy and be able to size the borehole system for peak load and long term energy extraction (section 2.4). Validation are performed for some of the models towards measurements or analytical calculations (See sections 4.3 and 8.4). However, reliable long term measurements of complex borehole storages are rarely available, thus thorough validation work of the models are limited.

Thermal response test

In most cases, a thermal response test (section 2.2) is applied when larger borehole storages are planned. Some of the software can use the output results from such tests as inputs (table 3.1). If this is not possible for the selected model, a more complex method have to be used to trim the model based on simulating the test by providing the input temperature and flow rate and comparing output temperature while adjusting the parameters in the model.

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