DESIGN AND SIMULATION OF HVAC SYSTEMS WITH BOND GRAPH'S

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ABSTRACT

An approach to conceptual design which combines technical systems theory and design methodology with bond graphs will be presented. Bond graphs are analyzed from a technical systems theory and design methodology viewpoint. The framework for the analysis is van den Kroonenberg's theory of methodological design. This theory provides a general, formal and well-defined model for describing technical systems at various levels of abstraction. In the EBIB-project an Electronic Library of Installations Blocks is developed by Kropman, The University of Twente and The Netherlands Energy Research Foundation ECN. The University of Twente and the Netherlands Energy Research Foundation ECN developed re-usable and sharable model components in the thermodynamic domain for the OLMECO design library. The OLMECO project is an Esprit project for building an Open Library for Models of in mEchatronic Components. The usability and reusability of the model library is demonstrated by a large-scale evaluation experiment, modelling and simulating the heating installation of a hospital in The Netherlands.

DESIGN, AN INTRODUCTION

The design of the building, and its HVAC system and plant, cannot really be dealt with separately since they effect one another. However, the only practical approach to the HVAC system design is to consider discrete parts of the whole as if they were independent. The approach presented here shows how a complex set of interrelated problems can be broken down into smaller and reasonably discrete units.

The general aim of design is "structuring the known data of nature in a way leading to an effective control of matter in relation to mans need and wants", (Van den Kroonenberg 1986). The result of this activity, the product model is frequently called "a design" i.e. a complete description of the object to be manufactured. The development of an integrated process model of design must be considered as a prerequisite for a CAD system.

METHODICAL DESIGN: HIERARCHICAL ABSTRACTION

To develop the required model of design an existing model has been extended: Methodical Design. The design approach developed and taught at the University of Twente in the Netherlands since the late sixties, was compiled and formalized in the seventies into "Methodical Design" e.g. (Van den Kroonenberg 1986) and elaborated by (De Boer 1989). It is based on system theory and also on the ideas of the German school: (Beitz 1985). The Methodical Design approach has been selected for three reasons: (1) it is a problem-oriented approach; (2) it is the only model emphasizing the execution of the process on every level of complexity; (3) it is one of the few models explicitly distinguishing between stages and activities.

The methodical design process can be described on the conceptual level as a chain of activities which starts with an abstract problem and which results in an concrete solution. Four main phases are distinguished: problem definition phase, working principle phase, detail design phase and realisation phase. An important feature in Methodical Design is the distinction of levels of complexity based on abstraction hierarchy. In methodical design a number of levels of design complexity are distinguished: 'system', 'installation', 'multiple machine', 'machine', 'component', 'part' and 'material'. It should be stressed that this distinction in seven levels in methodical design will normally work out alright. In specific cases however it may be necessary to introduce one or more extra levels of abstractions in order to describe the complexity of an object properly e.g. module, assembly and for sub-component. The design phases and complexity levels constitute the main elements of Methodical Design.
One of the corner-stones of the concept is the functional hierarchical structuring based on abstraction. Hierarchical abstraction means the decomposition of information into levels of increasing detail, where each level is used to define the entities in the level above. In this sense each level forms the abstract primitives of the level above.

The design problem as defined here is how to obtain a physical description of a technical system given a high-level (abstract) specification. Theoretically, one can envision a continuous decrease in abstraction ranging from one extreme to the other.

In other words: the design is gradually taking shape. In practice, however, design will never be of a completely top-down nature. In order to determine what the next refinement action will be, a designer has to have knowledge of what the possibilities roughly are. Knowledge about the functions possible realised given specific physical properties of the realisation material is propagated upwards. In the framework presented here, this bottom-up knowledge is represented as sets of generic components (that are known to have several possible physical realisations and representations) at different levels of abstractions. The sets of generic components are located at distinct levels of abstraction, ranging from the system level to the physical level.

Generic components represent behaviours that are known to be physically realisable. They are generic in the sense that each component stands for a range of alternative realisations. This also implies that the generic components still have to be given their actual shape. Relevant technical or physical limitations manifest themselves in the values of a specific set of parameters belonging to the generic components. These parameters are used to get a rough impression of the consequences of certain design choices at the current level of abstraction for the final result. This vision requires a central model description of the installation. This model, named meta-model, consists of all the components of an installation and their individual relations. This approach is related to the approach of Meta-modelling (Gawthrop & Smith 1996). The specification language is based on object representation.

SIMULATION FOR DESIGN

Complex product design teams are increasingly using simulation as a design approach within their design process. Simulation has traditionally been used to design, analyze, and test product functionality. Simulation is going through a revolution relative to actual physical testing and the step-wise refinement, design-analyze-test, basic approach.

Historically, series of tests were performed to validate a product design's performance. These tests were then simulated via derivative simulation for later, small changes to avoid the cost of a physical test in similar circumstances. Simulation techniques, computers, and simulation tools have become quite powerful in many areas. Now, predictive simulation is being performed. Testing is only used to validate the simulation. In certain cases, a test anomaly results in the test itself, rather than the simulation, being questioned as to accuracy. When the design domain reaches the predictive simulation stage, design by simulation, as a design approach, begins to be possible. In this case, simulation tools have advanced to the point where the product's performance characteristics are first determined by simulation, and then reduced to a statement of design. This design by simulation first is unlike the first two types of simulation, where the design is done first and then tested within a simulation.

BOND GRAPH TECHNOLOGY

When inspecting the engineering literature one may have the impression that modelling means transformation from a scenario description to mathematical equations. However, it appears that in fact only limited set of abstract mechanisms is used when making this transition. For example, storage of some quantity occurs in many different circumstances, but maps to a singly type of physical process. This generic set of physical mechanisms defines an abstract level between the component description and the mathematical model. However, this type of causal knowledge is usually left implicit and as a consequence many attempts to automate the modelling process are based on ad hoc mathematical descriptions for each device for every type of problem. One exception to this rule of implicitness is found in the bond-graph literature, (Top and Akkermans 1994). Here, the concise graphical form of the graph with its well defined semantics (Paynter 1961), (Karnopp et. al. 1990), (Breedveld 1984) has made it possible to explicitly represent the mechanisms that were tacitly used in electrical, mechanical, thermodynamical and other domains. This has significantly contributed to the communication of these models and the explicitness of underlying modelling assumptions, as is shown by the rapidly growing number of applications. Also, the bond graph paradigm apparently fits well into the computational approach to engineering, since it has provoked a suite of computer based modelling systems (Top 1993).

To perform model-based reasoning about physical systems we need a knowledge representation that expresses the concepts of the physics involved. It must also define a formal language to formulate these concepts such that it allows a computational approach (Top, Akkermans 1992). Bond graph technology is a technique which can be used by theoretical model building for physical systems. Bond graphs describes the energetic and dynamic behaviour of physical systems in a concise manner (the "bond" indicates energy exchange links between elements of the physical models: the name is from an analogy with the chemical bond). The corresponding mathematical representation of the dynamic system (sets of differential and algebraic equations or the equivalent block diagrams) can be very easily generated from the bond graph.

These mechanisms can be considered as elementary, abstract process that interactively determine the behaviour of a system. They actually represent generalised physical laws. These processes will be subdived into five basic types:

* **Storage processes** accumulate and release extensive quantities. They are represented by the generalised capacitor (C) and the generalised inertia (I). For example, an I-process in the mechanical domain refers to storage of kinetic energy. It mathematically means that Newton's second law is applied.
* **Dissipative processes** convert energy irreversibly into heat inside the system (RS), or, if the system is considered to be isothermal, heat is lost into the environment (R). The latter generalises Ohm's law.

* **Sources and sinks** (Se,Sf) allow interactions between the system and its environment. In doing so they directly impose effort or flow at some point in the system.
* **Conversion processes** The generalised transformer (TF) transforms effort energy into flow energy or vice versa. Slightly more exotic, but essential, is the gyrator (GY). It typically links observable between different domains.
* **Distribution processes** Individual efforts and flows can be influenced by several of the above processes simultaneously. Flows may be distributed through the system and efforts may be interrelated. However, distribution is restricted by the principles of continuity and conservation. The bond graph method expresses these principles in a very concise and consistent way as junctions in a network of energy paths, viz., the common effort junction (0) and the common flow junction (1).

ENGINEERING MODEL LIBRARIES

The Methodical Design approach depends on the availability of a collection of submodels, and it provides the organizational frame work required for structuring and maintaining such a collection. Model libraries can be used to share and reuse knowledge that is not part of an abstract theory (such as physics) but still generic across different applications. A model library is structured along two dimensions. First, there is a part of hierarchy that is defined by the decomposition of functional components. Every functional component knows about one or more decompositions to its immediate sub-components and about the super-components it can be a part of. Second, models are ordered in a taxonomy based on invariant properties. More detailed models (that is, models based on more detailed assumptions) can inherit general properties form less detailed ones. This framework is used in practice as a basis for organizing the library to be developed in the project. A complete model - i.e. a model for a particular device within a certain task environment - is composed by selecting a library component from each level, while keeping the references to possible alternatives. The information that can be retrieved from the library in terms of the three levels is (Top, Akkermans 1993);

* **Component level.** This level describes the hierarchical decomposition of the model in terms of functional components and is domain dependent. For each component the energetic interface and a component label is defined. The ports in this interface are specified with regard to their domain and type (energetic, input signal or output signal). The interconnections between components are defined by undirected energy bonds or directed signals.
* **Process level.** This level describes the bond graph - no more and no less. Its external ports refer to the ports of the associated component model. At the bond graph level power directions and domains are known for all bonds. Causal directions however are not represented as a part of the model, because they do not add information: the are inherent to the bond graph. Note that the original, un simplified bond graph contains all information available at this level and must be stored as such. A condensed bond graph can always be expanded unambiguously into a full bond graph.
* **Mathematical level.** This level provides the relations that are different than the ones that would have been derived under the assumption of linearity. Thus, no relations need to be specified for bond-graph junctions, since they are always linear. The relations for sources on the other hand always have to be specified, unless they consist of a single parameter. The relations are given in accusal form, referring to individual elements in the associated bond graph.

EBIB

Creating mathematical models is time consuming when one has start from scratch for every new application. However, many similar components will occur frequently, so their models can be expected to be corresponding. In the EBIB; Dynamic Model Components for a Heating Systems Library Project. Kropman B.V., The University of Twente and the Netherlands Energy Research Foundation ECN worked together to study the possibilities for building a library of model components. A simple central heating system is described in terms of a functional components model and a bond-graph model. The EBIB-project provides an initial set of library model components which is expected to be adequate for the typical HVAC configurations handled by Kropman B.V.

A library of model components is developed in the EBIB project in order to support model-based design and diagnosis of systems for central heating and hot-water supply. With these models the expected behaviour of designed installations can be studied. In that way, it is possible to check the proposed system behaviour against the given requirements and to generate alternatives.

OLMECO

The University of Twente and the Netherlands Energy Research Foundation ECN developed re-usable and sharable model components in the thermodynamic domain for the OLMECO design library. The OLMECO project is an Esprit project for building an Open Library for Models of in mEchatronic Components. The core of the OLMECO software is a conventional (OO/relational) database for storage and retrieval of mechatronic model fragments; we will give an impression of its structure by considering the most important parts of the Conceptual Schema of the database (see Top, Breunese et.al. 1994), for some examples of its use see also (Top, Breunese et.al. 1995).

The OLMECO conceptual schema has been represented with the object-oriented modelling technique, called OMT, of (Rumbaugh et.al. 1991). The basic structure of the OLMECO library follows the differentiation between ontological aspects, as discussed in the previous section. It is noteworthy that there are three different points, where the user can make separate modelling choices. Systems can be decomposed in different ways, functions of which device components are the carrier can be realized by different physical processes, and physical processes can be specified by different mathematical constraint expressions. Similar suggestions for structuring the modelling process not only come from AI, but are also proposed in the engineering literature (de Vries et.al. 1993), (de Vries et.al. 1994).

The proposed generic structure of the OLMECO library has two important advantages:

1. It separates different groups of modelling decisions, thus giving handles for user support and facilitating a piecemeal approach to engineering model construction, and

2. It provides a breakdown of stored models into parts that have a generic nature, thus enhancing reusability and shareability of library models.

Component Taxonomy

A component taxonomy can be stored in the library by means of the kind-of generalization/specialization relationship in Figure 1. This information can be used by the modeller to quickly access the components he or she wants to use. Figure 2 shows the taxonomy of the thermodynamic library. For the components on the right, decompositions and/or process descriptions are available.

The keywords provide another way to index the library. The idea is that these keywords provide the link between specific component names used in the thermodynamic domain and the generic model components stored in the library. The keywords wall and radiator are examples of this. Both heat flow through the metal of a radiator and heat flow from one side of a wall to the other can be modelled with the thermal barrier component.

For large libraries like the OLMECO library (Breunese et.al. 1996), the component taxonomy also becomes very large. This shows that the taxonomy browsers in the library software must be able to cope with large amounts of components and be able to present parts of this taxonomy in a clear way to the user.

A MODELLING AND SIMULATION EXPERIMENT: THE SCHIELAND HOSPITAL HEATINGSYSTEM

To test the usefulness of the OLMECO library, UT and ECN have contributed to the library with thermodynamical models for components like pipes, valves, splitters and mixers, heaters and heat exchangers.

The modelling experiment for the thermodynamic domain consisted of the modelling and simulation of a large central heating system. This section describes this experiment. During the experiment there were two questions in mind:
the practical usability and the reusability of the thermodynamic library.

The subject of the experiment is the modelling and simulation of the existing heating system of the Schieland Hospital, a general hospital in Schiedam, The Netherlands. The schematic drawing of the system that has been modelled is given in Figure 3. In fig. 5 the Screendump of the bond graph editor CAMAS is given and in fig. 6 the thermodynamic part of the bondgraph representation. The system consists of two coupled subsystems: one subsystem around the heater (heater group, abbreviated hg) and one around the radiator (radiator group or rg). The model contains a large number of components from the thermodynamic library and is mathematically complex because of the structure of the system and the fact that both hydraulic and thermodynamic behaviour are modelled. The model of the system has been incrementally constructed in three stages. First the component model has been made, then the physical model and finally the mathematical model. For a detailed description of this we refer to (Top, Borst et.al. 1995). In this section, only a global description will be given.

Component model

The first step in the modelling of the system is to construct the component model by using the thermodynamic library. This has resulted in the model shown in Figure 4. Names of the instantiated components are printed in bold face. All components, except for the controller, are instantiations of generic components from the library. The name of the library component a model component is based upon, is printed in italics at the top left corner of a component.

Three components need further explanation. Because the heater group pump is considered to be a top level component and not a subcomponent of the heater, the heater has a decomponent (i.e. not based on a library component) that supplies to the controlled mixing valve the information whether it is open, closed or partially open. The radiator has a modelled as a pipe with external conduction. In such a 'pipe', the water that runs through it can lose its heat through the wall of the pipe to the environment, in this case the room. The abstraction from radiator to pipe with external conduction has been specified in the library by means of the radiator keyword attached to the pipe with external conduction component (see Figure 2). Furthermore, to increase the accuracy of the model, the radiator has been decomposed into four segments.

Physical Process Model

For the construction of the physical models, the physical processes that have to be modelled in order to obtain an accurate model must be chosen. Table 1 gives an overview.
The importance of this table is that for each row in this table,

there must be a process description in the library that models all the physical processes that are marked. For example, the process description used to model the pipes in the system can be found. For all rows in the table similar model fragments form the library could be used.

Mathematical Model

For most of the processes in the physical model there is only one mathematical relation applicable. Only for the hydraulic resistances in the pipes, splitters and mixers and the thermal resistance of the heater and radiator important choices had to be made. For the hydraulic resistances for instance, the relations for pipes with a rough surface and turbulent flow the mathematical relations for the Reynolds number of (VDI 1977) were used. All relations used in the model were available from the library.

Determination of Model Parameters

Before simulation, the values of the parameters in the model need to be determined. The VDI Wärme Atlas (VDI 1977), an atlas of relations for heating systems written by the society of German engineers, gives the relations for the determination of the model parameters. They depend of different types of data about the system. Characteristic values of materials, like specific mass, specific heat capacity and heat transfer coefficients can be found in engineering handbooks on materials. Some of the parameters required for the Schieland hospital model are:

Pipes, splitters, (controlled) mixers, radiator and pumps (16 in total): specific mass, specific heat capacity and viscosity of water; volume of the water and initially stored heat; length, diameter and water flow area of the component; roughness of the material the component is made of.
Pipes with bends (4 pipes, 22 bends: number and sharpness of the bends.
Radiator (4 segments): heat transfer at 90/70/20°C.
Controlled mixing valve (1): minimum and maximum volume flows at a pressure of 105 P5Pa.
Splitters (2) and mixers (1): water flow areas and angeles between in and out flows.
Pumps (2): supplied pressure.
Heat sources (2): supplied heat flow or temperature.

The relatively large amount of time it took to compute the parameters for the modelled system suggests that the next step to improve the support of engineers would be to help them with this process. This requires an extension of the OLMECO library to make it possible to specify the parameter relations from the atlas, characteristic values of materials, measurement data and geometry.

SIMULATION RESULTS

Two simulations have been carried out, a simulation of the hydraulic behaviour of the system when the position of the valve changes, see figure 5, and secondly, a simulation of the thermodynamic behaviour when the heating system is switched on. The prediction of the thermodynamic behaviour can be found in (Top 1995).

SUMMARY

The first conclusion that can be drawn from this experiment is that the OLMECO library provides good assistance in the modelling process. This is reflected in amount of the time it took to construct a large and complex model like the one described in this section and the quality of the result. Modelling the system took a small amount of time due to the fact that the library contained most of the required model fragments and to the fact that the model could be specified incrementally, starting with the component model which is very similar to the schematic drawing of the system. The other steps to processes and mathematics were guided very well by the suggestions the library contained for possible process descriptions and mathematical relations. The quality of the model fragments in the library contributes positively to the quality of the instantiated model.

The second conclusion is that the thermodynamic library is diverse enough to support compositional modelling of real world systems. The modelled system is considered to be large and contains a variety of components typical for the whole domain.

The experiment carried out suggests an extension of the OLMECO library. This can be concluded from the time it took to determine the model parameters. Therefore we suggest an extension of the library in which it is possible to specify the way the parameters of a model component can be determined, like it is described in engineering handbooks. The parameter relations in the library could then be used for automatic parameter computation from geometric data supplied by the user. The present way to store parameter relations in the library is not sufficient because the parameter relations that have to be used can be depend on geometric aspects of the component that is modelled. For instance, cylindrical and non-cylindrical pipes are modelled by the same component and the same equation for the hydraulic resistance, but the way to determine the parameters is different. This at least suggests a fourth view on the domain of physical modelling, that of geometry, and implies an additional ontology projection. The same hold for the material properties of components. Methodical design is proposed as a theoretical basis for automated design of physical-systems. Design is viewed as a problem solving activity in which functional reasoning is central. In order to allow a stepwise approach in which each design decision has well - defined implications, three different ontological levels have been distinguished for designing energetic - process;

* Functional components
* Physical Processes
* Mathematical description

These levels provide a structured framework for model libraries, which in addition could contain separate entries for structural and behaviourial observation data for validation purposes. Bond graphs are shown to provide a core model representation from which a variety of models may be derived to verify the design process. The benefits of evolutionary Methodical Design for process design improvement strongly depend on the availability of generic models stored in structured libraries. We believe that model libraries based on the approach presented here will significantly advance the state of automated process design.

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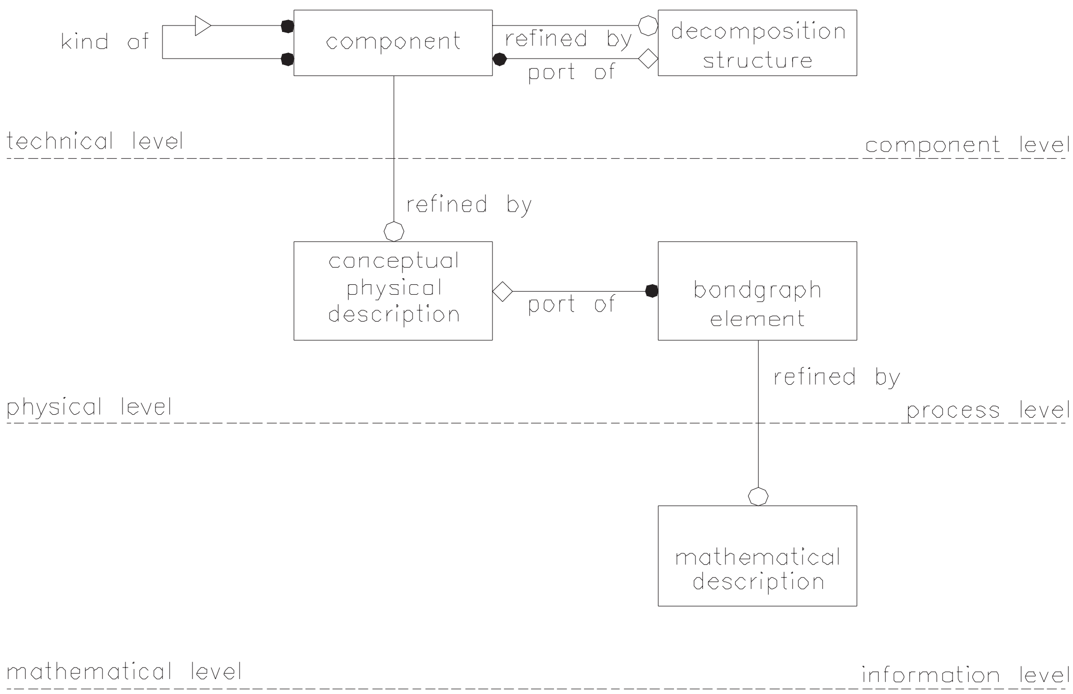

Fig.1 The general conceptual schema of the OLMECO library.

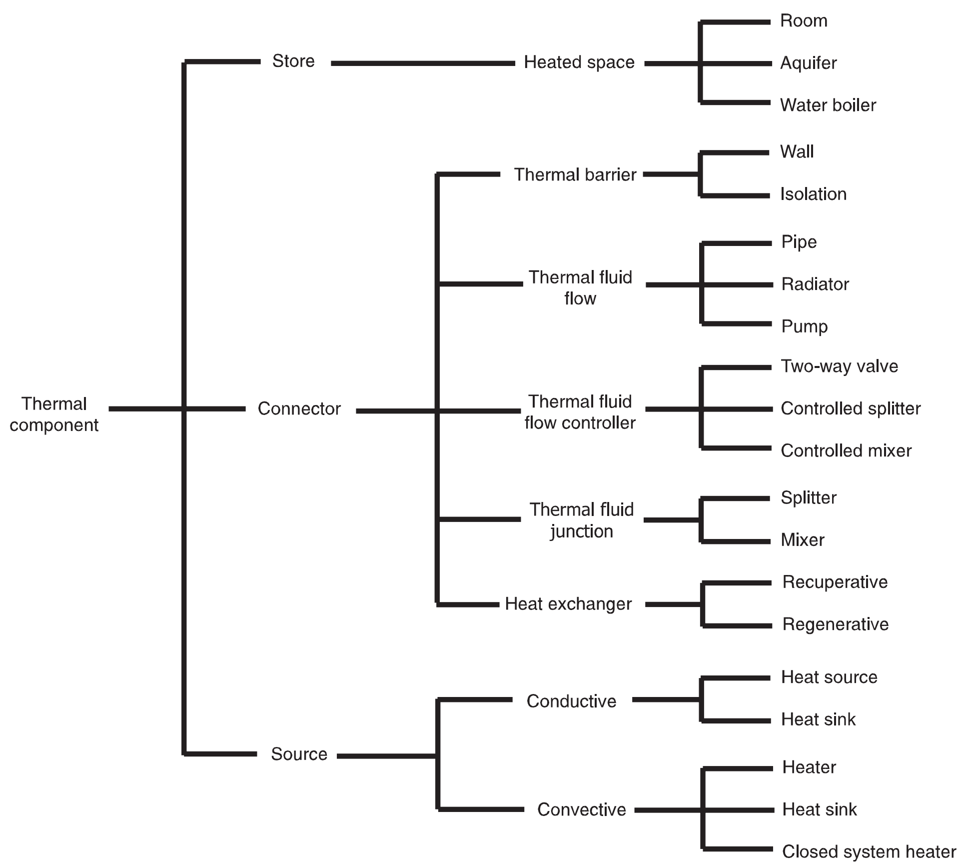

Fig.2 Taxonomy of thermal components.

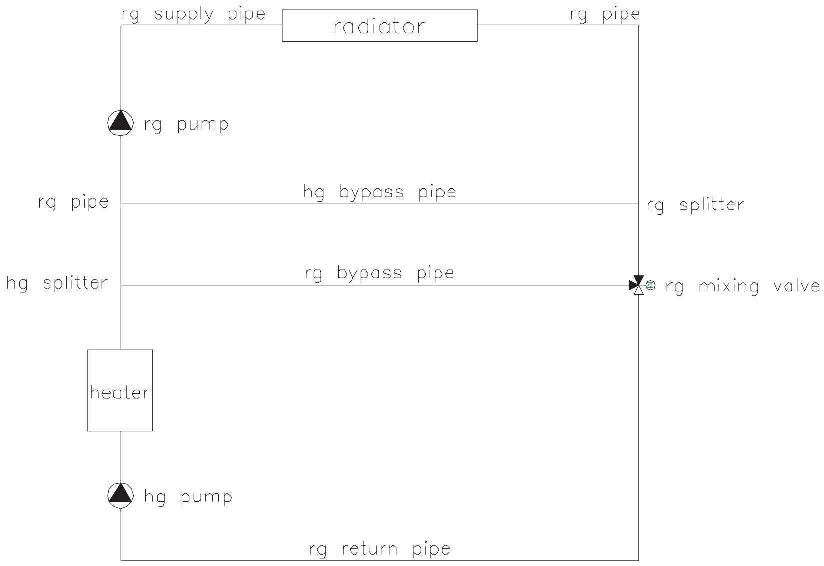

Fig.3 The simplified Schieland hospital heating system.

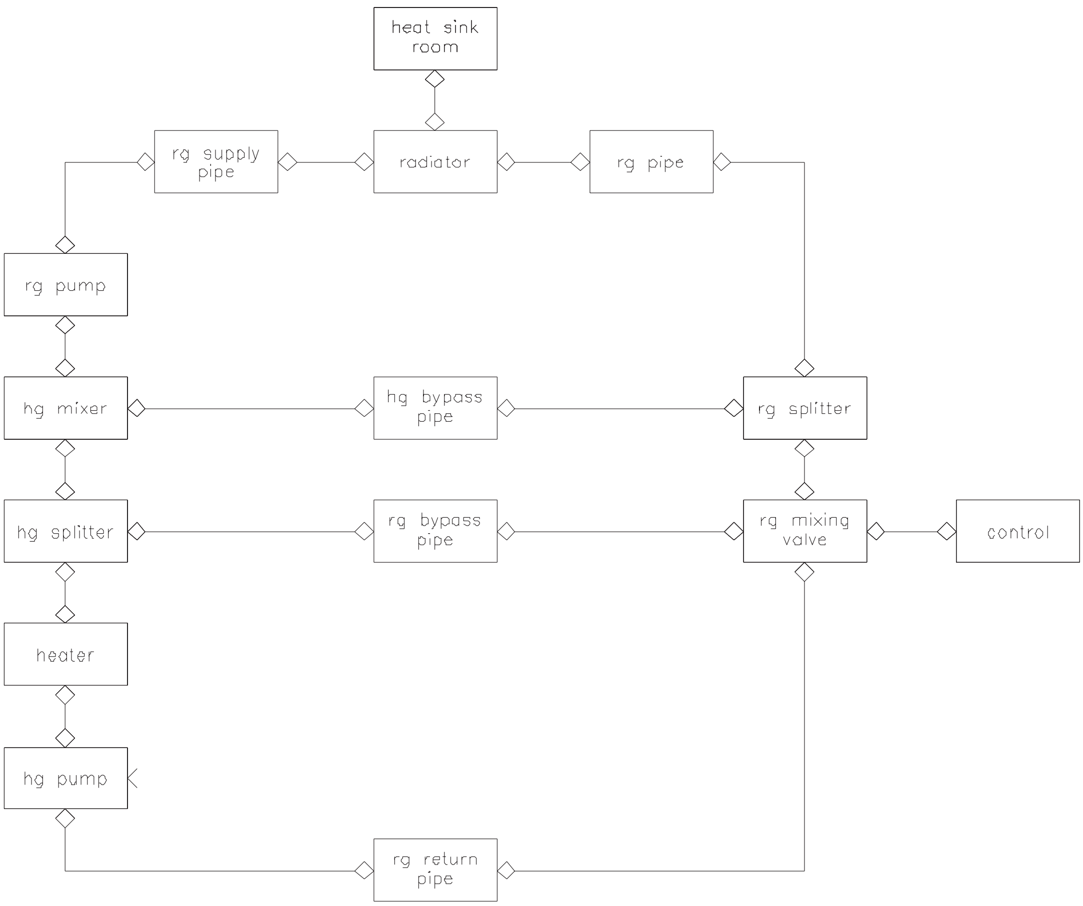

Fig.4 Component model of the Schieland hospital heating system

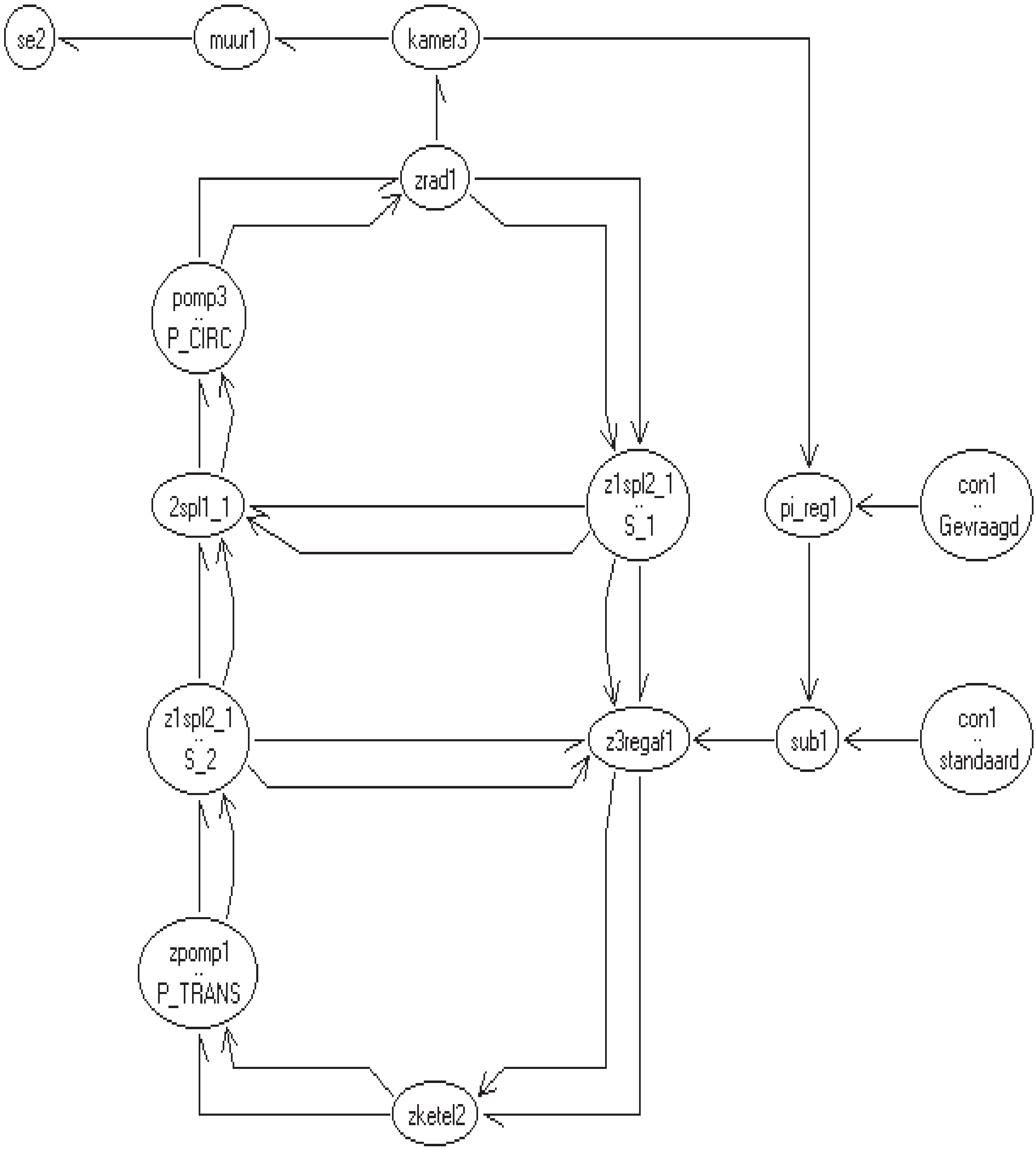

Fig.5 Scren dump of the bondgraph editor CAMAS for the model of the Schieland hospital heating system.

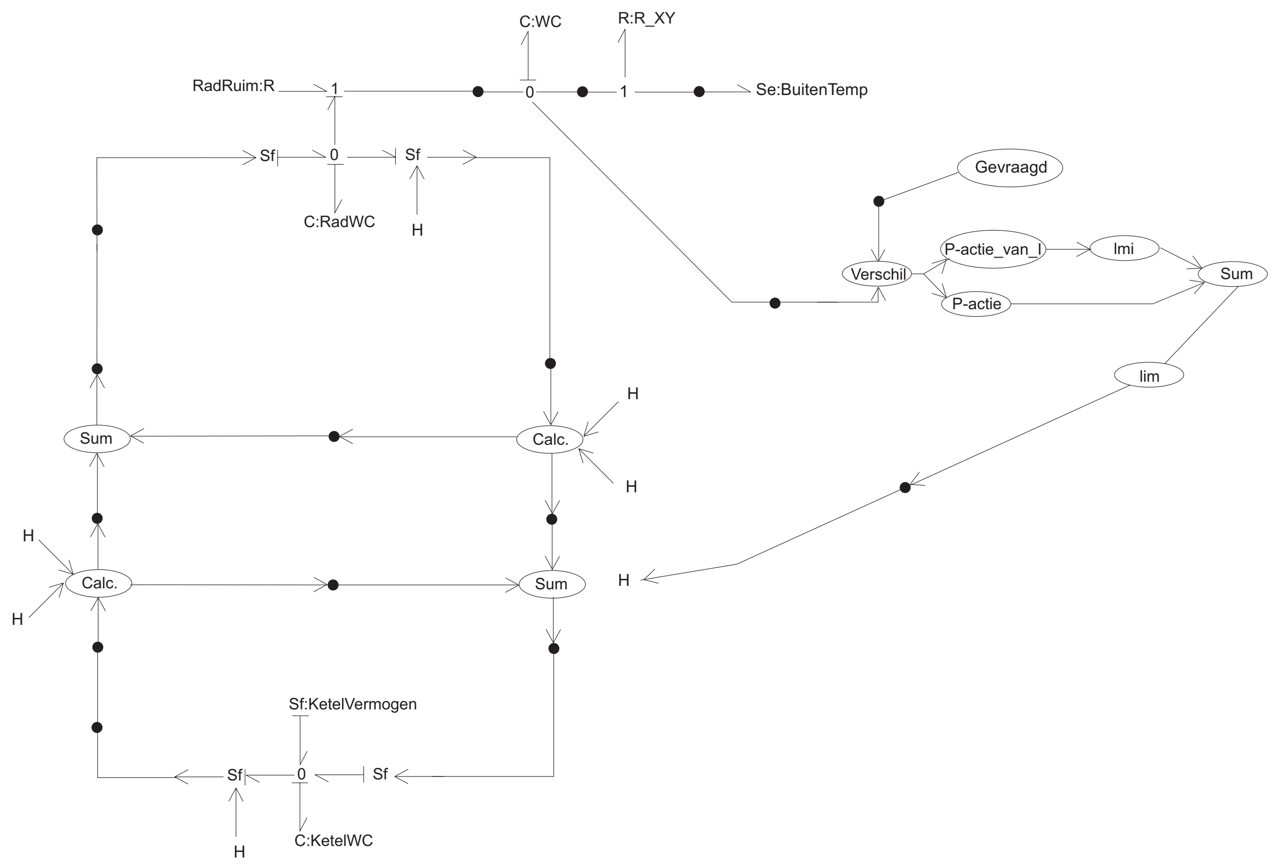

Fig. 6 The thermodynamic part of the bondgraph of the model of the Schieland hospital heating system.