Boderc: Model-based design of high-tech systems

A collaborative research project for multi-disciplinary design analysis of high-tech systems.

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Chapter 7

Heat modeling in copiers

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7.1 Introduction

Heat is one of those system aspects that is influenced by multiple engineering disciplines. Because it is difficult to communicate design decisions between disciplines, as discussed briefly in Chapter 1, it is difficult to find the optimal design with respect to these system aspects. One way in which the design process can be improved is to use model-based design. Using models, it becomes possible for the disciplines to communicate insights and make trade-offs in an early stage of development, before design changes become prohibitively expensive.

In this chapter, an example of a heat model is shown that can be used for these purposes. First, the relevance of heat in a printer is explained by linking heat to the fundamental goal of a printer: making high-quality prints. This gives insight in the questions to be answered by modeling. Then some modeling techniques for heat are discussed, and a case is studied in which a heat model is constructed.

7.1.1 Relation to key drivers

Heat can lead to many potential design issues. To streamline the design process, priorities need to be assigned to potential issues. To assign priorities, heat should be linked to the key-drivers (see Chapter 3) for a printer. Thus, the effect of heat flow on the customer perception of the printer can be investigated.

A customer can observe the following effects of the heat house holding:

- The amount of energy needed to establish the temperatures required by the printing process determines the amount of time needed for the printer to warm up in preparing for the first print (Time-to-first-print).
- The temperatures of paper and toner at the moment they meet in the fuse pinch, strongly define how much and how deep the melted toner penetrates into the paper fibres and strongly influences the printing quality (one of the key drivers for an Océ printer). As such, this effect is also taken into account in the printing accuracy model of Chapter 9.

- The amount of heat lost during printing affects the speed at which the printer can print. Throughput is also a key driver, as shown in Chapter 3.

- The average energy consumption of the printer over a normal ‘office’ day is part of the running costs for a printer. Most power consumed by a printer is used to maintain heat flows. Also, power usage has been restricted by environmental agencies.

- The peak energy consumption of the printer partially determines how easy it is to install a printer at a customer site. This is nation dependent: in Europe, a regular socket can supply roughly twice the power a regular socket in the USA or Asia can supply.

These issues serve to illustrate the importance of proper heat management for a printer.

### 7.1.2 Temperature constraints within a printer

Printing is a physical process in which a toner image is produced using electro-magnetic forces, which is then transferred to the paper and fused. Fusing is performed by applying heat and pressure to the toner and paper, such that the toner melts and enters the paper. In Figure 7.1, the main parts of the VarioPrinter 2090 are shown: the pre-heater (VVW) that rises the temperature of the paper before fusing; the imaging unit that generates the toner image; the Toner TransFer belt (TTF) that transports the toner from the imaging unit to the fuse pinch, and the fuse pinch where toner is fused on the paper. While intended to increase the life-time of the imaging unit, the TTF also separates the warm and cold areas. The printing process is described further in Chapter 1.

Most of the energy consumed by a printer is used to establish and maintain these temperature levels, and many key drivers are influenced by the resulting flow of heat. As an example, the key driver *Time to first print* will be taken. This time must be as short as possible, and is directly determined by the speed with which the temperature levels can rise to acceptable levels in a printer. Whether the temperatures are ‘acceptable’ is determined by the following constraints:

- If the fuse temperature is too low, the toner will not penetrate the paper properly. It will form a layer on top of the paper which is easily removed through bending and scratching.

- If the fuse temperature is too high, toner will be too fluid and may be smudged by mechanical contacts.
When forming the toner image, toner must not stick to any surfaces except to the paper where it is intended. This means that the temperature of those surfaces must stay well below the fusing temperature to prevent accidental fusing and soiling of these surfaces.

Toner and paper dust will invariably contaminate parts of the rubber belt with which toner is fused to the paper. The surface is cleaned using a special drum that is sufficiently warmer than the surface being cleaned. In this manner toner sticks to the cleaning drum and traps the paper dust.

Temperature constraints apply to the imaging unit to prevent damage.

A printer will usually not produce prints continuously. Often, the printer will enter stand-by mode when no jobs are being processed. During stand-by the temperature levels must drop as little as possible to minimize the time to first print. If the printer is not used for a longer period, it should enter sleep-mode and finally the power should be switched off, to meet environmental requirements. During these phases, the temperatures must also drop as little as possible. The cool rate is determined by the construction of the printer. This leads to a number of trade-offs:

- The heat capacity of the printer should be large during printing and stand-by, and small during warm-up.
• To minimize the heat lost during stand-by, the printer should be thermally insulated. However, while heat is transferred from hot areas to cool areas during cooling, it must be ensured by the design that the maximum temperatures for the cool areas are not exceeded.

• The rollers should have high thermal resistance to minimize heat loss, but should have low thermal resistance to equalize heat distribution e.g. over the rubber TTF belt.

Model-based design can be used to meet the constraints and find the optimal trade-offs.

### 7.1.3 Heat modeling goals

If a model is to be used in model-based design, it must give answers to specific questions. For example, an important printer property is the time required to warm the printer when it has cooled after being shut-down for a long period. Environmental agencies specify the maximum warm-up time. It is one of the main figures of merit for a printer. An interesting question is if a current design will have an acceptable warm-up time. A model can be used to give the answer.

Various strategies can be used to heat the printer, by distributing the available power in different ways to the various parts of the printer. Using a prototype, different methods of heating the printer can be tested empirically. However, only one such experiments can be performed per day, due to the need for the well insulated printer to cool before the experiment can be repeated to test an alternative strategy. Thus development time can be gained if a suitable model is available to determine which strategy is optimal, and how the temperatures react when a printer starts printing after warm-up.

Another reason to use modeling is that it gives insight in how the current design can be optimized. For example, a model gives insight into which are the dominant heat losses, so that efforts to reduce loss can be focused on the areas with the most impact.

### 7.2 Heat modeling techniques

Heat is a property of matter. Each chunk of matter stores heat, and achieves a certain temperature depending on the amount of heat stored. This behavior can be modeled similarly to the storage of electrical charge. For example, a capacitor stores electrical charge, resulting in an electrical potential over the capacitor. Another analogy that can be used is the storing of fluid in a container, which results in a pressure at the bottom of the container. Here, the electrical analogy will be used most often. Just like the storage of heat can be modeled similar to the modeling of charge in a capacitor, the transportation of heat can be modeled similar to electrical charge, which is transported through resistors. As with electrical resistors, heat resistors are assumed to not store heat.

Heat can be transported through conduction by the mechanical construction, convected through the flow of air inside the printer, and radiated by hot surfaces. Also,
Heat is transported by the movement of objects (e.g., sheets or the TTF belt) through a printer. Heat conduction and convection are linear resistance effects, although the resistance may depend on system parameters e.g., rotation speed. Heat radiation is a non-linear resistance effect, following the Stefan-Boltzmann radiation law [16].

Heat is inserted into the printer as electrical power. Most of the electrical energy consumed by the printer is turned into heat. A printer has several heaters which generate heat from electrical energy. They can be modeled as perfect heat sources.

The heaters, the mechanical contacts through which heat is conducted, and the air flows inside the printer that are responsible for convection, are often controllable e.g., through actuators. As such the heat resistances must be modeled as variables, and their control is to be included in the model.

Using heat sources, heat capacitors and heat resistances, thermodynamical models can be made. Two main methods exist: finite-element modeling where mechanical parts are modeled in detail, and lumped models where the thermal properties of parts are lumped together.

7.2.1 Finite Elements Models

In Finite Elements Models (FEM), the assumption is that real matter consists of an infinite number of infinitely small heat capacitances interconnected by heat resistors, and that reality can be closely approximated using a fine-grained grid of partial differential equations. This can be done in one, two or three dimensions, depending on the modeling needs.

FEMs are well suited to determine the temperature distribution of an object or system of objects, and to predict the actual thermal characteristics of these objects. However, when studying a complete printer, this modeling technique is too detailed: to keep model complexity acceptable, only the average temperatures of objects and average object characteristics can be taken into account. Océ uses FEMs to optimize the shape of individual components in a printer that are related to heat distribution, such as, for instance, a pre-heater.

7.2.2 Lumped heat modeling using bond graphs

In a lumped model of a printer, the model is simplified such that only the most interesting temperatures are explicitly included. The assumption is then that there are a number of parts that directly determine this temperature, and that these can be lumped together into a single heat capacitance. The interaction between areas of different temperatures are modeled using heat resistors between the lumped capacitances. If necessary, the model can be refined by adding heat capacitances to better model reality.

Bond graphs can be used to construct heat flow models in two ways [68]. As bond graphs represent energy flow regardless of the type of energy, they can be used to model interactions between the thermal domain and other domains, for instance mechanical or electrical. The convention for a bond graph is that the product of the two variables
associated with a bond must equal power. For example, in the mechanical domain the
variables are Force and Speed; in the electrical domain they are Voltage and Current.
For the thermal domain, these variables should be Temperature and Entropy flow. This
choice allows direct interaction with other domains. However, with this choice the
capacitances and resistances of the thermal domain will be non-linear, making them
complicated to model.

It is also possible to model heat flow using linear elements with Pseudo bond
graphs. Here, the two bond variables are Temperature and Heat flow. As heat flow is
a form of energy flow, this choice of variables means that the product of the two bond
variables does not equal power, hence these models are called pseudo bond graphs.
Direct connections between domains are not allowed in pseudo bond graphs. However,
as the transformation of energy between domains is not directly relevant for a printer,
pseudo bond graphs are well suited to make lumped thermal models of a printer.

7.3 Modeling heat flow with pseudo bond graphs

A heat flow model using pseudo bond graphs usually consists of the following ele-
ments:

- Heat sources. These inject heat into the model, and represent e.g. electrical heat-
ing elements.
- Heat capacitances. These stores heat, and represents physical mass.
- Heat resistances. These forms the connection between two heat capacitances.
  The amount of heat that flows depends on the temperature difference between
  the two masses and the resistance, which is dependent on e.g. material and con-
struction.

An storage element analogous to the electrical inductor is not needed for heat models,
as there is no physical effect that would require it for accurate modeling.

Using these elements, and the usual 0 and 1 junctions, a model can be constructed
(see [20]). In Figure 7.2 a bondgraph model of a simple heater is shown. The bond-
graph model is equivalent to the iconic model shown left in Figure 7.2. the simulation
tool 20SIM supports both types of models.

7.4 A case study

7.4.1 Modeling goal

The goal of the model described in this case study is to be able to predict the time
in which the printer is ready for printing, and what happens during the first minutes
of printing when all temperatures settle to the new situation. A printer is ready for
printing when it has been warmed to such an extent that the fuse temperature stays within acceptable bounds if printing starts at that time. Thus the following phenomena should be modeled:

- The heating of the parts that determine the fuse temperature. These are mainly the pre-heater (VVW) and the rubber TTF belt.
- The heating of paper sheets in the pre-heater.
- The exchange of heat between the TTF and sheets during fusing.
- The main elements that extract heat out of the TTF (various rollers and other losses to the environment).

### 7.4.2 Modeling strategy

The following simplifications have been made:

- The printer is modeled in one dimension: two or three dimensional distributions have largely been ignored. However, it is taken into account that the TTF does not have a uniform temperature: just before the heater, the TTF surface temperature is the lowest, just behind the heater it is at its highest. From the base temperature of the TTF and the amount of heat put into it, the temperatures at other locations are calculated.
- When interacting with the TTF, sheets are not modeled individually but as a continuous heat flow.

Using these simplifications, it is expected that the fuse temperature can be predicted with sufficient accuracy.
Based on these assumptions, a model can be made of the printer heat flow. The tool 20SIM was used to construct the model. The heart of the model is shown in Figure 7.3. The model is based on the temperatures of the TTF-core and the pre-heater (‘VVW_plate’). From these locations, connections are made to:

- The heaters that insert heat to the system: HoD_straler and heater_VVW.
- The sensors T_VVW_sensor and T_sensor.
- The various rollers that are in contact with the TTF.
- The paper that extracts heat from the pre-heater and exchanges heat with the TTF.
- The environment to which heat is leaked.
The rotational speed of the printer is an input to the model. This is because the heat flow through a rolling contact is dependent on the roll speed. Through experiments, the following relationship was found:

\[ R = \frac{c}{\sqrt{v}} \]

where \( R \) is the heat resistance; \( v \) is the roll speed, and \( c \) is a constant depending on material characteristics and construction details, that is determined experimentally. In 20SIM, this formula is easily inserted in the heat resistances.

Many of the contacts are dependent on the mode of the printer. For example, to prevent unnecessary heat loss, rollers like the imaging unit are only connected to the TTF during printing, not during warm-up. This effect is modeled by giving the heat resistance between TTF and imaging unit a second input, besides the rotation speed, that determines whether there is contact or not.

The contact between TTF and paper was hard to model. The paper is first heated in the pre-heater, before the contact with the TTF is established. To model the heating, a resettable integrator is used that is reset at the start of each page, using the Start Of Page (SOP) signal. If a normal capacitance / resistor combination is used, unwanted interactions between VVW and TTF would result. Thus the paper / TTF interaction is modeled by a power source that is driven by the final paper temperature (Tpap).

The model shown in Figure 7.3 is not self-contained. There is an interface to a higher level that determines the amount of power inserted into the printer, the input variables printer status and printer speed. Due to this structure, the model can be used for simulation but also for validation. To validate the model, earlier measurements can be inserted into the model using the variables, as shown in Figure 7.4. During simulation, a controller can be implemented that uses the temperatures generated by the model to control the virtual printer.

### 7.4.4 Identification and validation

The model includes various parameters that need to be specified to reflect the design choices made. Some of these parameters can be calculated analytically, but most of them need to be identified from measurements.

Obtaining measurements for identification is not a trivial exercise. To be useful, measurements need to have the following characteristics:

- The thermal conditions of printer and environment need to be known accurately.
- The state of the printer needs to be known accurately. For this a log needs to be maintained of the changes to the prototype.
- The relation between measurements and simulation results needs to be as clear and simple as possible.
- Only one parameter should be changed during the experiment, preferably using a simple profile, e.g. a step or sinus profile. This enables the modeller to see if the model structure is sufficiently accurate.

- The behavior and configuration of the control software inside the prototype must be known exactly.

- The state of mechanical switches in the printer must be known at all times. These are determined by the software controlling the prototype, which will frequently change.

As thermal experiments have a long duration, care must be taken that the printer is not disturbed during the experiment. Also, the measurements must be continuous during the experiment. Measuring should not stop when the printer is shut down.


7.4.5 Managing multiple experiments

When performing measurements on a prototype, it is important to be able to compare different measurements with each other. A model is always a simplification of reality. Thus, there will always be differences between model and reality. By comparing modeled and measured temperatures for many experiments, it can be evaluated if the ‘typical’ case is correctly modeled.

An advantage is taken from the separation of the control model from the physical model. The state of switchable contacts and the power injected into the printer is measured, and are injected into the physical model. Then, the outputs of the model are compared with the measured outputs, and parameters are tuned to get a proper response.

A scripting language is needed to do this effectively. It must be possible to quickly modify C and R values, evaluate the models quickly in a batch process, and present the results in a way that gives overview. At the time of writing, 20SIM did not offer a scripting language. Therefore, C-code was generated automatically from the detailed model, and this C-model was evaluated using the Matlab scripting language in Simulink. Figure 7.5 shows how the 20SIM model was encapsulated in Simulink. Figure 7.6 shows the top-level Simulink model.

This set-up allows the evaluation of the model with measurements taken in different conditions, to see how robust the model is. If the evaluation shows that the model is not accurate in different conditions than those used for identification, the model is an oversimplification. Missing elements can then be added to the model. Also, this set-up gives the possibility to implement automatic tuning of model parameters. However, in the current implementation this is not present yet. This is a topic for future research.

7.5 Conclusions

As shown in this chapter, heat flows can be modeled using 20SIM. However, identification of the model parameters from experiments takes considerable effort.
At the time of writing this chapter, the model was still under development. Thus no definite results can be given. However, the expectation is that using this model, the following can be achieved:

- Optimization of the warm-up procedure.
- Testing and tuning the control algorithms for temperature.
- Optimization of critical parts of the heat flow design.

It is expected that it will be straightforward to re-use this model for other printers of comparable design. Also, the modeling strategy described in this chapter can be used to construct heat models for any printer. It is also expected that by using the model described in this chapter, the design time needed to optimize the heating of a new printer can be substantially reduced.
Bibliography


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