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Heat flow modeling in copiers

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MSc Report

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Summary

This project, in combination with Océ-Technologies BV, deals with the modeling of heat flows in copiers. The intermediate is important for the power consumption as well as the printing quality of the copier and therefore the intermediate is taken as a case study for this research. Two models for the description of dynamic thermal systems influenced by mechanical movement have been developed in this paper: an intuitive method using elements that move in space (MEM-model) and a method that uses static elements based on the configuration of the system (SEM-model). The connection of the models with boundary conditions and the link to physical parameters are elaborated.

The warm-up or ‘slow’ dynamics of the intermediate show the same results for both models. The stationary temperature gradients or ‘fast’ dynamics are also the same for both models and are similar to the results of the Matlab model. Because of the modularity of the SEM-model, this model is chosen to serve as building blocks for future use at Océ. The SEM-model is validated with measurement data of a copier; in a dynamic experiment with duration of around one hour the model could predict the temperature values over the intermediate within a range of 5 degrees Celsius for 98% of the time. The average absolute error was less than 2 degrees Celsius.

Some recommendations are done for future use: (1) validation must be repeated when new applications are modeled, (2) the estimation algorithm of the end of element temperature can probably be improved to increase simulation speed and (3) the introduced building blocks can be included in a 20sim thermal library.

Samenvatting

In samenwerking met Océ-Technologies BV is dit project opgezet met als doel het modelleren van warmtestromen in printers. Het intermediate speelt een belangrijke rol in de warmtestromen binnen en de kwaliteit van de printer en om deze reden is het intermediate gekozen als case studie voor dit onderzoek. Twee modellen om dynamisch, thermisch gedrag als gevolg van mechanische beweging te beschrijven zijn ontwikkeld: een intuïtieve methode die gebruik maakt van bewegende elementen in de ruimte (MEM-model) en een methode die statische elementen gebruikt gebaseerd op de configuratie van het systeem (SEM-model). De verbinding van het model met randvoorwaarden en de link met fysische parameters zijn uitgewerkt.

Het langzame opstartgedrag van de intermediate geeft dezelfde resultaten voor beide modellen. Snelle, stationaire temperatuurverschillen zijn ook hetzelfde voor beide modellen en zijn vergelijkbaar met de resultaten van het bestaande Matlab model. Vooral vanwege de modulariteit van het SEM-model is dit model gekozen om dienst te doen als bouwstenen voor toekomstig gebruik bij Océ. Het SEM-model is gevalideerd op meetdata van de printer; in een dynamisch experiment met een lengte van ongeveer één uur kon het model de temperatuurwaarden op het intermediate voorspellen binnen 5 graden Celsius voor 98% van de tijd. De absolute gemiddelde fout was kleiner dan 2 graden Celsius.

Enkele aanbevelingen kunnen gedaan worden voor toekomstig gebruik: (1) validatie moet herhaald worden als nieuwe toepassingen worden gemodelleerd, (2) het algoritme dat de temperatuur aan het einde van een element inschat kan waarschijnlijk worden verbeterd om de simulatiesnelheid te verhogen en (3) de ontworpen bouwstenen kunnen in een 20sim library opgenomen worden.

Preface

In front of you is the report that will finish my time as a student at the University of Twente. After almost six years my study in Electrical Engineering with a master in Control Engineering has come to an end. The past eight months I have worked with pleasure on my Master thesis dealing with the modeling of heat flows in copiers. I had a great time working together with Océ, on one of the largest R&D departments settled in The Netherlands.

First of all I would like to thank my supervisors, from the university Jan Broenink and from Océ René Waarsing and Peter van den Bosch, for giving support, comments and advice. Furthermore I would like to thank Peter Breedveld for some interesting discussions about the bond-graph modeling part of my assignment.

There are more people I would like to mention, for example my lab mates at the university that made drinking coffee much more fun. For the necessary distraction during evenings and weekends I need to thank my housemates and my team mates of football club v.v. Drienerlo. And, last but not least, I would like to thank my parents for giving me support all those years.

Bram Krijnen

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1 Introduction

Heat is one of the aspects in a copier that strongly influences the key specifications of the copier. For example, the time-to-first-print is highly dependent on the temperatures required for printing and thus the amount of time needed to warm-up the copier (Heemels and Muller, 2006). Other key drivers are the printing quality and speed: both largely determined, or restricted, by the temperature of the intermediate and paper when they meet in the fuse pinch. Nowadays power consumption starts to play more and more an important role in copier design and since a considerable amount of the input power is converted into heat, a thermal model can be valuable in the development process of copiers.

The goal of this project is to create a white box model to predict the dynamic thermal behavior of the copier correctly. Dynamic, thermal behavior in this case is defined as temperature values and power flows as a function of time with varying input conditions. The generated model should be modular, such that it can be reused in the design of new copiers.

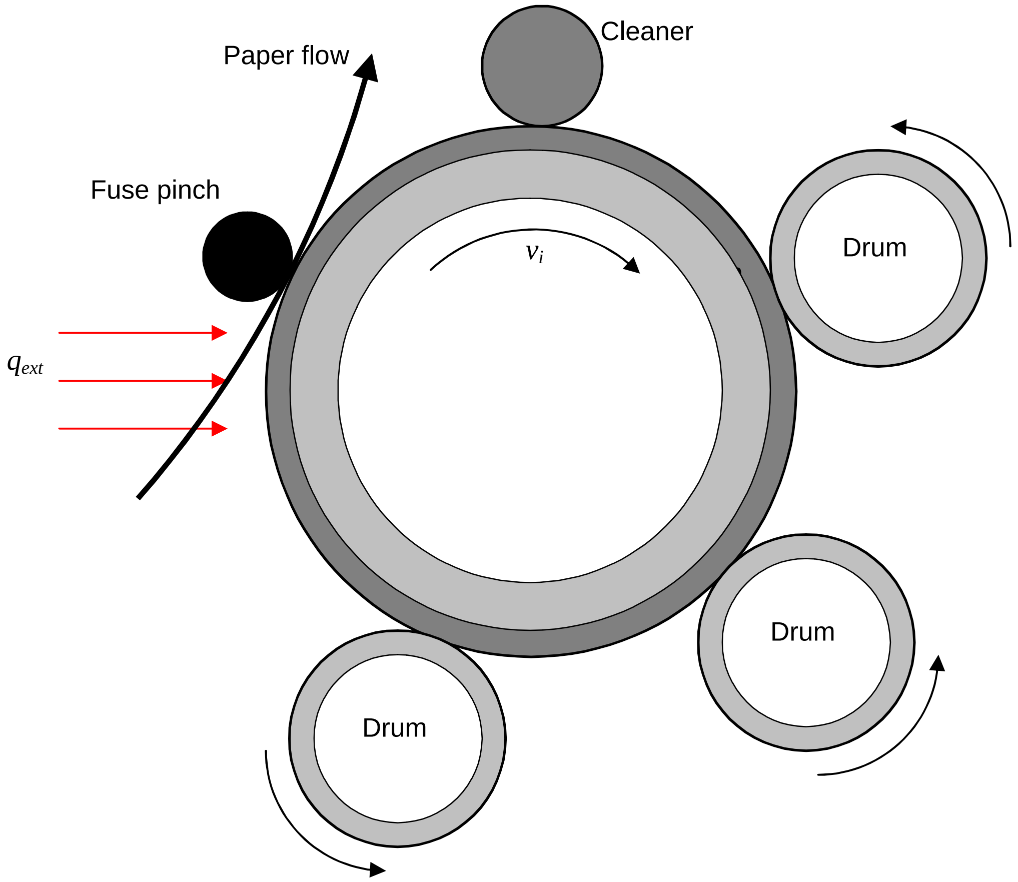

Figure 1 – Overview of the system

The intermediate is important for the power consumption as well as the printing quality of the copier and therefore the intermediate is taken as a case study for this research. In essence, the intermediate is situated as shown in Figure 1. One or more drums drop the toner on the rotating intermediate. The intermediate is heated and the melted toner is fused to the paper at the fuse pinch. A model will be developed to predict temperature distribution over, for example, the top layer of the intermediate and power flows towards and from the connected drums and cleaners. It is assumed that mechanical movement only provides heat transportation; mechanical energy will not be converted to thermal energy or vice versa.

At the Control Engineering group of the University of Twente, bond-graph modeling is the common method to model dynamic behavior of systems in all physical domains. Thermal systems can be modeled in two ways, namely using power-conjugate bond graphs and pseudo bond graphs (Breedveld and Amerongen, 1996; Karnopp *et al.*, 2000). From a physical system theory point of view, power-conjugate bond graphs are the well-known way to use bond graphs; the effort variable temperature T and the flow variable entropy flow $\dot{S}$ form a pair whose product is power. A disadvantage of using power-conjugate thermal bond graphs is the non-linearity in the thermal capacity due to an asymptotic approximation of the absolute zero temperature. In the coupling with other domains it is however often necessary to use power-conjugate bond graphs. In pseudo bond graphs linear constitutive relations can be used for capacities and resistances. The effort variable is still the temperature T, but the flow variable is the power that flows through the bonds, i.e. heat flow q. Special attention should be paid to describe the interconnection between the thermal domain and other physical domains. Since the only interesting interaction with another domain in our system is the linear velocity of the intermediate v_i, there is little reason to work with power-conjugate bond graphs. All bond-graph drawings and related equations in this paper are therefore in the pseudo bond-graph domain.

As a starting point of the project an existing thermal model in Matlab for static situations is analyzed in section 2. In sections 3 and 4 two different options to model a system like in Figure 1 are introduced. Then the interconnection between the models and the boundary conditions is discussed in section 5, together with the link to parameters in section 6. Afterwards both models will be verified in section 7 and a model comparison is made in section 8. Validation on actual measurement results is done in section 9 and finally in section 10 some conclusions and recommendations are done.

2 The starting point

A way to look at the system is to divide the intermediate in elements that successively encounter different boundary conditions. Imagine sitting on top of the intermediate and following the contour of the intermediate, moving through the system. Boundary conditions are dependent on the configuration of the copier, but known. In the general case, the intermediate will consecutively be heated, fused, cleaned and reprinted by a number of drums. When assumed that the system after some time will get in stationary situation *and* the heat flow in longitudinal direction due to conduction is negligible compared to the heat flow imposed by the mechanical movement of the intermediate, it is sufficient to describe only one element with variable length and varying boundary conditions. The simulation will continue until the set of differential equations, given the boundary conditions and initial values, reaches the stationary solution. Figure 2 illustrates the basic concept behind this approach. For example Matlab is a tool that is perfectly suitable to support this way of modeling. A model using this concept is currently available at Océ and serves as a starting point for the generation of the dynamic models introduced in this paper.

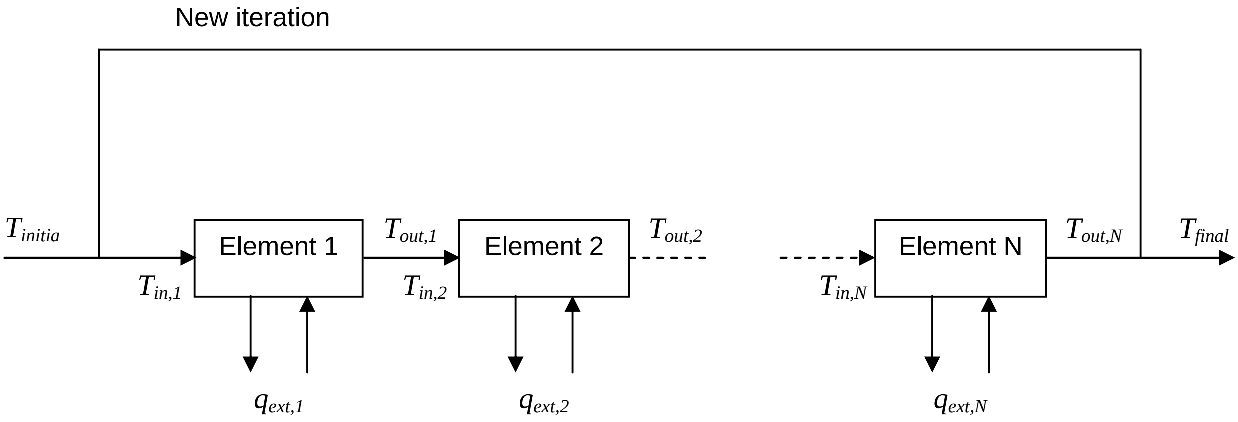

Figure 2 – Iterating towards a solution

It is hard to say the system is power continuous and dynamic, since at a certain moment in time it is not possible to give an actual value for all temperatures in the intermediate. So, when interested in the dynamic behavior of the copier one cannot use the model presented here. Two solutions can be thought of: (1) including the dimension time in a correct way into the available model and (2) creating a completely new model, with as a starting point the idea of a dynamic and power-continuous system. In this paper option (2) is chosen and the generation of a dynamic model using bond graphs will be presented.

3 Moving Element Method

The first type of the dynamic model to describe the behavior of the copier uses an intuitive approach. The intermediate is simply divided into a number of equal-length elements and the boundary conditions are switched between these elements. What actually happens is that the elements move through the system over the contour of the intermediate. In the rest of this paper this model will be referred to as the Moving Element Method (MEM-) model. Because the complete contour of the intermediate is covered with elements, all power flows to and from the intermediate, caused by different types of boundary conditions, are described in continuous time. The number of elements that together will represent the intermediate is a parameter that can be changed to increase or decrease precision and coherently simulation time.

To show the practical applicability of this idea, a simple bond-graph model of the intermediate consisting of four intermediate elements and two external contacts (boundary conditions) is presented in Figure 3. The two contacts, which are simple external temperature sources connected to the intermediate via thermal resistances Rext1 and Rext2, are encircled. The switching zero-junction x0 provides time scheduling on the connection between external contacts and the four heat capacities representing the intermediate. In the switching zero-junction the configuration of the system is used to allocate the initial positions of the external contacts with respect to the intermediate.

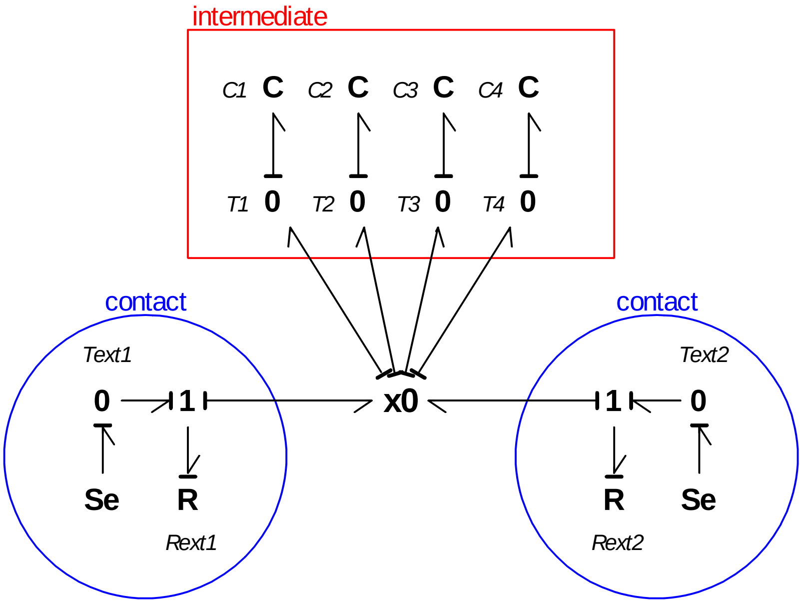

Figure 3 – Basic MEM-model with four intermediate elements and two contacts

In the intermediate of the copier a temperature gradient exists in the longitudinal direction, in the transversal direction a temperature gradient does exist as well. When the intermediate gets into contact with, for example, a temperature source, the top of the intermediate will heat up or cool down to the temperature of the external contact. Dependent on the contact time, the heat will flow deeper from or into the intermediate. This means that when this ‘fast’ dynamics of the contacts is important to the overall power balance of the system, more layers should be modeled. Figure 4 gives an overview of how the intermediate is divided into elements and layers to describe all relevant dynamics.

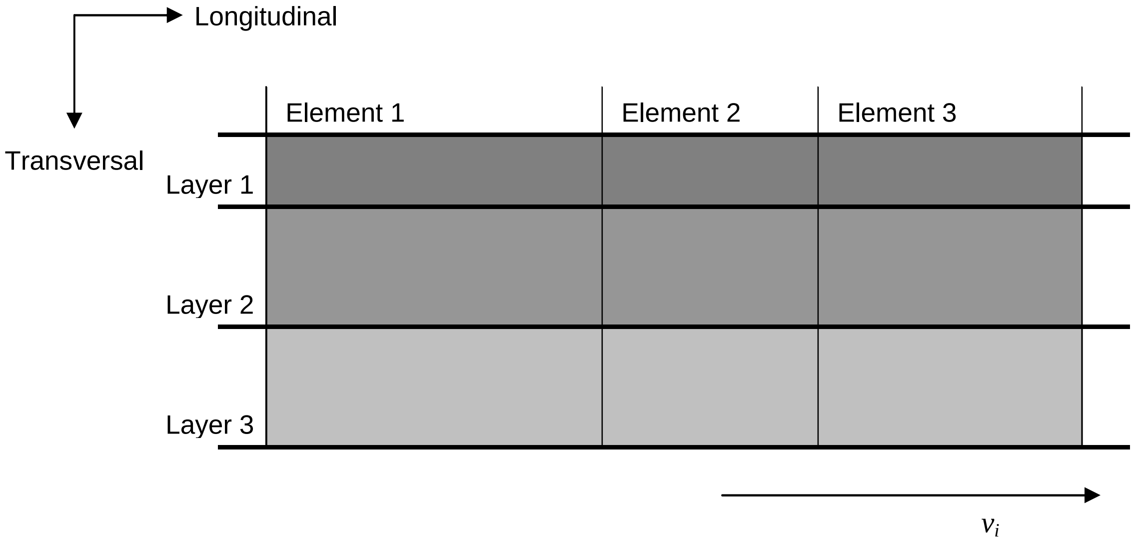

Figure 4 – Longitudinal elements and transversal layers for discretization of the system

To ease scaling and visualisation of the model, it is possible to combine the capacities of a certain layer inside the intermediate in a multiport C element. In this case, in longitudinal direction the intermediate consists of four elements and therefore the multiport C element is four dimensional. The resulting bond-graph model is shown in Figure 5. The model consists of an intermediate with two layers between which conduction can take place. Again the intermediate is in contact with two external contacts.

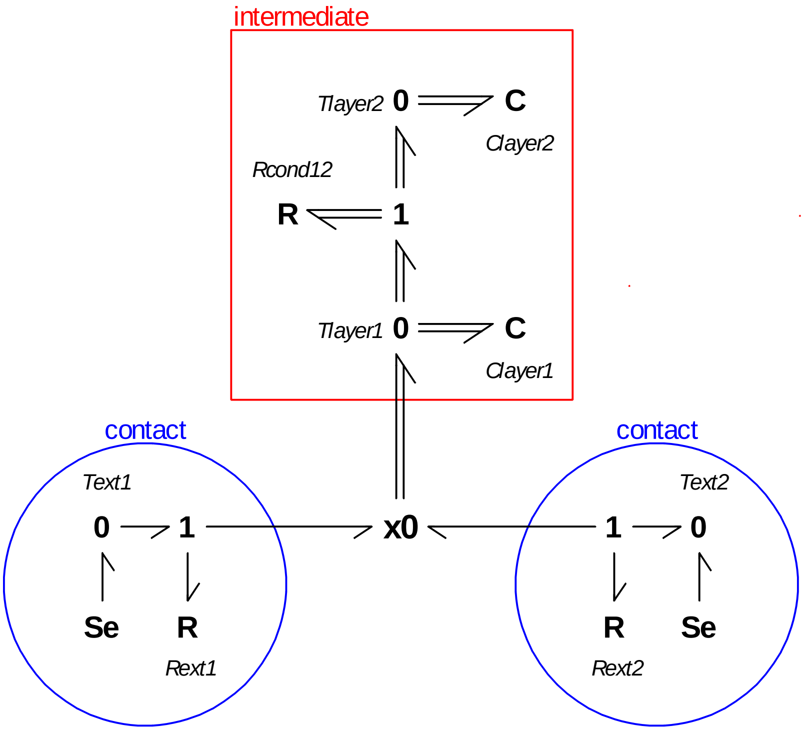

Figure 5 – Extended multiport MEM-model with multiple layers

Conduction can take place not only in the transversal direction of the intermediate; also in longitudinal direction conduction occurs. However, in the longitudinal direction another heat transfer mechanism plays a role: convection, heat transfer imposed by the velocity of the intermediate. The Péclet number is used to prove that conduction is negligible compared to convection. The Péclet number is dependent on element length, intermediate velocity and material properties like density, specific heat and conductivity (Kaviany, 2002).

4 Static Element Method

In contrast to the MEM-model described before, it is possible to look at the system in a different way; the intermediate is again divided into a certain number of elements, but now the elements are defined by the length and position of the boundary conditions. Furthermore the elements have a static position in the copier and heat flows through the elements; this model will be called the Static Element Method (SEM-) model. The concept of static elements is explained using Figure 6.

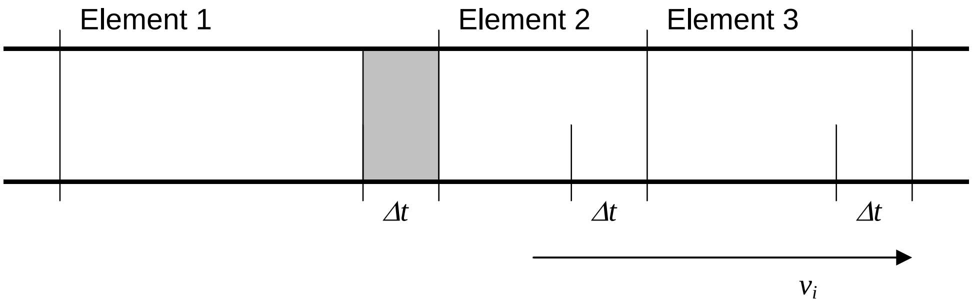

Figure 6 – Schematic concept of the SEM-model

Figure 6 shows three elements with different length. The stored energy in element 1 is calculated using the temperature of the element T_1, the volume of the element V_1 and the material properties c_p and ρ.

$$Q_1 = c_p \cdot \rho \cdot V_1 \cdot T_1 = c_p \cdot \rho \cdot l_1 \cdot w \cdot d \cdot T_1 \; [J]$$

In this equation the width w and depth d of the elements are considered constant for the complete intermediate, only the length l of the elements is variable. The transfer of energy from one element to the next due to convection in a time span of Δt can be visualised by the grey area in Figure 6. The power flow q as a result of the movement of the intermediate follows directly from the relation $v_i = {}^{l_1}\!/_{\Delta t}$.

$$q_{12} = \frac{dQ_{1\to 2}(T_1, v_i)}{dt} = c_p \cdot \rho \cdot v_i \cdot w \cdot d \cdot T_1 \; \left[{}^{J}\!/_{s}\right]$$

A bond-graph convection element is introduced to impose this flow, represented by a modulated resistor. The heat flow is completely determined by the velocity v_i and the temperature T_1 of the 'source' element. Three successive lumps using the new convection element are shown in Figure 7.

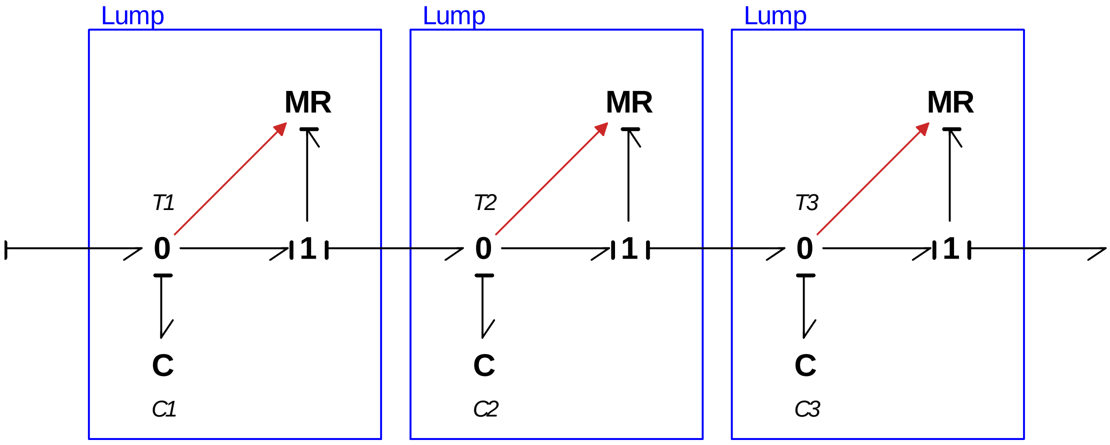

Figure 7 – The bond-graph convection element

In the graph the temperature signals are represented by red signal arrows, while the velocity of the intermediate is defined as a global variable to reduce the number of connections that must be made to get the model to work. Like in the MEM-model, it is necessary to equip the model with extra material layers. It is possible to simply duplicate the structure from Figure 7 and interconnect it with resistances; a more aesthetic solution is the use of a multiport model, shown in Figure 8.

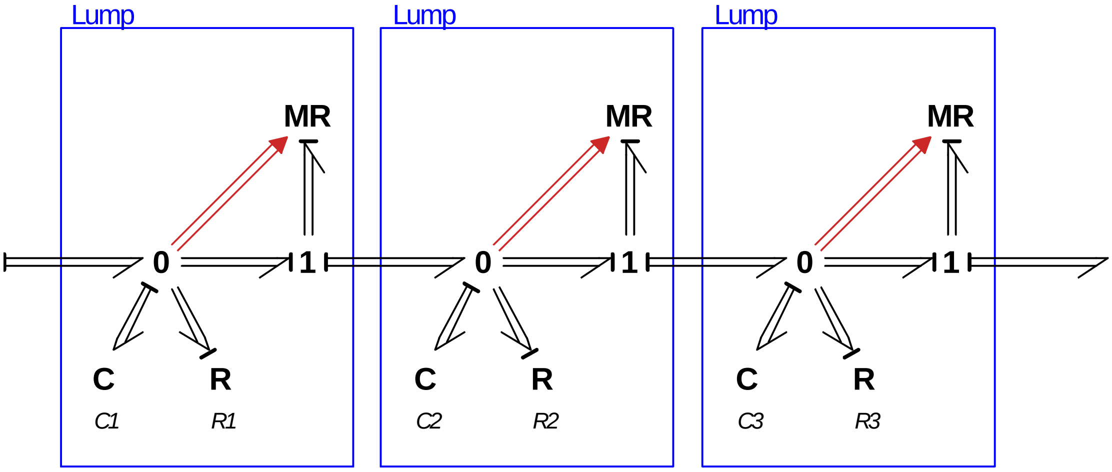

Figure 8 – The multiport model of the convection element

The resistor representing conduction between the different layers of the model can be directly connected to the temperature zero-junctions of the lumps. The implementation however is not that straightforward, since it should introduce a power flow between the elements of the multiport heat capacity due to the temperature gradient in the zero-junction of the lump. Consider that the flow direction is into the multiport resistor and that the conduction between the layers may never cause a loss of stored heat inside the multiport capacity. These conditions lead to a singular matrix to describe power flow between the layers.

$$\vec{q}_1 = \begin{bmatrix} \frac{1}{R_{1,12}} & -\frac{1}{R_{1,12}} & 0 & 0 & 0 & \dots \\ -\frac{1}{R_{1,12}} & \frac{1}{R_{1,12}}+\frac{1}{R_{1,23}} & -\frac{1}{R_{1,23}} & 0 & 0 & \dots \\ 0 & -\frac{1}{R_{1,23}} & \frac{1}{R_{1,23}}+\frac{1}{R_{1,34}} & -\frac{1}{R_{1,34}} & 0 & \dots \\ \dots & \dots & \dots & \dots & \dots & \dots \end{bmatrix} \vec{T}_1$$

This matrix must be interpreted as follows: the heat flow out of the top layer capacity $C_{1,1}$ is dependent on the temperature difference between $C_{1,1}$ and $C_{1,2}$ and the in-between resistance $R_{1,12}$. ‘Normally’ this $R_{1,2}$ would be connected with a one-junction between the zero-junctions $T_{1,1}$ and $T_{1,2}$, but it cannot be implemented in multiport bond graphs in that way.

The temperatures visualised by the multiport zero-junction represent a vector of temperatures averaged in longitudinal direction. Since the copier usually consists of a limited number of different boundary conditions, a low number of elements should be sufficient to model the dynamic behavior of the system. The problem encountered is that the introduced convection element takes the average temperature of the element to calculate the power flow towards the next element. The temperature at the end of the element can be considerably different from the average temperature of the element. This is caused by the redistribution of energy due to conduction and by the inflow or outflow of energy due to the boundary conditions. A solution is to estimate the temperatures at the end of the element based on the knowledge of the element.

A dynamic description of the element can be given by the state space equations:

$$\dot{T}_1 = AT_1 + Bq_{ext}$$

The A-matrix does have the same structure as the conduction matrix given before, since this conduction is the only ‘internal’ behavior of an element:

$$A = \begin{bmatrix} -\frac{1}{R_{1,12}C_{1,1}} & \frac{1}{R_{1,12}C_{1,1}} & 0 & 0 & \ldots \\ \frac{1}{R_{1,12}C_{1,2}} & -\frac{1}{R_{1,12}C_{1,2}} - \frac{1}{R_{1,23}C_{1,2}} & \frac{1}{R_{1,23}C_{1,2}} & 0 & \ldots \\ 0 & \frac{1}{R_{1,23}C_{1,3}} & -\frac{1}{R_{1,23}C_{1,3}} - \frac{1}{R_{1,34}C_{3}} & \frac{1}{R_{1,34}C_{1,3}} & \ldots \\ \ldots. & \ldots & \ldots & \ldots & \ldots \end{bmatrix},$$

$$B = \begin{bmatrix} \frac{1}{C_{1,1}} & 0 & \ldots \\ 0 & \frac{1}{C_{1,2}} & \ldots \\ \ldots & \ldots & \ldots \\ & & \end{bmatrix}$$

When it is assumed that the internal dynamics in an element described by the state space equations is slow compared to the ‘traveling time’ through an element due to convection, the temperature increase or decrease from the beginning of the element to the end will be approximately linear; in this case the average temperature of the element is halfway the element. An error will be introduced by this assumption and if this error appears to be large in an element, it is necessary to split the element into multiple shorter elements.

If the average temperature of the element is seen as the initial temperature to use in the state space equations, the temperature at the end of the element is the solution of the state space equations after a time interval determined by the speed of the intermediate and half the length of the element, $\Delta t = {}^{2v_i}\!/_{l_1}$. The exact solution is:

$$\vec{T}_2(\Delta t) = e^{A\cdot\Delta t}\vec{T}_1 + A^{-1}\left(e^{A\cdot\Delta t} - I\right)B\vec{q}_{ext}$$

The calculation of this exact solution causes numerical problems because the A-matrix is singular, this implies that the inverse of the A-matrix does not exist *and* the calculation of $e^{A\cdot\Delta t}$ is instable. An approximation of the temperature at the end of the element can be made by discretization of the state space description:

$$\vec{T}_{k+1} = \left(A\vec{T}_k + Bq_{ext}\right)\cdot \Delta t + \vec{T}_k$$

When this calculation is done in one step, it equals the result using the first order approximation of $e^{A\cdot\Delta t}$, being $I + A\cdot\Delta t$. It is also possible to take smaller time steps and iterate to a more accurate solution. Due to instability problems in the calculation of $e^{A\cdot\Delta t}$ (Moler and Van Loan, 2003), a value for the number of iterations needed to obtain an accurate solution cannot be given. More efficient ways to calculate the solution of this set of differential equations is probably possible but not investigated in this project.

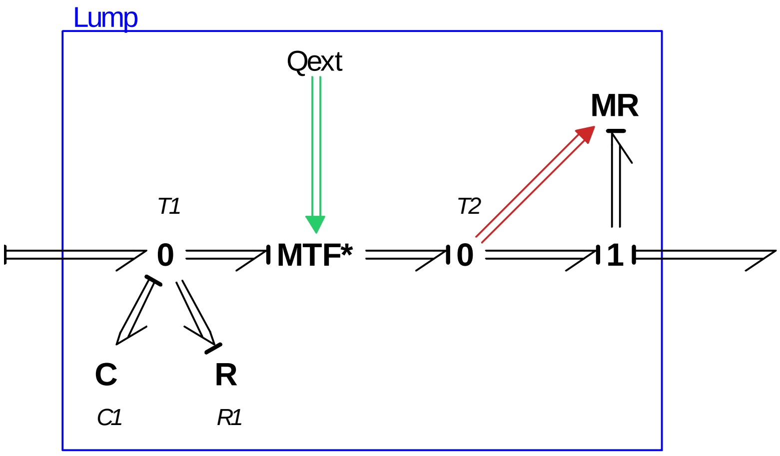

Figure 9 – Lump model with end of element temperature estimation represented as a MTF

The estimation of the temperature at the end of the element does not affect the energy balance of the model, since these temperatures are only used to calculate the magnitude of the power flow from one element to the next. In pseudo bond graphs the only use of the effort variable is the determination of the stored heat in a capacity; it does not affect the power flow since the power flow is completely determined by the flow variable in a bond. Figure 9 uses a modulated transformer MTF* to make an estimation of the temperature at the end of the element. The inflow or outflow of power due to the boundary conditions, necessary in the calculation of the end of element temperature, is represented by the signal flow Qext into the MTF*. Note that the transformation ratio is only applied to the temperatures and not to the power flows; to preserve power continuity the incoming flow should by definition be equal to the outgoing flow. This is a side effect of working in the pseudo bond-graph domain.

5 Modeling the boundary conditions

In the MEM-model the boundary conditions or contacts with the external world are already introduced. The switching zero-junction, Figure 5, keeps track of the boundary conditions and performs time scheduling to connect the external contacts with the correct intermediate element. In case of the SEM-model, the boundary conditions are continuously connected to the same lump, because the elements are static in position, see Figure 10. Here it is assumed that only the top and bottom layer of the intermediate element can be connected with a boundary condition, the rest of the heat flows are explicitly set to zero, depicted with the Sf0 elements.

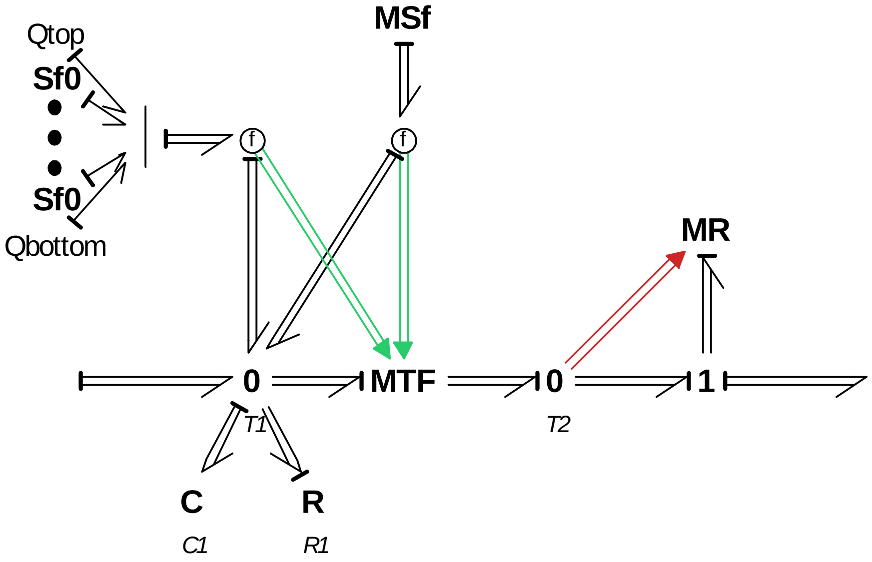

Figure 10 – Lump of the SEM-model with connection to boundary conditions

Here, in the SEM-model another flow source is present. This modulated source of flow, MSf, is introduced to model the inflow of power into an element of the intermediate by radiators. Heat radiators are commonly used at Océ to insert heat at a specific position into the intermediate. In most of these cases it is approximately known in what elements and in what layers a relative amount of the total heat is absorbed. Both the inflow and outflow of power by external contacts and by heat radiators is important to consider in the estimation of the temperatures at the end of the element.

Similar to the way presented in Figure 5, it is possible to connect heat radiators to the various layers of the intermediate in case of the MEM-model, but for every layer where external flows are relevant, a new switching zero-junction needs to be introduced.

Now the connection of boundary conditions to both of the models is discussed, a short description of the various external contacts is given:

- Drums and cleaners are actively cooled elements that are controlled to keep a certain temperature. In case a temperature gradient in the drum or cleaner can be neglected, it is sufficient to simply model the contact as a temperature source Se. When a temperature gradient inside the drum or cleaner is present, this contact can be modeled in the same way as the intermediate (since drums and cleaners are also rotating).
- Rollers and pinches are passive heat capacities. When rollers or pinches are in contact with the intermediate, they will finally reach a static temperature based on the power flow from the intermediate to this element and the loss of energy by radiation into the air or physical contact with ‘cold’ parts of the copier.
- Typically, physical contact with drums, cleaners, rollers or pinches only covers a small part of the surface of the intermediate; the rest will be in contact with air. In the simplest case the environment can be modeled as a static temperature, but in limited volumes it might be necessary to model the environment as a heat capacity.

6 From physical properties towards parameters

To create a model that has any practical applicability, the physical properties of the materials need to be rewritten into parameter values. Basically there are two types of parameters that need to be calculated: heat capacities (1) and thermal resistances. Thermal resistances can be split into resistances caused by conduction (2), radiation (3) and convection (4).

1. Heat capacities can store heat inside the element, based on the specific heat capacity c_p and density ρ of the materials:

$$C = c_p \cdot \rho \cdot l \cdot w \cdot d \;\left[\frac{J}{K}\right]$$

2. Conduction describes heat flow in between the material layers *and* towards the contacts with the various boundary conditions, based on the conductivity k of the material and the area A through which it takes place:

$$R = \frac{l}{k \cdot A} \;\left[\frac{K}{W}\right]$$

Since the conductivity of most gasses is very low, this will not be the dominating resistive effect on the contact between the intermediate and the air. Radiation and convection do play a role in heat transfer towards the air:

3. Radiation is described by the Stefan-Boltzmann law, for a non-perfect blackbody radiator it is given by

$$q_{rad} = \varepsilon \sigma A \left(T^4 - T_\infty^4\right) \;[W]$$

In simple applications it is sufficient to use a linearized version of this fourth order heat loss equation (Incropera and DeWitt, 2002).

$$q_{rad} = h_r \cdot A \cdot (T - T_\infty)\ [W] \text{ with}$$

$$h_r = \varepsilon \cdot \sigma \cdot (T + T_\infty)(T^2 + T_\infty^2)\ \left[\frac{W}{m^2 K}\right]$$

4. Convection is described by a linear relation between power flow and temperature difference:

$$q_{conv} = h_c A(T - T_\infty)\ [W]$$

The determination of h_c, the convection heat transfer coefficient, is difficult for non-generic systems. Based on some assumptions on the characteristics of the air flow, i.e. whether the flow is laminar or turbulent, and characteristics of the intermediate, whether it can be approximated by a flat plate with a characteristic length D_H, a value for h_c can be found using the Nusselt number:

$$h_c(v_i) = \frac{k_{air} \cdot Nu(\mathrm{Re}(v_i), \mathrm{Pr})}{D_H}$$

Since there are several approximations and assumptions that play a role in the determination of the environmental heat loss due to radiation and convection, it is chosen to use experimental data to obtain a parameter value to describe the heat loss towards the environment. Note that the heat loss towards the environment is linear resistive behavior, dependent on the velocity of the intermediate.

$$q(v_i) = h(v_i)A(T - T_\infty) = (h_r + h_c(v_i))A(T - T_\infty)\ [W]$$

7 Model verification

Two modeling techniques, using static and moving elements, have been introduced in this paper so far. Since the project goal is to come up with reliable building blocks that Océ can use in the design trajectory for new copiers, two topics should still be handled. First of all, model verification is done by comparing the simulation results of both the models. The second topic is to validate the model on the basis of measurement data; this can be found in section 9.

A non-existing configuration is created to compare ‘slow’ and ‘fast’ behavior of both models. The distinction between slow and fast dynamics is made since both are present and important in the behavior of the copier. Slow dynamics is encountered during for example the start-up of the copier; it takes time before the copier is able to start printing. In this case a net inflow of power exists. Fast dynamics is encountered during one rotation of the intermediate. In stationary situation there still exist temperature gradients over the intermediate, based on the inflow and outflow of power caused by external contacts. But in this case there is no net inflow or outflow of power: the sum of the power inflow equals the sum of the power outflow.

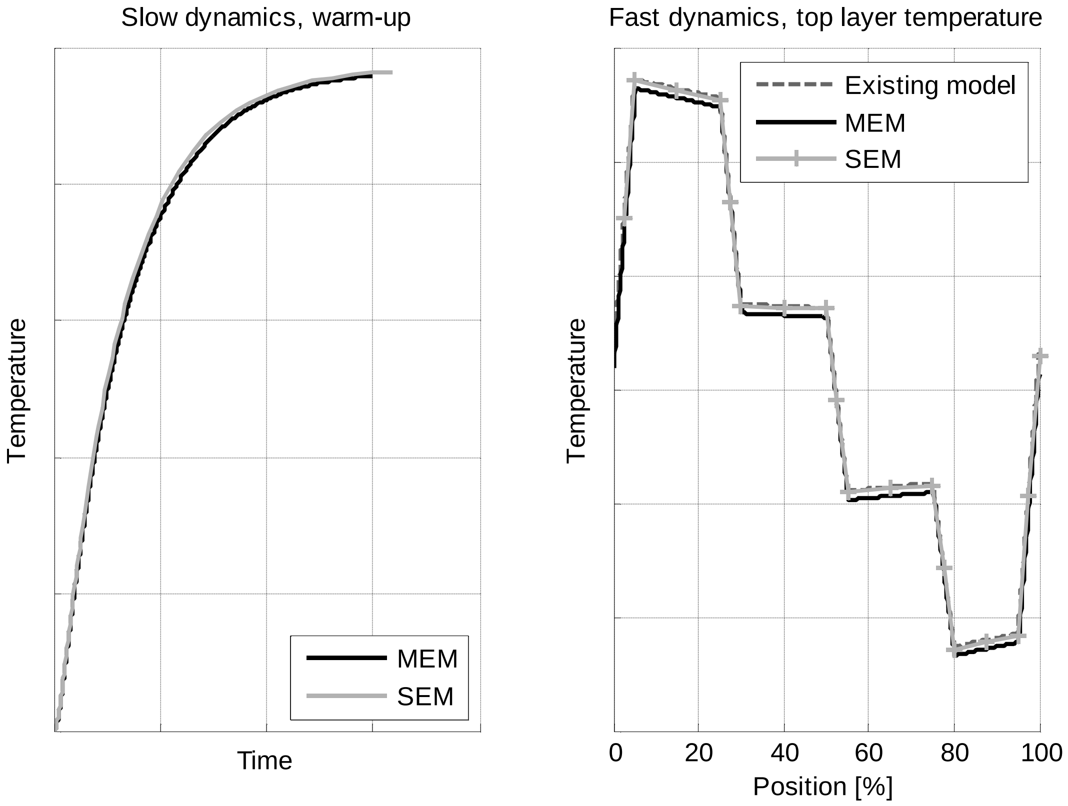

Figure 11 – Start-up and steady state comparison of the dynamic models

Both types of dynamic behavior need to be described by the model, the result can be found in Figure 11. In Figure 11 (left) it can be observed that the start-up behavior of both models, starting at zero degrees Celsius until a stationary temperature is reached, is similar.

Element	Length [%]	Top boundary condition
Heater	5	Heater
Free	20	-
Cooler	5	Cooler
Free	20	-
Cooler	5	Cooler
Free	20	-
Cooler	5	Cooler
Free	15	-
Heater	5	Heater
sum	*100*	

Table 1 – Configuration imaginary verification models

The intermediate in this experiment is heated to get in stationary situation: the total power inserted into the model equals the loss of power through three rollers that are actively cooled and continuously connected to the intermediate. The configuration of the system is presented in Table 1. As can be seen a unitary length of 5% of the total length of the intermediate is used as element length for the MEM-model. All boundary conditions are connected to the top side of the intermediate. The intermediate consists of three material layers: from outside to inside there are two layers of rubber and a layer of glass. The temperature of an element moving over the top layer of the intermediate due to the velocity v_i, the fast behavior, is also plotted in Figure 11 (right). Looking at this plot it is good to notice that the temperature is plotted against the location on the intermediate. Again, both models provide similar results. The course of the temperature is what can be expected; the thin top layer shows fast behavior due to its low capacity. First the intermediate is heated, it slowly cools down due to conduction to deeper material layers, it cools down fast due to contact with a cooler, which is repeated another two times until it is heated again.

Another result that can be obtained from the model is the power balance. When the model gets in a static situation, the total power added to the model should equal the total power lost by the model. Table 2 compares the relative power flows from the intermediate to the actively cooled cleaners for both dynamic models and the existing Matlab model at Océ. It can be seen that the predicted power flows to the different cleaners are similar for all the models and that the sum over the inflow and outflow of power is close to zero.

	MEM [%]	**SEM [%]**	**Existing Matlab [%]**
Heater1	+50	+50	+50
Heater2	+50	+50	+50
Cooler1	-36.6	-36.7	-36.8
Cooler2	-33.0	-33.0	-33.2
Cooler3	-30.0	-30.0	-30.1
sum	*0.4*	*0.3*	*-0.1*

Table 2 – Power balance in stationary situation

8 Model comparison

Looking purely at the results that both models provide, it is not easy to choose for one of the two models. Several model aspects will be analyzed in this section, resulting in the selection of only one model to use in validation.

8.1 Sampling

The output of the models is different; in case of the MEM-model, the temperatures of the capacities can be considered to be moving in space. This implies that when one is interested in looking at the top layer intermediate temperature, like in Figure 11 (right), this looks the same as the time plot of a single element in the model. In case of the SEM-model the temperatures of the capacities are static in position. This means that it is easy to follow a temperature in time at a fixed point in the copier, but for example the temperature contour over the intermediate is composed of linear interpolations between the available temperature values, represented by a cross in Figure 11 (right).

8.2 Simulation speed

An analysis of the simulation speed is done to compare both models; the results can be found in Table 3. Two things directly draw the attention:

- The SEM-model needs fewer states. This is caused by the variable length of the lumps in this approach, which is hard to implement in the MEM-model due to problems in timing and assignment of parameter values. In the actual copier the difference between the number of states needed in the MEM-model and the SEM-model even increases, since external contacts with drums and cleaners are generally very short compared to the total length of the intermediate.
- The SEM-model does benefit by the use of integration methods with variable step size (MBDF). This is caused by the character of the model; initially the SEM-model needs small steps, but when the copier gets in stationary situation all temperatures will reach static values and the step size can be increased. The maximum Euler integration step of the SEM-model is limited by the start-up behavior of the model. In the MEM-model, the elements never reach a static temperature, as can be seen in Figure 11 (right). The step-size is limited by the necessity of at least two sampling points on the shortest contact time of the intermediate. This maximum integration step concerns both the Euler and the MBDF method.

		20sim MEM	**20sim SEM (100 iterations)**
Number of states		60 (20·3)	27 (9·3)
Simulated time		500s	500s
Euler	*Maximum integration step*	~0.25s	~0.6s
	Simulation time	41.3s	26.0s
MBDF	*Maximum integration step*	~0.25s	>25s
	Simulation time	>100s	0.81s

Table 3 – Analysis of simulation speed

All experiments are done in 20sim using the same initial conditions on both models. To eliminate variations in computation time, time values shown in the tables are average values over three runs. The number of iterations used in the SEM-model is set to 100, while in this specific experiment 5 iterations would have been sufficient. Since the number of iterations does have some influence on the simulation time, this effect is shown in Table 4. The simulated time in this case is 5000s, which explains the difference in simulation time for 100 iterations between Table 3 and Table 4. When the system one wants to describe needs very thin layers and short elements, around 250 iterations is not exceptional and it can be seen that the simulation time starts to increase approximately linear with the number of iterations.

#iterations	**Simulation time [s]**
1	0.32
10	0.41
100	0.92
1000	6.32
10000	59.30

Table 4 – Influence of number of iterations

The disadvantage of the SEM-model is the use of iterations to estimate the end of element temperature. For complex systems that describe fast dynamics, the temperature estimation can consume a lot of time. On the other hand, the MEM-model will be slow on detailed systems as well. The major advantage of the SEM-model is that all elements reach a static temperature in steady state operation, which means that appropriate integration methods can increase step size to make simulations faster.

8.3 Design

Another advantage of the SEM-model is, in our opinion, the more user-friendly way to interconnect lumps to boundary conditions, which can be done graphically. The SEM-model can be considered to be more modular compared to the MEM-model: building blocks can be easily distinguished for the SEM-model. Because of the modularity of the SEM-model, this model is chosen to serve as building blocks for reusability in the design of new copiers.

9 Validation

Validation is performed on the SEM-model. Especially since it is hard to find a reliable value for the convection heat transfer coefficient, a tuning phase is inserted in the validation process. The real world copier does have a lot of settings and therefore inputs, but only few are found to be really important in the thermal behavior of the copier. These input variables are filtered from the software or measured in operation mode of the copier. Temperature sensors are added to compare measurement and simulation data. In Figure 12 it can be seen that P_{print}, the power needed during printing, $P_{standby}$, the power needed in standby, and the velocity of the intermediate v_i are the most important inputs to determine the dynamic behavior of the copier, as well as of course the contact of the intermediate with the boundary conditions.

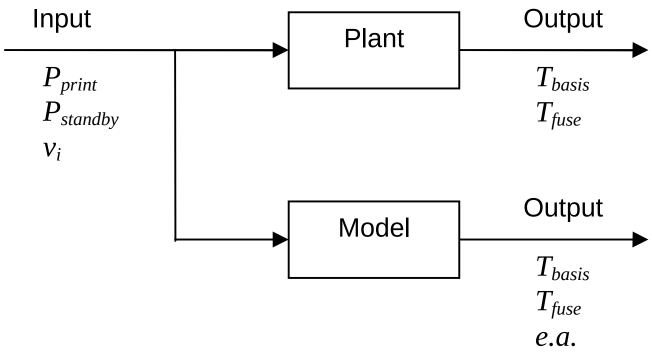

Figure 12 – Validation setup

The inputs of the actual copier were measured over a time span of around one hour when several dynamic actions were performed:

- Switching between standby and printing (switching the contact between intermediate and drums, cleaners, rollers, etc.)
- Intermediate velocity variations during printing
- Fuse temperature variations during printing

Due to confidentiality reasons no explicit results (graphs) can be presented in this paper. An internal Océ report is written with more verification and validation results.

In the copier the inputs P_{print} and $P_{standby}$ are controlled based on measured temperature values, which is not a part of the model and therefore not implemented in this validation setup. Some validation results can be summarized, see Table 5.

	T_{basis}	T_{fuse}
Average error ($T_{simulated} – T_{measured}$)	0.0867 [°C]	-0.092[°C]
Average |error|	1.704 [°C]	1.759 [°C]
Final error	0.639 [°C]	0.451 [°C]
#measurements |error| < 2°C	84%	73%
#measurements |error| < 5°C	97%	96%
time |error| < 2°C	69%	58%
time |error| < 5°C	98%	100%

Table 5 – Validation results for the complete run

It can be seen that over a simulated time of around one hour the mean value of the absolute error for both the measured temperatures, T_{basis} and T_{fuse}, is smaller than 2°C. Another result that can be obtained from Table 5 is that over 95% of the measurements *and* the simulated time the error in the temperatures is less than 5°C. When the standby time of the experiment is not considered, the results can be repeated for the printing phase only. This is shown in Table 6.

	T_{basis}	T_{fuse}
Average error ($T_{simulated} – T_{measured}$)	-0.474 [°C]	-0.123 [°C]
Average |error|	0.485 [°C]	0.385 [°C]
#measurements |error| < 2°C	95%	83%
#measurements |error| < 5°C	100%	96%
time |error| < 2°C	95%	86%
time |error| < 5°C	100%	99%

Table 6 – Validation results during printing

Table 6 shows that almost all results improve with respect to the results of the complete run. The cause of this observation is an error in the standby temperature values, which can probably be reduced by better tuning of the heat loss to the environment. During printing both T_{basis} and T_{fuse} are over 85% of the time within a temperature range of 2 degrees Celsius of the measurement.

10 Conclusions and Recommendations

The project goal was to create a thermal model that is dynamic, modular and therefore reusable in the design of new copiers. Two models for the description of thermal systems influenced by mechanical movement have been developed in this paper: an intuitive method using elements that move in space (the MEM-model) and a method that uses static elements based on the configuration of the system (the SEM-model). In verification both models proved to give satisfactory results. The SEM-model is chosen to be the model that will serve as building blocks to Océ, since the SEM-model is considered to be more modular compared to the MEM-model.

The SEM-model is validated with measurement data of a copier; in a dynamic experiment with duration of around one hour the model could predict the temperature values over the intermediate within a range of 5 degrees Celsius for 98% of the time. The average absolute error was less than 2 degrees Celsius. When only the measurement data during printing is compared to the simulation data, the results improve: during printing both T_{basis} and T_{fuse} are over 85% of the time within a temperature range of 2 degrees Celsius of the measurement.

Some recommendations can be made, based on the research done and some interesting observations and discussions:

- Not only the thermal behavior of the intermediate can be described by the proposed model, it is not that hard to make a first model of the paper path with for example preheater, fuse pinch and finishers to obtain more insight in the loss of energy due to the heating of the paper. A basic model for this purpose was already created. Another interesting application for the model can be a third dimension in space; this option is not yet elaborated. It is recommended to exploit the capabilities of the model in new applications.
- Validation is done on a single intermediate, in several configurations and in various dynamic situations. The results of the model were satisfactory; some parameter tuning can probably enhance the results. This does give faith in the generated model, but still it is recommended to do additional validation especially when completely new applications are modeled, like the paper path.
- The estimation of the temperature at the end of an element is a good way to reduce the number of elements simply determined by the various boundary conditions that the copier encounters. For detailed systems with thin layers and short elements, the estimation of this temperature can consume a considerable amount of time. When simulation time becomes a problem, it is recommended to start looking at a faster implementation of this temperature estimation algorithm.
- A standard building block of the intermediate based on the lump of Figure 10 is created, together with building blocks to describe boundary conditions like ‘Air’, ‘Cleaner’, ‘Drum’ and ‘Pinch’. When more validation results are available, it is recommended to include the generated building blocks in a 20sim library.

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