Proceedings of the 2017 Winter Simulation Conference
W. K. V. Chan, A. D'Ambrogio, G. Zacharewicz, N. Mustafee, G. Wainer, and E. Page, eds.

COUPLED SIMULATION OF ENERGY AND MATERIAL FLOW – A USE CASE IN AN ALUMINUM FOUNDRY

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ABSTRACT

This work presents a simulative approach to combine material flow simulation with the energy flow simulation for a foundry use case. The casting process is strongly dependent on the conventionally true value of the temperature, and hence a high accuracy in the thermodynamic models is needed. The presented approach reaches this accuracy via the mathematical tool MATLAB. The coupled simulation of Plant Simulation and MATLAB models provides a possibility to combine a material flow simulation with a mathematical software. With the help of this tool even complex thermodynamic problems can be solved. Furthermore, this work examines different simulation scenarios and their results on the output and energy consumption of a foundry. The results show the influence of the charging intervals and the melt temperature on machine failure and hence on the casting part throughput.

1 INTRODUCTION

The German foundry is a high energy consuming industry and therefore strongly influenced by the German energy transition. To keep up with the competition it is essential to significantly reduce the energy consumption and the costs in the producing small and medium sized businesses. There are various ways to improve energy efficiency in foundries in the field of horizontal techniques, oven-, furnace-, cooling system technologies, alloy development, melt supply, lubricant use or casting machine improvement. (Fehlbier 2003, Herrmann et al. 2013, Reonen et al. 2012, Röders et al. 2006, Schwam et al. 2006, Vrancken 2004).

Also the simulation plays a role in improving the energy efficiency via casting simulations which can reduce the feeding system or simply improves the casting quality and hence reduces the production rejects. Though there are additional simulations that can positively influence the energy efficiency in a foundry, for instance the simulation of the energy and material flow.

Usually a foundry consists of at least one smelter, one casting machine with a holding furnace and a melt supplying unit, in most cases a forklift transporting a casting ladle. In this paper we examine a foundry, producing aluminum parts via the high-pressure die casting (HPDC) process. The HPDC-process excels by a very high productivity and the possibility to produce even very thin walled casting parts like i.e. automotive structure parts. The cycle time is low, 60 – 180 sec and the part, including gating and overflow system weighs from 5 – 30 kg. Due to the very high productivity of the HPDC-machine it is not possible to charge the machine in sequence, but an additional holding furnace is needed to buffer the melt and to keep it at, or even heat it up to the temperature required for the process. The temperature of the melt significantly influences the quality of the casting part. If the temperature is too low, the flow length is reduced and issues with the filling and cold flow appear. If the temperature is too high, the melt absorbs more hydrogen, leading to gas porosity, shrink holes may appear and the mold is exposed to a higher load. Accordingly, having the right temperature at the right time is essential for a successful casting. There are different influences affecting the initial temperature of the casting process which are:

- Temperature drop of the melt during the transport of the ladle due to thermal conductivity, convective heat transfer and thermal radiation
- Temperature drop of the melt in the holding furnace due to thermal conductivity, convective heat transfer and thermal radiation
- Temperature rise due to electrical heating of the holding furnace
- Temperature rise and drop due to the mixing process of the melt in the holding furnace and the melt in the ladle

To solve the heat transfer equations of the different cases, a numerical solution is needed which is not given by current used material flow simulations. Thus a new approach combining the material flow and the energy flow, described by the developed thermodynamic models is required, leading to a precise prediction of the temperature development in the casting process.

Results of this approach will gain knowledge about the thermodynamic processes of the melt supply, which will help improving the dimensioning of the holding furnace, the filling frequencies and the superheating of the melt in the smelter. In addition, it gives a better understanding of the consequences of machine, furnace or transporting unit failure and their effects on the casting quality.

To test whether this approach delivers useful results when applied with detailed thermodynamic modeling, this work provides an example of an exact modeling of the thermodynamic phenomena appearing in a foundry. It starts with an overview of related works in the field of material and energy flow simulation and how they differ to the shown examination. Afterwards, the use case and the thermodynamic models needed for the modeling and the simulation are described, followed by a verification of the models. With the aid of different test runs, this work takes a look at the effects of failure and temperature drop on the casting process and finally discusses the results in regard to the used simulation approach.

2 RELATED WORKS

When energy aspects have to be considered in simulation of production and logistics, there are several different approaches. They differ in applied tools, the use cases and the requested results (Wenzel et. al. 2017).

Nawzad and Klahr (2012) have developed a simulation approach using a discrete-event simulation (DES) tool and combine it with an energy systems optimization tool. Both tools run independently. After the run the input data of the optimization tool is adjusted for the model to achieve the same throughput as the DES-model. This is necessary because the optimization tool cannot take into account failure, blocking and other states that a machine can reach in a system. The authors state that the output data becomes more realistic as dynamic changes in the system are considered by the combination of both tools. However, there is no direct communication or coupling between the models (Nawzad and Klahr 2012).

Solding and Thollander (2006) also use discrete-event simulation to achieve lower energy costs in the casting process of a foundry. They state that by reducing the maximum load, they achieve lower costs. There is no detailed simulation of the heating process in the oven (Solding and Thollander 2006).

Esteban and Penya (2012) describe another example where a scheduling problem in a foundry is solved by applying different algorithms to achieve lower energy consumption. Due to the stocks being predefined, the stocks melt at a constant temperature. This makes it impossible to test what consequences the scheduling will have on the melting process (Esteban and Penya 2012).

Thiede (2012) develops an approach for considering energy consumption in material flow simulation using just one simulation tool and applies his solution to a use case in an aluminum die casting company.

The focus is to develop measures and strategies to reduce energy cost without loss of throughput. This approach, however, does not allow for a detailed analysis on a physical level and considers the process as a "black box" (Thiede 2012).

As the use case of this paper consists of a problem where both material and energy flow have to be simulated in detail, the authors chose a simulation approach developed by the department of Production Organization and Factory Planning of the University of Kassel. It was firstly developed in the "SimEnergy" project (Peter and Wenzel 2015) and further enhanced to improve the usability and to reduce the required workload for simulation (Peter and Wenzel 2017). There the authors show that the developed approach is well suited for simulating problems where material and energy flow are relevant for the outcome. We conclude that this approach is capable of delivering results of higher precision than a purely discrete-event simulation with additional bricks for evaluation. The described problems to simulate interdependencies can be solved by coupling two separate tools that allow for consideration of both material flow and production processes as well as thermodynamic processes.

In this paper we chose a use case with complex thermodynamic cooling and heating processes which requires the use of numerically solved differential equations. While simpler calculations can be executed in a discrete-event simulation tool via programmed methods, these tools are incapable of solving differential equations numerically. This use case tests whether the developed approach is suitable for solving such complex interdependencies or not.

3 DESCRIPTION OF THE USE CASE

In this work we analyze a model foundry. It is based on real-world processes and uses real or realistic input data for modeling. It does not match an existing foundry though. The model foundry includes one smelter, one HPDC-machine, one holding furnace and a supplying forklift transporting a casting ladle. The smelter serves only as a melt supplying unit which is not modelled itself. The smelter supplies the ladle with 720 °C hot aluminum melt which is then transported to the holding furnaces. One charge transported by the forklift contains 600 kg of aluminum alloy. The initial melt temperature for the casting process must neither fall below 680 °C nor exceed 720 °C to produce a casting part free of error. The holding furnace is resistance heated with a power of 45 kW, its maximum capacity is 1,000 kg. The cycle time of the HPDC-machine is 120 sec and each shot weights 10 kg. The forklift has an assumed average speed of 1 m/sec. It has an availability of 70 %, a mean time to repair (MTTR) of 30 min and reaches the holding furnace after a distance of 500 m. There, the smelted portions are unloaded and the forklift returns to its waiting position. As soon as the holding furnace contains less than 150 kg of melted aluminum it orders new supplies and the forklift starts another tour. From the holding furnace the aluminum is fed into the HPDC-machine with a cycle time of 120 sec. The HPDC-machine has an availability of 85 % and a MTTR of 1 h.

4 THERMODYNAMIC MODELS

To accurately predict the energy flow of the ladle and holding furnace, thermodynamic models are needed. A challenge for the modeling is finding the balance between accuracy and calculating capacity and also to determine the right boundary conditions and material data.

In this paper we make some assumptions due to the simplification of the calculations or missing exact data without affecting the overall validity of the model. The assumptions can e.g. be heat conductivity not depending on the temperature or a steady state condition in a small temperature interval.

In general three different heat transfer phenomena appear in every cooling process, the heat conduction, conductivity and the thermal radiation which are described in the following sections. The geometry of the ladle and the holding furnace are similar and can be described as a standing cylinder. The surface temperatures differ between the actual melt temperature and the temperature at the surface of the circumference of the cylinder.

4.1 Thermal Transmittance on the Circumference of a Standing Cylinder

The thermal transmittance of a cylinder with n different material layers insulating the melt is described in equation (1) (Stephan et al. 2013):

$$\dot{Q}_{conv.circ.} = \frac{\pi \cdot H \cdot (T - T_{amb.})}{\frac{1}{h_i \cdot d_i} + \sum \frac{1}{2 \cdot \lambda_n} \cdot \ln\left(\frac{d_{o,n}}{d_{i,n}}\right) + \frac{1}{h_o d_o}} \tag{1}$$

Where $\dot{Q}_{conv.circ.}$ symbolizes the convective heat flow on the circumference of the cylinder, H the height of the cylinder, T the temperatures, h_i the inner and h_o the outer heat transfer coefficient (HTC), λ_n the thermal conductivity of the different layers, and d_i and d_o the inner and outer diameter of the cylinder.

This equation is valid for stationary heat transfer but has sufficient accuracy for the small temperature drop of the melt in the ladle during the transport and the holding furnace.

The inner convective heat transfer is usually over one order of magnitude higher than the convective heat transfer on the outside or the conductive heat transfer of the materials and can be left out of the equation without losing accuracy. The used materials differ whereas the holding furnace usually has a very effective insulation and circumference temperature of less than 60 °C (thermal resistance > 4 K/W) whereas the ladle is less effectively insulated with thermal resistance of about a tenth of the holding furnace. These values can of course differ in a wide range and depend on the used materials and the condition of the equipment. The convective heat transfer on the surface of the circumference of the standing cylinder is calculated with standard Nusselt (Stephan et al. 2013) equations which are not further described in this work. In the examined temperature regime the HTC is about 8 W/m^{2}K for the ladle and about 4,5 W/m^{2}K for the holding furnace.

4.2 Convective Heat Flow of the Melt Surface and Bottom Plate of the Standing Cylinder

The convective heat transfer of the melt surface is shown in equation (2) (Stephan et al. 2013):

$$\dot{Q}_{conv.meltsurface} = h_{conv.meltsurface} \cdot A \cdot (T_{Melt} - T_{amb.}) \tag{2}$$

Where $\dot{Q}_{conv.meltsurface}$ stands for the convective heat flow and $h_{conv.meltsurface}$ for the HTC of the melt surface. A symbolizes the actual surface and $T_{Melt} - T_{amb.}$ the temperature gradient between melt surface and ambient air.

The calculated HTC is about 12.5 W/m^{2}K (Nusselt equation for heat flow of a plain surface) in the temperature regime of the hot melt surface resulting in a high heat flow. The model is valid for open topped ladles and holding furnaces. Covered or partly covered tops decrease the heat flow of the melt surface.

The bottom plate of the ladle and holding furnace has no significant effect on the heat transfer, hence there is no necessity to represent it in the thermodynamic model.

4.3 Heat Flow due to Thermal Radiation

In many cooling applications the thermal radiation plays a minor role. The reason for that lies in the low temperature regime and the radiation dependencies on the 4th potency of the temperature. In a foundry, on the other hand, the temperature of the melt is over 700 °C and the thermal radiation plays the main role in heat transfer.

The simplified thermal radiation equation is shown in equation (3) (Baehr and Stephan 2016):

$$\dot{Q}_{rad} = \sigma \cdot \varepsilon \cdot A \cdot (T^4 - T_{amb}{}^4) \tag{3}$$

Where $\dot{Q}_{rad}$ stands for the heat flow via thermal radiation and σ for the Stephan-Boltzmann constant, the emissivity ε for aluminum alloys is about 0.2 (Röders et al. 2006) resulting in a high heat flow via radiation for the melt surface. The radiation on the circumference of the ladle and the holding furnace is too low to significantly influence the heat transfer and is therefore left out of the thermodynamic model.

4.4 Heat Transfer Equation of the Ladle

Combining the different heat transfer phenomena for the ladle (index L) results in equation (4):

$$\frac{dU}{dt} = \dot{Q}_{conv.circ.L} + \dot{Q}_{conv.sur.L} + \dot{Q}_{rad.L} \tag{4}$$

As mentioned in the previous chapters, the convective heat transfer at the bottom plate and the thermal radiation of the circumference of the ladle are negligible. Presuming a constant specific heat capacity c_L and mass m_L leads to equation (5):

$$\frac{dT}{dt} = \frac{1}{m_L \cdot c_L} \cdot \left(\left(\frac{\pi \cdot H_L \cdot (T - T_{amb.})}{\sum \frac{1}{2 \cdot \lambda_n} \cdot \ln\left(\frac{d_{o,n}}{d_{i,n}}\right) + \frac{1}{h_{conv.circ.L} d_{o,L}}} \right) + \left(h_{conv.sur.L} \cdot A_{sur.L} \cdot (T - T_{amb.}) \right) + \sigma \cdot \varepsilon \cdot A_{sur.L} \cdot (T^4 - T_{amb}{}^4) \right) \tag{5}$$

4.5 Heat Transfer Equation of the Holding Furnace

The heat transfer equation of the holding furnace (index HF) is very similar to the ladle because the same heat transfer phenomena appear, though there are, of course, different material and geometry parameters. In this case the holding furnace is electrical resistance heated, and hence an additional term for the power P appears in (6):

$$\frac{dT}{dt} = \frac{1}{m_{HF} \cdot c_{HF}} \cdot \left(\left(\frac{\pi \cdot H_{HF} \cdot (T - T_{amb.})}{\sum \frac{1}{2 \cdot \lambda_n} \cdot \ln\left(\frac{d_{o,n}}{d_{i,n}}\right) + \frac{1}{h_{conv.circ.HF} d_{o,HF}}} \right) + \left(h_{conv.sur.HF} \cdot A_{sur.HF} \cdot (T - T_{amb.}) \right) + \sigma \cdot \varepsilon \cdot A_{sur.HF} \cdot (T^4 - T_{amb}{}^4) \right) + P \tag{6}$$

4.6 Mixing Process of the Melts

For simplification reasons the mixing process is defined as a no time consuming event. The melt in the ladle gets mixed with the melt in the holding furnace and a mix-temperature T_m of both masses sets in. The mixed temperature is calculated as shown in equations (7):

$$T_m = \frac{m_{MHF} \cdot T_{MHF} + m_{ML} \cdot T_{ML}}{m_{MHF} + m_{ML}} \tag{7}$$

4.7 Implementation of the Simulation Models

This section explains how the models are implemented into the simulation tools. Plant Simulation, Version 12, is used for the material flow model. MATLAB Simulink, Version 2016a, is used for the energy models calculating the temperatures. Section 4.7.3 explains how the two models are coupled using TCP/IP interface. Finally, section 4.7.4 exemplifies the verification and validation of the simulation models.

4.7.1 Implementation of the Mathematical Models in MATLAB Simulink

The MATLAB Simulink model is used to simulate the thermodynamic processes in the casting ladle and holding furnace. The temperature in the casting ladle is in our basic model 720 °C on departure. It cools down during the tour of the forklift until it reaches the holding furnace where it is mixed with the melt in the holding furnace. In our model we assume that mixing happens in zero time. The model runs with a sample time of 60 sec and uses a 4^{th} order Runge-Kutta solver to numerically solve the differential equations. The Simulink model provides data about the temperature in the casting ladle and the holding furnace over time, about the current and the aggregated heating energy input of the holding furnace and about the current temperature change in the holding furnace. Furthermore, it decides whether the temperature of the aluminum is high enough for a secure casting process. The model is strictly deterministic and does not contain any random processes.

4.7.2 Implementation of the Material Flow Model in Plant Simulation

The material flow model is implemented in Plant Simulation, version 12. The system boundaries are drawn after the melting furnace which is represented as a source which provides the melted aluminum. As the aluminum is transported and used as portions, every portion required for the production of a part is modeled as a discrete object, the smelted portion. At a loading station the smelted portions are loaded onto a forklift equipped with a ladle which can load 60 smelted portions which equals 600 kg of melted aluminum. The forklift is usually waiting at a waiting position and starts its tour once the holding furnace reports demand for melted aluminum. The availability of the forklift represents technical failure as well as absence of the driver or blockage of the driveway. The holding furnace is modeled as a buffer followed by the casting machine which can fail due to technical difficulties or due to the melt being not hot enough for a safe casting process. After the casting machine, the casted parts go to a sink and leave the system. The Plant Simulation model contains random numbers in the availability and the MTTR of the forklift, the holding furnace and the casting machine. Plant Simulation uses an Erlang distribution for the simulation of failures. Production times or driving speeds are assumed constant. After the discussion of the two models, the next section will explain how the models are coupled.

4.7.3 Implementation of the Model Coupling

Both models transmit and receive data every 60 sec. In Plant Simulation this is controlled by a generator block, which is connected to the method sending the data. After sending data the model run in Plant Simulation is paused until it receives data from MATLAB. In MATLAB TCP/IP receive blocks are used for receiving data, configured in "blocking mode", which stops the simulation until data is received. A "to instrument" block is used for sending data. Stopping the models between sending and receiving data assures time synchronization between both tools. This means that both models run in 60 second intervals and are triggered cyclic. This solution was developed and described in Peter and Wenzel (2017).

The temperature of the melt in the ladle is calculated in MATLAB. This calculation is reset every time a forklift leaves the loading station at the smelting oven, so that the starting temperature is constant for every tour. Plant Simulation transmits data at the start of the tour of the forklift. Once the forklift arrives at the holding furnace, Plant Simulation transmits data again. This is the point when MATLAB reads the temperature of the melt in the ladle and uses it for calculation of the temperature in the holding furnace after mixing the melt. Another value that is important for calculation of the temperature in the furnace is its fill height. Thus, Plant Simulation aggregates the amount of casted parts for one minute and transfers this value to the MATLAB model where the fill height is calculated. It is old fill height minus the amount of used melt in the past minute. As the cycle time of the casting machine is 120 sec, the aggregated production for one minute is either zero or one.

The MATLAB model decides whether the temperature of the melt in the holding furnace can guarantee a safe casting process. If the temperature undercuts a critical value, the MATLAB model transmits this to Plant Simulation, where the casting machine is then in failed state.

Thus, we achieve bi-directional coupling of the models, with the material flow influencing the heating and cooling in the thermodynamic model and the temperature of the melt influencing the availability of the casting machine in the material flow model.

4.7.4 Verification of the models

Both simulation models are implemented with certain abstractions but the input data is based on a real life foundry and values found in literature (Röders et. al. 2006, Reonen et. al. 2012). After implementing the models within the two software tools several simulation runs are carried out to verify the model behavior. First of all, time synchronization as one part of the model behavior has to be tested. This is done by interrupting the Simulink model anytime during the simulation run. The time on the simulation clock shows the exact same value as in the Plant Simulation model. Secondly, data is recorded into arrays by both tools every minute of simulation time. Both models show 7,200 data points, for a 5 day simulation run (5 days equal 7,200 minutes) and the recorded values match. Due to the visualization of both models on two monitors, we can see that the mixture of the aluminum in the holding furnace appears at the exact time when the forklift arrives at the furnace in the Plant Simulation model. Another method used in the verification is to split up the differential equations in the temperature calculations into the radiation and convection parts of the heat transfer to prove the plausibility of each individual factor by comparing them to measurements in a real-world foundry.

5 EXPERIMENTS, RESULTS AND DISCUSSION

The goal of this research is to analyze what benefit is created by using a coupled simulation when simulating the casting process in a foundry. At first, we want to examine if the critical temperature, where a safe casting process is no longer possible, is ever reached and how much this influences the output of the model. For this purpose, both models are parameterized. As the Plant Simulation model contains random numbers (the availability and MTTR of different machines), we conduct five simulation runs with different seed values and all other parameters remain unchanged. In the beginning of each simulation run the model is in a steady state. Melt and ovens are preheated. The holding furnace is already filled with a certain amount of melt. There is no warm-up period in the models. Five simulation runs are considered enough as it is more important to test the simulation approach with an exact thermodynamic modeling than to achieve accurate key performance indicators (e.g. throughput). If the approach is applied to a real world foundry, more simulation runs would be advised. Each simulation run has a duration of five days with no breaks in between (= 120 hours). It takes about three real world minutes on average to simulate five business days when animation in the DES model is activated and charts are displayed live in Simulink.

There are three reasons that can lead to a halt of production: technical failure of the casting machine, temperature caused failure of the casting machine and no melt in the holding furnace due to failure of the forklift. For each simulation run all three reasons for failure and their impact on throughput are documented. The results can be seen in Table 1. The technical failure of the casting machine is caused by an availability of 85% and an MTTR of 30 minutes. The lack of melt is caused by the forklift not being able to deliver melt in time, e.g. because of forklift failure. Temperature based failure is caused by undercut of the critical temperature of the melt, calculated in the MATLAB model and transmitted to Plant Simulation. The influence of temperature based failure is small compared to the technical failures caused by the relatively low availabilities. While the temperature sinks too low twice on run 1, 4 and 5, this never happens in Run 2. The behavior for the technical failure of the casting machine and for the lack of melt is rather constant over the simulation runs.

Table 1: Results for the five simulation runs.

	Run 1	**Run 2**	**Run 3**	**Run 4**	**Run 5**	**Average**
technical failure of casting machine						
percentage failed	13.74%	13.74%	13.74%	17.01%	16.22%	14.89%
amount of failures	36	36	36	41	42	38.2
average duration of failure (hh:mm:ss)	0:27:28	0:27:28	0:27:28	0:29:51	0:27:48	0:28:01
failure due to lack of melt						
percentage failed	0.79%	1.37%	0.79%	2.65%	0.87%	1.29%
amount of failures	6	6	2	11	4	5.8
temperature caused failure						
percentage failed	0.42%	0.00%	0.67%	1.50%	3.13%	1.14%
amount of failures	2	0	1	2	2	1.4
average duration of failure (hh:mm:ss)	00:15:00	00:00:00	00:48:00	00:54:00	01:52:30	00:45:54
throughput for 24 hours (in parts)	3,090	3,082	3,075	2,891	2,918	3,011.2

With the temperature based failure being such a rare event, we want to examine at which point it occurs in the simulation and what causes it. Figure 1 displays the temperature in the holding furnace over time (7,200 minutes = 5 days) for Run 1 (see Table 1). The critical temperature for a safe casting process is 680 °C, which is undercut twice. Once around minute 2,400 and once around minute 4,800.

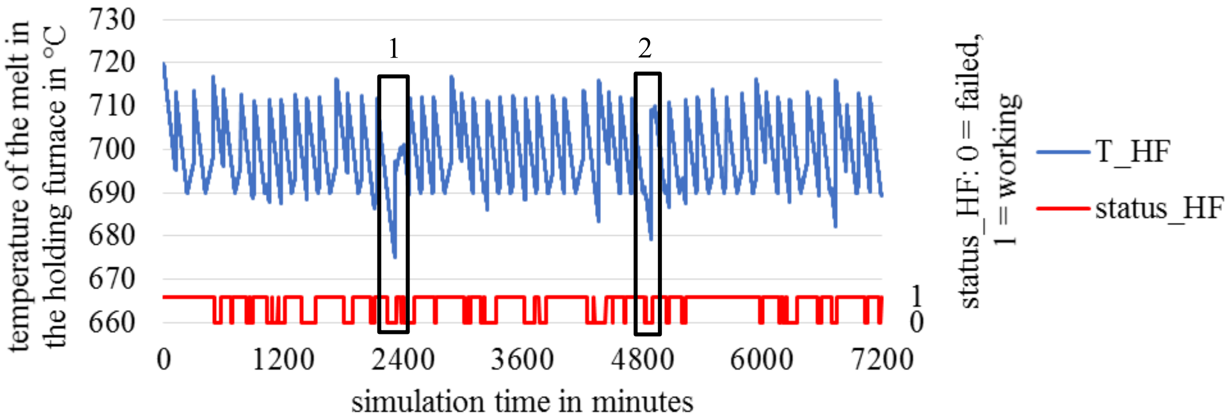

Figure 1: Temperature of the melt and status of the holding furnace for Run 1 over time.

The temperature curve shows regular spikes. These are caused by the mixing of the hot melt from the casting ladle arriving on the forklift and the cooler melt in the holding furnace. Smaller, less steep spikes are caused by the heating of the holding furnace, which is activated once the temperature drops below 690 °C. The heating of the holding furnace can fail. It has an availability of 75% and a MTTR of one hour. The red curve at the bottom of the chart displays the status of the heating in the holding furnace. It can be working (value 1) or failed (value 0). Although the heating fails quite often, is has basically no effect on the casting process, as the arriving hot melt raises the temperature high enough in regular time steps. However, if the failure of the heating occurs at a point where no melt has arrived for a long time and the temperature is short of 690 °C (see point 1 and 2 in Figure 1), when the heating would usually heat up the aluminum, the temperature drops further until the casting process has to be stopped. After the furnace starts working again, it heats up the melt, production continues and new, hot melt arrives. This behavior can be observed in all four simulation runs, where temperature caused failure occurs. As it highly depends on random events happening at certain times in the simulation there is also the chance of no temperature caused failure during five days of simulation like in Run 2. A longer simulation time frame would lead to a higher chance of failures in one run.

As heating the melt before transporting it requires a lot of energy and the temperature loss is higher the hotter the melt, we wanted to test how a lower temperature of the melted aluminum before being transported by the forklift influences the model behavior. Thus, we reduced it from 720 °C to 715 °C, leaving all other parameters unchanged. Again five simulation runs were done with varied seed values. Table 2 shows the results for the temperature based failure and the throughput of the system. Technical failure and lack of melt are not of special interest in this case as they are very similar to the first experiment.

Table 2: Results for the five runs of the second experiment.

	Run 1	**Run 2**	**Run 3**	**Run 4**	**Run 5**	**Average**
temperature caused failure						
percentage failed	22,86%	1,44%	3,99%	27,24%	8,93%	12,89%
amount of failures	1	1	2	3	5	2,4
average duration of failure	27:26:00	01:44:00	02:23:30	10:53:40	02:08:36	08:55:09
throughput for 24 hours	2307	3061	2846	2124	2735	2614,6

This time the chances of temperature based failure are higher than with a melt temperature of 720 °C. There is an extreme case in Run 1 with one, but very long failure. This is caused by the holding furnace not being able to heat the melt enough before it fails again. This happens due to the low availability of the furnace of just 75%. Figure 2 shows the temperature in the holding furnace over time (7,200 minutes = 5 days) for Run 3 (see Table 2).

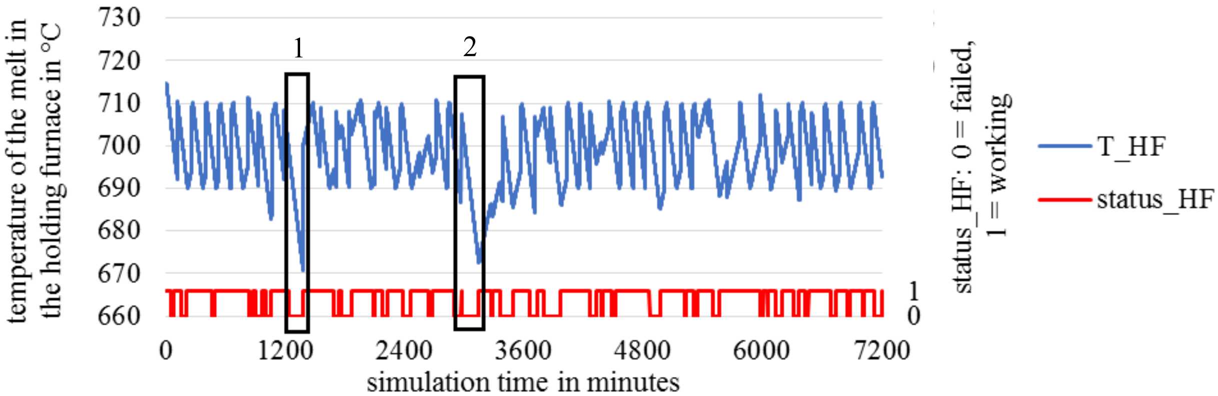

Figure 2: Temperature of the melt and status of the holding furnace for Run 3 over time.

The same behavior as in the first experiment can be observed (see points 1 and 2 of Figure 2). This time, however, the temperature almost never rises above 710 °C due to the lower temperature of the melt in the ladle on the forklift. The temperature buffer in case of heating failure is smaller this time, leading to more temperature based failures.

As stated at the beginning of this experiment the energy requirements for heating the melt before transportation is lower with a lower temperature on departure. In the Simulink model we also calculate the total heating energy used by the holding furnace. For the first experiment it was 1,551 KWh on average, for the second experiment it was 3,180 KWh on average. It is doubted whether this justifies the energy savings in the smelter, especially as this is usually the more efficient process than a holding furnace. However, this was not further examined in detail as it is outside of the system boundaries.

Our simulation experiments show that it highly depends on the exact time of heating failure occurring in combination with a long time since melt was last delivered and a critical temperature value in the holding furnace. This can be modeled well with the chosen approach as the temperature in the furnace can be calculated accurately and the discrete-event simulation is well suited for simulation of random events.

6 CONCLUSION

The aim of this work is the examination of a foundry with the tools of a combined material flow and energy flow simulation. The foundry case is chosen due to the very temperature sensitive process. For an exact simulation of the energy flow, complex thermodynamic models are needed which have to be solved numerically. Common approaches have neither the sufficient accuracy nor the numerical tools to display the appearing phenomena.

With the help of the combined simulation tools, an accurate model is built and simulation experiments are conducted. The results prove that applying this simulation approach to a use case in the casting process is a valid option when accurate results are desired and interdependencies between material flow, production and energetic values are important for the simulation results. A simulation in a DES tool does not provide methods to simulate thermodynamic processes with such high accuracy and does not provide a solver for numerical solving of differential equations. Whether this accuracy is needed and worth the effort or whether simplified calculations in a DES tool meets the requirements is still subject to research.

For the foundry industry the presented approach gives important information about the usage of the holding furnaces and also the energy consumption overall. With the aid of the approach, the recharging can be planned precisely considering e.g. a low energy consuming production. Furthermore, the simulation gives the possibility for the right dimensioning of holding furnaces. Besides, consequences of the failure of the HPDC machine or the holding furnace on the process and the energy consumption are revealed.

The presented approach can easily be expanded on a real foundry with a numerous amount of different casting machines, holding furnaces, forklifts and smelters. Additionally, there is no limitation in the complexity of the thermodynamic models used in the simulation, hence even new and more complex and complicated models can be implemented. The capability of the presented approach is immensely expanded compared to common simulation approaches and should be used in all applications where an accurate temperature modeling of the process is necessary.

NOMENCLATURE

$\dot{Q}$	heat flow, W	λ	heat conductivity, W/(mK)
A	surface, m^2	ε	emissivity, -
T	Temperature, K	σ	Stephan-Boltzmann constant, $W/(m^2K^4)$
H	height of the cylinder, m	U	internal Energy, J
d	diameter of cylinder, m	t	time, s
h	heat transfer coefficient, $W/(m^2K)$	m	mass, kg
c	specific heat capacity, J/(kgK)	P	power, W

Subscripts

conv.	convective	circ.	circumference
amb.	ambient	i	inner
o	outer	n	index
rad	radiation	sur.	surface
L	ladle	HF	holding furnace
m	mixed	MHF	melt holding furnace
ML	melt ladle		

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