Coupled Simulation of Energy and Material Flow using Plant Simulation and MATLAB Simulink

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Abstract. This paper describes the state of the art in integrating energy considerations into the simulation of production and logistic processes. It presents different approaches to integrating energy analysis into simulation. Furthermore, we discuss a solution developed within the research project *SimEnergy*, a use case for application and the results of the project. We explain how the developed solution was improved after the project had shown that it delivers comparable results to the original approach. We use the obtained results to develop a simplified model in *Plant Simulation* and compare the results to the coupled simulation solution. Furthermore, we analyze the impact of the temperatures chosen for restarting the machines in the output of the production line. A second use case demonstrates the differences between a coupled model and a simulation in *Plant Simulation,* if the timing of a temperature-based failure is important for the simulation results. We conclude with a presentation of prospects for further research.

Introduction

With the growing importance of energy consumption in the production of goods, the consideration of energy influences during the planning phase has also gained relevance. This is also noticeable in the research field of simulation-based planning. Various works discuss different solutions in terms of how energy aspects can be integrated into the simulation of material flows. Within a research project titled *SimEnergy* the Department of Organization of Production and Factory Planning at the University of Kassel developed a solution for simulation-based planning and evaluation of energy efficiency for production systems in the automotive industry in collaboration with the simulation service providers SimPlan AG and Limon GmbH and the application partner Volkswagen AG. This paper provides an overview of the state of the art in combined simulation of energy and material flows, describes the technical solution developed in the *SimEnergy* project and discusses further developments regarding the technical solution and some results of the simulation experiments. The paper concludes with further prospects for research and development.

1 Combined Simulation of Material and Energy Flow

When planning new production lines, companies use energy efficient technologies and procedures as a matter of course, but consideration of energy aspects when planning production or logistic systems is still subject to research [1]. Static approaches, such as the energy value stream analysis, [2] are not capable of taking into account dynamic interactions or stochastic distributions. With both being major requirements for a secure planning, simulation is a useful tool for the securing of planning results [3, 4]. Simulation is used not only in production and material flow planning but also when designing technical building services for cooling, heating or providing process energy [5, 6]. Some use cases require consideration of the material key performance indicators on the one hand and of energy key performance indicators on the other as well as the occurring dependencies between both. This is why researchers have developed several approaches using simulation for combined energy and material flow planning. These approaches differ in their methodology and in the simulation tools used:

- Discrete event simulation with additional simulation objects or tools for evaluation of energy key performance indicators of the model [7].
- Discrete event simulation with Excel-based evaluation of energy key performance indicators after simulating [8, 9].
- Two separate coupled models: discrete event simulation for the material flow simulation and continuous simulation for the energy simulation [10–12].
- Simulation using a tool that supports discrete event simulation as well as continuous simulation in one model [13].
- Continuous simulation for both energy and material flow [14].

The first approach calculates energy usage based on the material flow simulation. Each machine state (working, standby or idle) is coupled with an energy consumption level. They either integrate the energy consumption objects directly into the discrete event model or outsource it into a separate database that runs parallel to the simulation. While the material flow simulation directly influences the energy consumption, it is not influenced by energy key performance indicators (e.g. current energy consumption) itself. These approaches do not simulate the energy or physical models separately.

The second approach is similar to the first. However, it does not perform the calculations for energy usage live but following the simulation run. The user has to export the results to a calculation software (e.g. Excel) and perform the necessary operations there. While less effort is required for modeling and developing the required simulation objects, evaluation of the results is more time-consuming. Again, there is no possibility to simulate effects of energy key performance indicators on the material flow system.

If bidirectional dependencies between energy aspects and material flow have to be evaluated online, only the last three approaches will offer a suitable solution. While combining both models in one tool (e.g. *AnyLogic*) requires less effort than building two separate models, the simulation user needs to have knowledge about material flow modeling as well as a detailed understanding of physical and thermodynamic processes depending on the level of detail in the models. Using two separate specialized tools provides advantages, because experts of the respective fields are already familiar with them and use them in a non-coupled way in their day-to-day business.

If a solution provides an interface for communication between models, the simulation experts can focus on building their respective models as they would normally do. Enhanced by the required elements for communication, those models can be used for a combined, coupled simulation of bidirectional dependencies between the material flow model and the physical energy model.

In the *SimEnergy* project, the team decided to use *Plant Simulation* by Siemens Tecnomatix as a discrete event simulation tool for simulating the material flow in production and logistics and *MATLAB Simulink* by Mathworks for simulating the thermodynamic physical processes. On the one hand, the application partner is an automotive company and *Plant Simulation* is the most common tool used for the simulation of material flows for production planning and logistics in the automotive industry in Germany [15]. *MATLAB Simulink*, on the other hand, dominates the market for continuous simulation of physical processes [16]. This is why a combination of the two tools seemed reasonable for implementing a coupled simulation of energy and material flow for the given use case.

As it has already been described, the different solutions for simulation of material flows and energy processes differ not only in the effort required for modeling and analysis, but also in the effort required for acquiring data. The more specialised and detailed the models, the more necessary data with a higher level of detail. If physical processes are simulated to gain energy key performance indicators regarding the temperature in the factory, data about the heat emissions of the machines, the insulation of the building and air circulation is required, which would not be necessary, if the aim is to calculate energy usage depending on the machine states over time. One can, however, expect a higher level of detail in the results. Depending on the use case and on the objective of the simulation studies you should choose a suitable approach. What a simulation using two specialised, coupled models could look like and whether or not it provides additional value to the user will be discussed in the following sections.

2 SimEnergy Solution

The following section presents the simulation approach developed in the project *SimEnergy*, describes the application in a use case and discusses the results.

2.1 Technical solution

The technical solution developed in the *SimEnergy* project consists of a direct online-coupling of the two simulation tools *Plant Simulation* and *MATLAB Simulink*. The *Plant Simulation* model contains the production and logistic model with all machines, conveyor belts, buffers, etc. It uses TCP/IP-sockets for network communication. The *Simulink* model contains all energy systems, such as cooling tower, pumps, pipes, heat exchangers, etc., that are needed to model the heating and cooling of the machines and the supporting infrastructure. All required assets are modeled in one large *Simulink* model, some of which are grouped into subsystems. The user has to export the *Simulink* model as C-Code, to compile it into a *.dll-file and to embed it into a specially developed wrapper application. The wrapper application runs the model *.dll-file and handles the data exchange via TCP/IP for the *Simulink* model.

SimAssist, a tool developed by SimPlan, acts as a communication platform. A specially developed add-in provides functions for network communication between the *Plant Simulation* model and the *MATLAB* wrapper application and for synchronization of the simulation time. This is necessary because *Plant Simulation* is a discrete event simulation tool, while *Simulink* is a continuous one. Time-synchronization is achieved by simulating in fixed time steps, which also are data exchange intervals. The *SimAssist* tool ensures that both simulation models are at the same simulation time step. Figure 1 visualizes the described architecture.

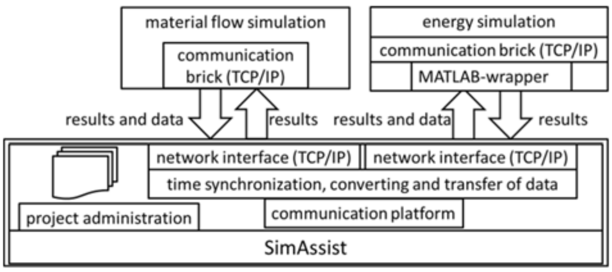

Figure 1: *SimEnergy* System architecture.

The *SimAssist* tool also handles the converting of data into different data types. This is necessary because *Plant Simulation* can only send and receive string data types, while *Simulink* requires numerical data types (e.g. real or integer).

The *Plant Simulation* model transfers the state of machines (working, idle and failed) to the *Simulink* model, which then calculates the temperatures accordingly. If the calculated temperature exceeds a critical value, the *Simulink* model transfers a message to the *Plant Simulation* model that the machine has to be set to 'failed'. If the simulation models contain more than one process, which requires data transfer, the models will combine all data into one string, which is transferred afterwards. This is the case when several machines exchange their states and influence the thermal model. The receiving model resolves the string into its components and transfers the data to the respective blocks in the model.

2.2 Application

The project team validated this approach by applying it to a use case in the automotive industry. The team chose the use case by means of two criteria: Firstly, whether the use case provides a clear connection between energy and material flow that justifies a coupled simulation, and secondly, whether there is enough input data available to build the two required models. The chosen production line consists of several interlinked machines for turning, washing and grinding of gearbox parts. A serially connected water pipe connects all electric cabinets of the machines and provides cooling water for them. On hot summer days, the electronics reach a critical temperature when the machines are at full load. Therefore, the machines have to be switched off. The interaction between the energy and the material flow exists firstly in the dependency between the temperature and the load of the machines (material flow influences temperature), and secondly, in the powering down of the machines when a critical temperature is reached (temperature influences material flow).

2.3 Results

Using the models, the project team executed several simulation runs. The user adjusted the critical temperature value for powering down in each simulation run to test the effects on the throughput of the production line. The simulation experiments illustrate that the solution provides valid results and that the coupling between *Plant Simulation* and *Simulink* works as designed. The correlation between the temperatures for powering down and the throughput of the production line is comprehensible [11].

3 Further Developments

While the *SimEnergy* solution provides an executable model-coupling platform with additional functionality for project management and export of results, it turns out to have several drawbacks. The biggest issue is the need to convert the *Simulink* model into a *.dll first so that it depends on a wrapper application to work properly. Furthermore, observing the animation of the model during the simulation run is impossible when converting it to a *.dll-file. Observing the animation of the model, however, is an important validation technique [3]. Besides, the user can only change the parameters of the simulation if this option is already prepared in the models beforehand and changes have to be made in the *SimAssist* software. Further changes require modifying the original model and a newly compiled *.dll-file. These three considerations led to the need to simplify the solution. The Department of Organization of Production and Factory Planning at the University of Kassel continued the development after the end of the project in 2015 by coupling the two simulation tools directly, abandoning all middleware. The next chapter describes the resulting solution.

3.1 Technical solution

As already described, there are three major problems which originally led to the development of a solution using *SimAssist* and a *MATLAB* wrapper application as middleware:

- The need for data type conversion between the models.
- The need for time-synchronization between a discrete event simulation tool and a continuous one.
- The need to resolve string data type network messages that contain data for several simulation blocks.

The authors solved the first issue by analyzing the possibilities that the simulation software provides and by extensive testing. Sending data from *Plant Simulation* to *Simulink* leads to the realization that the string data type, sent by *Plant Simulation*, is interpreted as ASCII Code in *Simulink*. Thus, when sending a figure one (1, e.g. for machine is working) or zero (0, e.g. for machine is idle) the 'TCP/IP receive block' in *Simulink* receives a 49 (for 1) or 48 (for 0) respectively. A simple mathematical operation in the model of subtracting 48 from the received value delivers the original message.

Information whether the machine is operating (1) or idle (0) is already enough for calculating its heat emissions. If more machine states are relevant they can also be expressed using numbers, like '3' for standby. Programmed methods in *Plant Simulation* retrieve the state of the machine and encode it into a single digit number.

Another problem that led to the original solution in the research project is the fact that the 'TCP/IP send' block in *Simulink* sends numerical data types, which *Plant Simulation* cannot interpret. After analysing the available blocks in *Simulink*, the authors decided that the 'to instrument' block is usable for communication with devices over network that require a string data type. *Plant Simulation* is able to interpret the messages sent by the 'to instrument' block and programmed methods convert the messages to integer variables.

Depending on the received value, machines can be marked as out-of-order, as idle or as working, thus simulating temperature caused failures. Figure 2 shows the newly developed architecture for directly coupled simulation models.

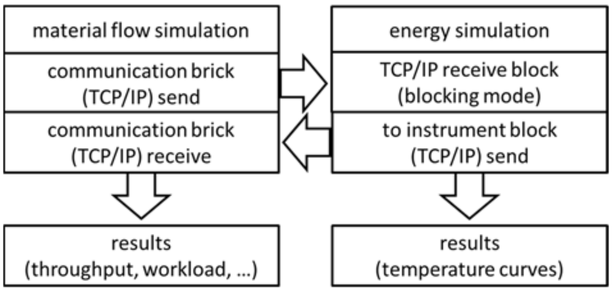

Figure 2: Architecture for directly coupled simulation models.

We transferred input data, such as the table containing the outside temperature during the day, which influences the cooling capacity of the cooling tower in the physical *Simulink* model, from the *Plant Simulation* model, where it was originally stored, directly into the *Simulink* model, eliminating the need to transfer that data, as it has no relevance for the material flow model.

Within the *SimEnergy* solution, the *SimAssist* software is responsible for time-synchronization between models. Now that we have developed a solution that no longer makes use of the SimAssist software, a new solution for time-synchronization has to be developed. In *Simulink*, we set the 'TCP/IP receive' block to 'blocking mode' so that the simulation continues to the next time step once data is received.

To prevent the *Plant Simulation* model from running ahead, we implement the sending sockets and the corresponding methods to stop the simulation time once data is sent. The simulation time continues once the model receives data from the *Simulink* model. The timer, which controls the time steps in which data is sent, is set to the same simulation time step as the *Simulink* 'TCP/IP receive' block. That means that both simulation models run alternately. The *Simulink* model is still a continuous simulation within each time step. However, when the time step is reached, it pauses until it receives new input data from the *Plant Simulation* model. This solution leads to both models running synchronously in fixed time steps. The received value is used for calculations within the entire time step. Consequently, changes in the machine states occurring in between two time steps have no effect on the *Simulink* model.

To further avoid the need to send several data encoded in one string, which leads to decoding problems, each machine connects to the respective blocks in the energy model by a separate socket block using different TCP/IP-ports. While this works well for now, it might get confusing for complex models.

To test this newly developed solution the team has modified the original models built by the simulation service providers in the *SimEnergy* project so that they use the new communication method. The results are positive: The runtime of the coupled models is comparable to using the SimAssist software. Time-synchronization worked well and both models run in fixed exchange intervals. The user reads the results directly from the models and is able to export the data to Excel for further processing. To simplify this process we write methods that store relevant data in tables and variables.

3.2 Experiments and results

As already mentioned in the introduction of this paper, it is questionable whether the increased workload for building two coupled simulation models provides any additional benefit for the user. One possible simplified solution would be to use a single *Plant Simulation* model and simulate the energy aspects using approximations. To compare both solutions, the authors ran coupled simulations first. The coupled solution delivered the following temperature curves with a critical temperature of 40° C and a restart temperature of 36° C.
In Figure 3 the curves M1 to M3 show the temperatures for the three examined machines.

T_Out shows the outside temperature during the day. Only M3 is subject to temperature caused powering off. The other machines are also affected because of the resulting blocking of the conveyor belt. The coupled *Plant Simulation* model shows the logistic key performance indicators like throughput in 24 hours and availability of the machines. M3 has temperature related failure rates of 18.54 % of the total operating time.

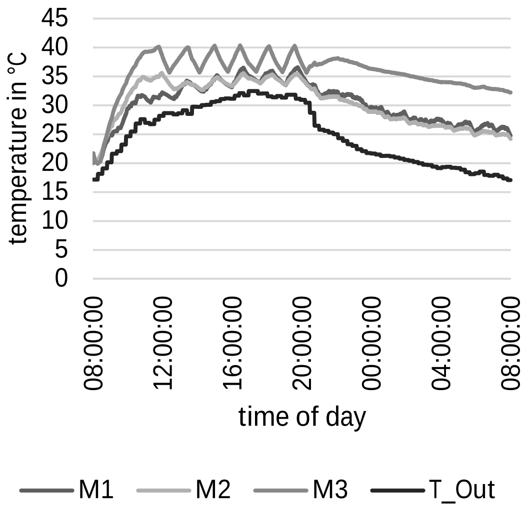

Figure 3: Temperature curves for the machines 1 to 3.

Table 1 shows the output of the three different products produced on this line for 24 hours of simulation time. As there are no random variables in the models and no parameters were changed, all three simulation runs deliver the same output numbers. We can also conclude that there are no randomly occurring issues with data exchange.

	drain_1 output	drain_2 output	drain_3 output	sum
run 1	688	549	467	1,704
run 2	688	549	467	1,704
run 3	688	549	467	1,704

Table 1: Output of three different product types in the coupled simulation model.

To test whether the same simulation results can be achieved by using a *Plant Simulation* model alone without coupling it with another model, we approximate the model behavior in *Plant Simulation*. The failure rate of 18.54 %, which resulted from the coupled simulation, is now used as availability in the machine block in *Plant Simulation*.

The block of machine 3 is parameterized with an availability of 81 % (rounded from 100 % - 18.54 % = 81.46 %) and a MTTR (mean time to repair) for cooling down of 10 minutes.

This time the simulation results depend on the random number seed. The failure rate and duration of machine 3 is the only parameter influenced by the random number seed. The residual model remains unchanged from the coupled experiment. We conducted five simulation runs with different seed values to obtain secure results. Table 2 shows the output numbers of each product type and the resulting average over the five simulation runs.

	drain_1 output	drain_2 output	drain_3 output	sum
run 1	674	543	474	1,691
run 2	658	492	430	1,580
run 3	696	575	485	1,756
run 4	706	582	496	1,784
run 5	695	571	489	1,755
average	685.8	552.6	474.8	1,713.2

Table 2: Output of three different product types in single Plant Simulation model.

As expected, the average output numbers are similar to the results of the coupled simulation.

3.3 Influence of on and off temperatures on output

According the Fourier's law, the heat flux density is proportional to the temperature gradient. When heat is only transported in one direction, the heat flow is described as in formula 1:

$$\dot{Q} = -\lambda * A * \frac{d\vartheta}{dx} \tag{1}$$

$\dot{Q}$ represents the heat flow, λ the thermal conductivity, A the surface, $d\vartheta$ the temperature difference and dx the thickness of the wall [17].

In our model, all variables apart from the temperature difference are constant or can be assumed to be constant during the simulation runs. That means that the effect of cooling the electric cabinet is biggest if the difference between the temperature of the cabinet and the temperature of the cooling water is as high as possible.

The longer the duration in which the machine is switched off, the smaller the benefit from the cooling because of the decreasing temperature difference. Thus, short intervals are desirable when switching the machine off for cooling.

We performed several experiments to examine these effects and their impact on the throughput of the material flow model. Table 3 shows the results of the experiments with 40° C as temperature for switching off (T_off) and 36° C, 38° C and 39° C for switching on (T_on).

T_off (°C)	T_on (°C)	output combined	failure rate	number of failures
40	36	1,704	18.54 %	6
40	38	1,774	15.43 %	10
40	39	1,811	13.75 %	13

Table 3: Results depending on the on/off temperatures.

As expected, we can see that with higher temperatures for switching on, the output of the production line increases and failure time decreases. However, the line had to be stopped more often with an increasing T_on. In conclusion, the output becomes higher for more frequent, but shorter off-times. The optimal operating situation is when the line never reaches the critical temperature. Thus, the operator should slow down production to such an extent that the machines approach critical temperature but never reach it.

3.4 Conclusion

Based on Chapter 3.2 we come to the conclusion that simple approximations in the material flow simulation lead to similar results in logistic key performance indicators. But it has to be remembered that the availability value for machine 3, which is the basis for the approximation, could only be obtained by using coupled simulation. Another possible way to obtain the required data is to measure the failure rates in the real-world system. If the system is still in the planning phase and no real machines are available, measuring is not an option. In this case, a coupled physics simulation of energy and material provides additional information to the simulation user and the additional effort might be justified depending on the use case.

Coupled simulation might also be useful for determining the optimal operating point for a production line if it depends on physical processes. However, in practice this may be difficult as the ideal operating speed depends on many variables like outside temperature or the load of all machines in the production line, which cannot be accurately forecasted. Furthermore, we neglected start-up times for machines in this scenario. Long start-up times will lead to preference of longer on/off intervals.

4 Second Use Case

The first use case from the *SimEnergy* project has only small differences in output values. Due to the relatively constant production of parts, the exact time of an occurring failure is not relevant to the output of the production line. To analyze the behavior of a system where the exact time of the failure (or any other event) matters, we define another u e case for our simulation.

4.1 Model description

To define a situation where the time of an event matters for the results of the simulation we built a model consisting of a soldering oven. It runs at a certain temperature, which is provided by a heater in the oven. Parts enter the oven on special workpiece carriers, which are transported on a conveyor belt and move slowly through the oven. At the end of the oven, they are separated into good and defective parts depending on the time spent in the oven. Figure 4 shows the conceptual model of the material flow model implemented in *Plant Simulation*.

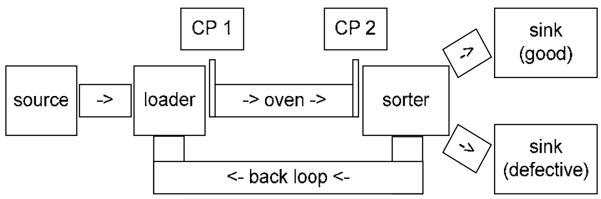

Figure 4: Conceptual model of the material flow.

The source generates the parts and a conveyor belt moves them to the loader where they are loaded onto the workpiece carriers. At checkpoint 1 (CP 1), the timestamp when they enter the oven is saved. After leaving the oven at checkpoint 2 (CP 2), the timestamp of exiting the oven is saved.

We use those values to calculate the time of stay in the oven for each part. At the sorter, we remove the parts from the workpiece carrier, which we put on a back loop to provide it for new parts at the loader. Depending on the time of stay in the oven, we separate parts into good parts and defective ones.

The *Simulink* model contains the model of the oven and its internal heating process and the heat loss via convection and radiation as well as the heat loss caused by the cold parts entering the oven. This heat loss depends on the material flow into the oven, which directly depends on the throughput. The *Plant Simulation* model collects throughput data for each time step (60 seconds) and transmits this aggregated value to the *Simulink* model, where the mass flow is calculated by multiplying the part count with the mass of the parts. The part temperature on entering the oven is considered constant. If the oven reaches a defined temperature, the *Simulink* model transmits a message to the *Plant Simulation* model that the oven is now ready. The production starts by the time the temperature of the oven has declined until it reaches the critical temperature. In this case, the *Simulink* model transmits a message to switch the oven to a 'failure' state. The production stops until the oven has heated up enough to continue production.

This time we entered random variables into our material flow model. The arrival time at the source is exponentially distributed and the working time at the loader is normally distributed. Parts do not arrive constantly at the source but in batches of 50. That means that there are times with production when a batch is in production and idle times. This way, we intended to examine the influence of the failure time on the throughput of the system and the throughput time of each part.

4.2 Experiments and results

At first, we performed coupled simulation runs. As the material flow model contains random variables this time we run five replications with a simulation time of 24 hours and look at the resulting values for throughput, throughput times and failures. Table 4 shows the average results for the coupled simulation experiment with five simulation runs with different seed values for the random variables.

key performance indicators	coupled simulation results
amount defective parts	212.2
amount good parts	1,438.6
total amount parts	1,650.8
maximum throughput time (hh:mm:ss)	00:14:38
minimum throughput time (hh:mm:ss)	00:03:40
average throughput time (hh:mm:ss)	00:05:15
failure rate (in percent)	15.56
absolute amount of failures	19.8
average time per failure (hh:mm:ss)	00:11:01

Table 4: Average results for the coupled simulation runs.

To compare the results of the coupled simulation with a simplified simulation in *Plant Simulation* as we did with the original *SimEnergy* models, we implemented the failure rate for the oven now into the *Plant Simulation* model as a failure profile with 84.44 % availability and a MTTR of 11 minutes as they result from the coupled simulation run. We set the 'failures relate to' setting to 'working time' because the oven can only fail due to critical temperature when it is working. Table 5 shows the results of the simplified failure behavior in the *Plant Simulation* model.

For the *Plant Simulation* experiment we performed 10 simulation runs. The average value for the 10 runs is shown in Table 5. As we can see, some values differ only slightly from the coupled simulation experiment. The differences are quite significant for some other key performance indicators. The higher maximum throughput time is caused by the unlikely event of two failures happening right after each other. In this case the throughput time of one part is considerably higher than in the coupled simulation model where two failures happening right after each other is impossible due to the nature of the heating and cooling model in *Simulink*. However, if some parts are affected by two failures, this also means that in total fewer parts are affected by failure thus reducing the total amount of defective parts. Failure rates in percent and the absolute amount of failures are smaller because in *Plant Simulation* failure rates only relate to working times. Thus, the failure times in relation to the total simulation time are reduced. Minimum throughput time remains constant. 3:40 min is the shortest time for a part to pass through the oven caused by the moving speed of the conveyor in the oven.

key performance indicators	coupled simulation	only *Plant Simulation*	difference
amount defective parts	212.2	103	51.46 %
amount good parts	1,438.6	1,568.8	-9.05 %
total amount parts	1,650.8	1,671.8	-1.27 %
maximum throughput time (hh:mm:ss)	00:14:38	00:29:42	-102.96 %
minimum throughput time (hh:mm:ss)	00:03:40	00:03:40	0.00 %
average throughput time (hh:mm:ss)	00:05:15	00:04:40	11.11 %
failure rate (in percent)	15.56 %	7.99 %	48.64 %
absolute amount of failures	19.8	11.1	43.94 %
average time per failure (hh:mm:ss)	00:11:01	00:09:54	10.16 %

Table 5: Comparison of simulation results.

4.3 Conclusion

In this second example we defined a scenario where the exact time of a failure is important for the simulation results as it influences the amount of defective parts and the throughput times. The approximation in *Plant Simulation* without coupling the model now delivers less accurate results compared to the coupled simulation. The thermodynamic processes of heating the oven and the cooling from the entering mass flow determine the exact time for temperature related failure. This behavior cannot be simulated accurately in *Plant Simulation* alone. Furthermore, to approximate the failure behavior we need data from the coupled model: The percentage of failure time and the average duration of failure. This data cannot be acquired without a coupled simulation because it depends on the material flow itself. Material flow key performance indicators like throughput and product type define the cooling of the oven and the temperature in the oven influences the material flow. Thus, both models depend on each other to deliver accurate results.

5 Prospects for Further Research

As the results for a coupled simulation approach using *Plant Simulation* and *Simulink* look promising, we are further developing this approach. Other use cases from theory and practice will provide further opportunities for testing whether the additional effort required for a coupled simulation delivers more accurate results than a simplified approximation in a single material flow model. Additionally, we will develop a guideline to support simulation users or service providers deciding which simulation approach under which circumstances will be the best one. For this purpose we will define criteria to identify interconnections between energy influences on the one hand and production and logistics on the other, which lead to the necessity of a coupled simulation.

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