Synergies from Process and Energy Oriented Process Chain Simulation – A Case Study from the Aluminium Die Casting Industry

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Abstract

Due to the significant ecological relevance and constantly rising prices, energy consumption more and more gets into the focus of manufacturing companies which strive to consciously consider energy consumption when planning and managing production facilities. Thereby it is important to take into account the interdependencies on different hierarchical levels in a production system (between single processes and the whole process chain). Against this background this paper presents an approach for a combined application of an energy oriented process chain simulation and a detailed process simulation. This approach enables an integrated evaluation of the interactions of parameter variations on both levels.

Keywords:

Energy Efficiency; Simulation; Aluminium Die Casting

1 INTRODUCTION

In modern automotive design lightweight construction plays a major role for reducing fuel consumption and improving the driving characteristics of automobiles. An extensively applied way for reducing the weight of automobiles is the substitution of steel parts through aluminium parts. Many of these parts have a very complex structure and still they need to be produced in mass production. While being able to fulfil these strict requirements in terms of quality and quantity aluminium high pressure die casting is a well established production technology. This is also reflected in the quantity of produced aluminium die casting parts. In 2008 only in Germany over 413,000 tons of die casted aluminium parts were manufactured causing over one million tons CO_2eq in the foundry. [1] [2] Having overcome the impacts of the recent global financial crisis the aluminium die casting branch recovers to well-known growth rates. By the year of 2005 the yearly growth rate in this industry branch in Germany was about 10%. Nevertheless the current growth rates in the aluminium die casting industry cannot hide the fact that this whole industry is under heavy pressure of reducing its overall costs in order to fulfil the requirements of its customers which are mainly automotive OEMs. As major cost drivers in this industry energy and aluminium prices need to be considered. Steadily increasing prices for raw materials (Figure 1, a) and energy (Figure 1, b) before the recent crisis and again a trend to increasing prices for aluminium and energy supplies after the financial crisis exert significant pressure to reduce energy and material consumption within the aluminium die casting process chain.

In order to increase the efficiency of production processes and process chains especially in energy intensive industries like the aluminium die casting industry, a systematic approach against the background of a comprehensive system understanding is necessary [4] [5]. It is not sufficient to focus on only single selected system elements of the production. To avoid focusing on minor relevant aspects and local optimisation as well as problem shifting the whole production system including all relevant input and output flows has to be taken into consideration. Against this background, Figure 2 shows fields of action in the context of energy- and resource efficiency in production. One can differentiate between the machine- or process perspective and the view on process chains or production/factory system, yet both are directly connected as depicted in the figure. Based on either singular or permanent data collection, the understanding of interrelations through modelling as well as on suitable methods for the evaluation and prediction of operating behaviour, it is the ultimate objective to integrate energy- and resource consumption as a further dimension into operational decisions (besides conventional objectives like for instance

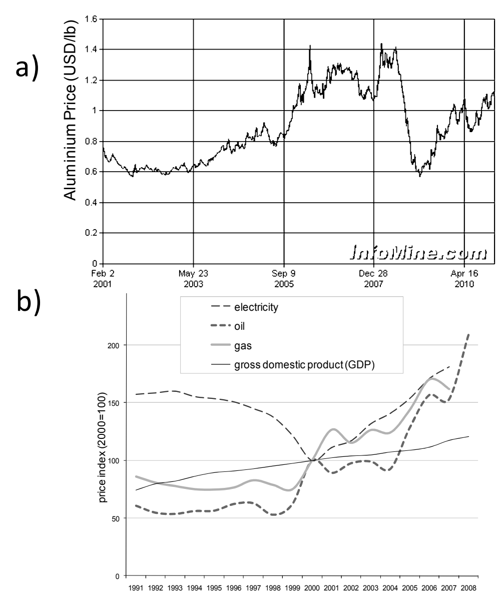

Figure 1: Development of a) Al (10 year progression 2000-2010, graph from infomine.com) and b) Energy Prices (compared to GDP) [3].

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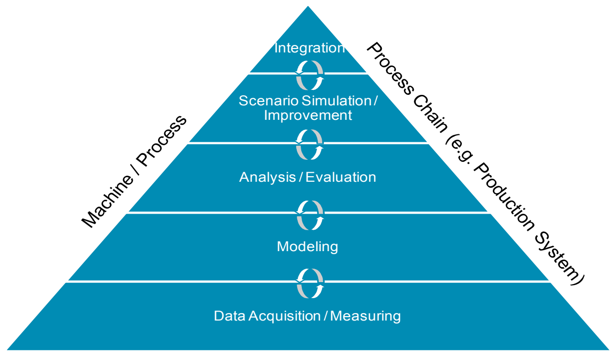

Figure 2: Fields of action for energy- and resource efficiency in production [5].

utilization, cycle times, quality rates). Within this systematic approach it is increasingly important to develop scenarios for improving the focussed process or process chain and to evaluate the impact of these measures based on a simulation approach before their individual implementation. The simulation of improvement scenarios becomes necessary as the energy and resource consumption behaviour of production machines is usually highly dynamical and also complex on process chain level due to the manifold interactions of the single subprocesses and also because of the their interdependencies with connected peripheral equipment and technical building services. [5]

The effect and synergy of a combined application of a process simulation (Magmasoft®) and a process chain simulation (energy oriented process chain simulation, developed by IWF, Technische Universität Braunschweig) will be discussed in this paper. As a basis the underlying aluminium die casting process chain will be introduced in the following.

2 ALUMINIUM DIE CASTING PROCESS CHAIN

2.1 Subprocesses and material/energy flows in the aluminium die casting process chain

According to the focus of the BMBF-funded research project ProGRess (www.progress-aluminium.de) the aluminium high pressure die casting process chain can be described as depicted in Figure 3. The process chain consists of four major steps in order to produce parts in a defined quality: smelting of aluminium, the die casting process itself, heat treatment to set up certain metal properties and one or several machining processes to realize the final geometry and surface quality.

The first step in the in-house process chain in aluminium die casting companies is a centralized smeltery in which different furnaces smelt large quantities of solid aluminium ingots to liquid aluminium that is transported in crucibles via fork-lift trucks to the diverse die casting cells in the casting plant. At the casting cells the molten aluminium gets filled into dosing ovens that are also used for maintaining a defined temperature within the metal before it is charged into the casting chamber. Usually natural gas is used for smelting the metal in the smeltery whereas electricity is used for maintaining the temperature in the dosing oven. An alternative solution for the supply of the casting cells with molten aluminium is the supply of liquid metal directly from the metal supplier to the casting plant and the casting cells. In this case there is no need for smelting furnaces in the casting plant and the energy for resmelting the aluminium after it has already been smolten during the alloying process can be saved. However in this case specific infrastructure needs to be implemented at the metal supplier and the casting plant. Furthermore the molten metal needs to be heated during the transportation between metal supplier and casting plant.

The die casting process itself takes place in casting cells that usually consist of the mentioned dosing oven, the die casting machine with its dies, tempering units, parts-removal robots, spraying devices for applying release agents and saws or stamping presses for removing e.g. gating systems and sprue waste from the work piece. Inside the casting cells the liquid aluminium is casted into solid semi finished parts. In this process electricity is consumed by the dosing oven, the die casting machine, the spraying device, the involved robots, the tempering units, the spraying robot and the saws/stamping presses. Additionally release agents, water and compressed air are used by the spraying device. As process output there are the semi finished parts and aluminium (gating systems, sprue) that is stamped off the semi finished parts. After a visual quality check the semi finished parts are processed by a mechanical treatment. As these operations can be manifold also the input and output flows can be very versatile. Besides diverse auxiliary flows (e.g. coolants or compressed air) at least the electrical energy consumption by the value adding processes and the peripheral equipment like e.g. exhaust air systems needs to be analyzed. In some cases the die casted work pieces also get a heat treatment in order to influence the material properties. Depending on the intended function of the product or by using self hardening alloys this process step is not necessary.

As it is illustrated in Figure 3 the described process steps are usually divided by quality gates where scrap material is assorted. This assorted material as well as swarf and in particular the gating system and sprue waste that are stamped off the work piece directly after the casting are transferred to the smeltery again and get resmelted and supplied to the casting cell afterwards as cycle material. Additionally, as mentioned, there are diverse auxiliary flows that are needed to ensure stable casting and machining processes like cooling water, release agents, lubricants, etc. that need to be taken into consideration when it comes to a holistic assessment of this process chain.

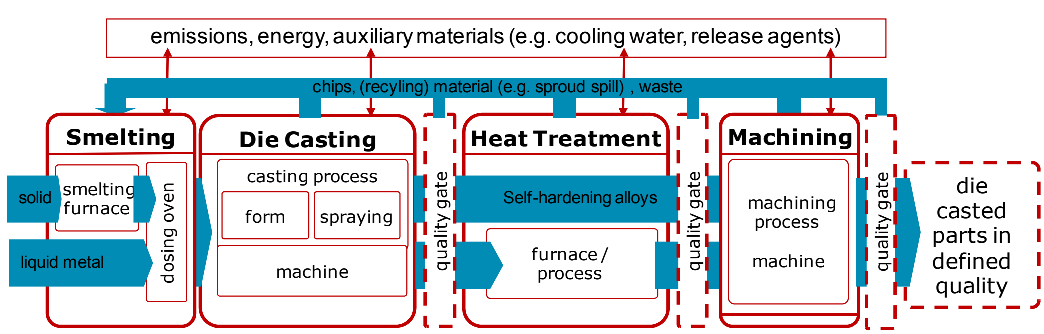

Figure 3: Aluminium die casting process chain.

2.2 Challenges in aluminium die casting in the context of energy and resource efficiency

The aluminium die casting process chain is strongly depicted by significant losses of energy as well as material. A major part of the energy input is needed for heating of material/parts (e.g. very high relevance of waste heat) [6]. But especially the heat balance of the die casting process itself is characterised by high energy losses. A large part of the energy input is lost in the process in terms of heat or by cooling processes. On the whole, the extensive heat losses in the die casting process are extremely dissatisfying in terms of environmental performance respectively energy efficiency. Figure 4 shows the main thermal energy flows in the die casting process of aluminium. Besides the heat losses in the value adding process also the heat losses in non value adding peripheral equipment cannot be ignored.

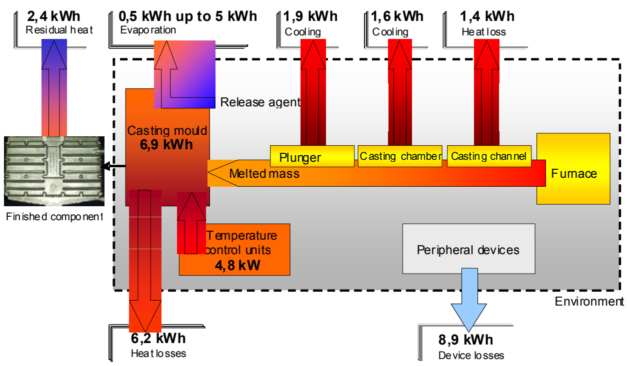

Figure 4: Thermal energy flows in the die casting process of aluminium [6].

Compared to the casting process itself even more heat is needed in the smeltery for the liquidation of aluminium. In this particular step of the aluminium die casting process chain the energy demand is directly linked to the amount of material that needs to be smelted and therefore can be reduced by reducing the amount of material that needs to be processed in the casting process [7]. However, it is exactly the bad exploitation of the raw material aluminium that is problematic in the process. Spillover and sprue (which can make up up to 50 % of the cast form and are determind by the product and tool design) as well as finished components, which do not meet the required quality demands, and parts from the start-up process are partly remelted into ingots as cycle material and have to run through the whole energy intensive process again. Depending on the production parameters or component this applies to 30-70% of the originally input material (Figure 5) [2]. The impact of the continuos resmelting of cycle material can be estimated regarding the fact that in an average aluminium smeltery 930 kWh of energy are needed for smelting one ton of aluminium. This value is based on the total energy consumption of a smeltery that uses shaft furnaces and can vary depending on the smelted alloy but still can be used for

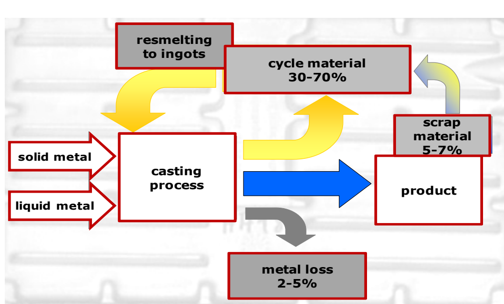

Figure 5: Cycle material in aluminium die casting [2].

assessing the impact of material efficiency in foundries in relation to their total energy consumption.

Furthermore, material losses of 2-5% occur, which cannot be re-integrated into the process again and which are simply lost. Whereas from the company's point of view those losses are mainly essential in terms of material costs, the energy-intensive and environmentally damaging exploitation of aluminium is especially critical from an ecological point of view (waste which potentially endangers the environment, large areas are necessary for the winning of bauxite, electrolysis for winning aluminium). Thus, from a global point of view, besides an extensive usage of recycled secondary aluminium an enhancement of material efficiency and therefore a reduction of aluminium consumption indirectly also leads to a considerable decrease of energy demand [8] [9].

Against this background measures for increasing the energy and material efficiency can be devided in two categories: organizational and technology/design oriented measures. Organizational measures adress measures like cycle time reduction and the reduction of unproductive idle modes whereas technology or design oriented measures adress measures that focus on the improvement of the production process itself (e.g. by using energy effcient drives or reducing scrap material) or the improvement of the product or the corresponding machine tools (e.g. through volume reduction of the product and its gating systems).

3 SIMULATION APPROACHES TOWARDS ENERGY AND RESOURCE EFFICIENCY IN ALUMINIUM DIE CASTING

3.1 Process simulation in aluminium die casting

Within the research project ProGRess the company Magma Gießereitechnologie GmbH simulates the effects of changing the geometry of e.g. gating systems and the effects of a variation of process parameters (e.g. cycle time and injection speed) on the quality of the casted products. By doing this optimized process parameters can be found through conducting manifold simulation runs. So e.g. the cycle time, quality rate or gating system volume can be reduced/increased in iterative simulation runs and the corresponding product quality (in terms of porosities, solidification behaviour, etc.) can be predicted in order to define the best process parameters according to the individual target function that still guarantee high quality products.

To illustrate the potential of a process simulation for the aluminium die casting process Figure 6 compares the original design of an aluminium die casting product and its gating system with an improved version in which the volume of the gating system has been reduced significantly. Through a process simulation that has been conducted with the software Magmasoft® it can be ensured that the quality of the product in terms of entrapped gas, solidification behaviour, etc. is not negatively affected by this measure. By applying this measure 25% of the metal in the gating system can be saved which leads to a decrease in the total aluminium shot weight of approx. 12% [10]. As described above this also directly affects the energy efficiency in the smeltery as there is no smelting energy needed for the saved metal.

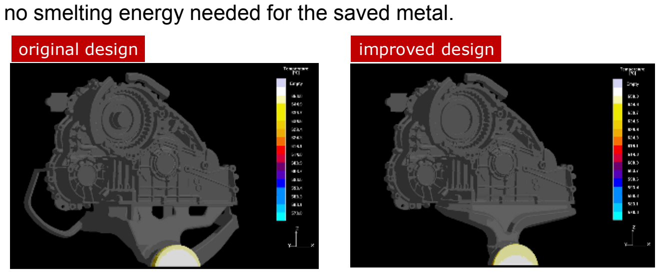

Figure 6: Design variation of gating system [10].

In this sample simulation run it has also been shown that besides the reduction of the gating system volume also the cycle time can be reduced by 8%. Although this is a respectable result it cannot be predicted whether this measure would lead to bottlenecks in the downstream process chain and therefore would flatten the effect on the production line.

3.2 Process chain simulation for aluminium die casting

In contrast to detailed process simulation approaches process chain simulation focusses more on the interdependencies and interactions of multiple processes within a factory. Referring to previous publications (e.g. [11] [12] [13]), the architecture (input, logic, user and evaluation layer) of the simulation that is used for this paper shall not be explained in detail here. Basically it is a modular, flexible approach which allows a realistic representation of the production system with all the interdependencies and dynamics of involved technical equipment. As an extension of well-known material flow simulators all energy related input and output flows are explicitly considered. This means that based on real metered consumption data the machine behaviour can be depicted with state charts – each operating state has a definable duration (e.g. based on certain time or trigger events) and is connected with a certain consumption of a resource (described as value or equation, e.g. depending on process parameters). Thus, with this technique the dynamic consumption behaviour of e.g. all forms of energy, any (auxiliary) materials or even emissions can be modelled. Furthermore an energy oriented process chain simulation can predict the overall energy consumption of whole process chains that result from single process parameter variations [11]. Sample load profiles (for electricity as well as compressed air consumption) that can be generated this way are illustrated in Figure 8. The derivation of the electricity consumption that is caused by the generation of compressed air is simulated in an integrated module in which the behaviour of compressors can be modelled. [12]

3.3 Synergies from a combined application of process and process chain simulation

The impact of organizational or technological or design oriented improvement measures regarding economical criteria (lead times, product-related costs, etc.) as well as ecological criteria (energy and material consumption) underlies dynamical effects within the process (e.g. thermodynamical behaviour of material flows) as well as along the process chain (e.g. dynamic energy demand, bottle neck situations). As these effects often depend on partial reciprocal interrelations of the individual subsystems of a production process or on interactions of subprocesses within a process chain a simulation approach is needed for the evaluation of improvement scenarios that are proposed to be implemented in the process chain. Especially detailed process oriented simulation approaches face the challenge that they can only serve with a very limited perspective when it comes to a holistic evaluation of a process chain. Still their potential for delivering a detailed view into the order of events of the main processes within a process chain is often more promising than the exclusive use of a process chain simulation. As it is often practically not feasible to run a detailed process simulation for every subprocess and as it is also not feasible to simulate the effect of every single process parameter in every kind of peculiarity due to restrictions of computing capacities a combination of the advantages of process and process chain simulation approaches is needed. One approach for the pre-evaluation of the effect on a process chain that comes from parametervariations within one single process will be introduced in the following. This pre-evaluation will set the boundaries for a parametervariation in a detailed process simulation that is used for the improvement of die casting operations. With these restrictions as input for detailed process simulations those simulation runs can focus on application areas that will lead to real improvements also on a process chain level. In this way a target-oriented improvement of production systems can be ensured.

4 CASE STUDY

The structure and characteristics of the interlinked processes of the underlying case study for the simulation and pre-evaluation of parametervariations is shown in Figure 7. In this case three casting cells with peripheral equipment serve two identical CNC milling machines for mechanical treatment before they are being transported automatically by a conveyor in a one piece flow into an abrasive blasting machine and finally to a palletizing device.

Elements of the process chain that are not depicted in Figure 7 are beyond the system boundary of the case study. Thus effects on upstream processes like smelting ovens are calculated based on the simulation results afterwards.

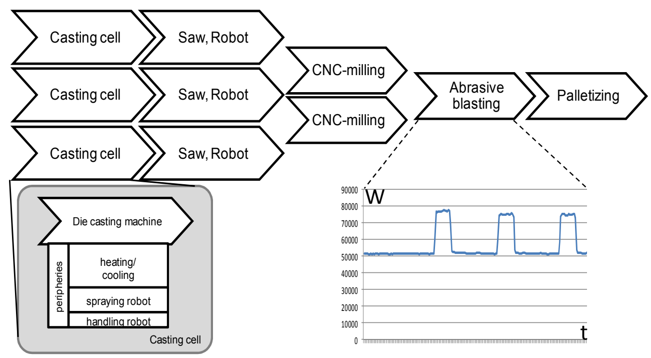

Figure 7: Process chain for simulation case study.

The simulation model that has been deduced from the process chain description is depicted in Figure 8. It is parameterized with real metered data like cycle times, (energy) load profiles depending on operation modes, process dependend material efficiency, etc. and focuses on the consumption of electrical energy in this case. Based on this model and the underlying parameterization for every subprocess of the process chain the effect of changing process parameters in the die casting process on the total energy consumption per part and the required throughput time per part can be estimated. The manipulated process parameters in this case are the cycle time and quality rate. Furthermore the effect of the quality rate in comparison to the material volume of the product and its gating system in terms of material efficiency can be evaluated in

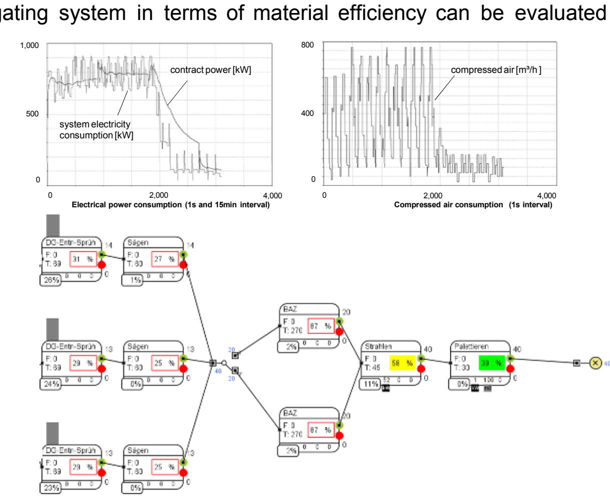

Figure 8: Simulation model based on case study process chain and sample load profiles.

order to evaluate levers for decreasing the embodied energy per part. As this is a process chain simulation only the effects on the process chain are considered. The effects of parametervariations on the intra-process behaviour (e.g. in terms of wear or differing load peaks through speed variations) need to be evaluated afterwards by a detailed process simulation.

4.1 Varied parameters on process and process chain level

The objective in this case is the production of 40 flawless parts.This output is set fixed. Through the variation of single process or design parameters manifold scenarios can be simulated. Table 1 depicts the single parameters (cycle time, material volume, quality issues, etc.) that also can be manipulated in detail in the process simulation Magmasoft®. In this case the shot weight is directly linked with the material efficiency. As the product design and the product weight are set fixed the aluminium shot weight can still be varied because of possible design variations of the gating system. As the gating system gets stamped off the product after the casting process it becomes cycle material and the volume of the gating system determines the material efficiency of the die casting process.

Regarding the two simulation approaches the volume of the gating system has a direct impact on the mold filling and therefore on the product quality that can be simulated in the process simulation. On the process chain level the material efficiency as well as the quality rate that determines another part of the cycle material have an impact on the total energy consumption regarding the smelting energy in the shaft ovens. The cycle time can be manipulated by changing the clamping time of the die casting machine (DCM). On process level this is linked with the simulation of the solidification behaviour and the shortest required cycle time for continuous solidification. On the other hand the effects of manipulated cycle times can lead to new bottleneck situations or changes in the length of standby or operative modes of succeeding processes on process chain level. It is assumed that the characteristic of the underlying load profile of the DCM is not affected by changes in the cycle time in this case as the varied clamping times represent only changes in idling times and no changes in the dynamic power consumption behaviour of the machine.

4.2 Simulation scenarios based on parameter variations

The described parameters are varied in a realistical and technical feasible range in different scenarios (see Table 1) in order to pre-evaluate their effect on the process chain as an input for a succeeding detailed process simulation. They are individually compared to a base run of the process chain simulation. Scenario 1 (S1) to scenario 5 (S5) describe an increase in material efficiency through an improved design of the gating system which leads to a decrease in the aluminium shot weight. S6 to S13 describe a variation in the cycle time whereas a decrease is considerd as well as an increase. S14 and S15 deal with a variation in the quality rate, which also affects the overall energy consumption as energy is wasted through scrap material. S16 is a combination of S5 and S9 and therefore describes the effect of reduced cycle times in combination with reduced aluminium shot weight. This combination

Scenario	Shot weight	Material Efficiency	Cycle Time	Quality Rate
Base run	100%	71,10%	100%	100%

Scenario	Shot weight	Material Efficiency
S1	98%	73%
S2	96%	74%
S3	94%	76%
S4	92%	77%
S5	90%	79%

Scenario	Cycle Time
S6	98%
S7	96%
S8	94%
S9	92%
S10	102%
S11	104%
S12	106%
S13	108%

Scenario	Quality Rate
S14	95%
S15	98%

Scenario	Shot weight	Material Efficiency	Cycle Time	Quality Rate
S16*1	90%	79%	92%	100%
S17*2	90%	79%	92%	100%
S18*3	90%	79%	92%	100%
S19*4	90%	79%	92%	100%
S20*5	90%	79%	92%	100%

*1: Combination of S5 and S9 *4: Only 2 DCMs
*2: Abrasive Blasting: Lot Size 1 *5: Only 2 DCMs and S16
*3: Abrasive Blasting: Lot Size 10 and S16

Table 1 : Scenarios and parametervariations for process chain simulation case study.

is noteworthy as usually a reduction of shot weight enables a reduction of cycle times as the solidification of the metal takes less time when less material is casted. S17 and S18 describe the effect of selected organizational measures for an improvement of the process chain. Lot sizes of a process with high energy consumption during standby modes (abrasive blasting, see Figure 7) are varied and the process is simulated to be shut down during idling times in order to avoid standby energy consumption. S18 combines S17 with S16. S19 describes the reduction of DCMs in the process chain from three to two as another orgainzational measure. S20 combines S19 with S16.

4.3 Process chain simulation results as boundary conditions for process simulation

Figure 9 shows the simulated energy consumption per flawless part in relation to the result of the base simulation run which is paramterized with real metered process data and parameters. The base run itseld shows that the die casting cells are the main electricity consumers with a share of about 73%. The abrasive blasting process as well as the compressors for the generation of compressed air have a share of 11% each whereas the saws, robots and CNC-milling-machines have a share of only 5% in total.

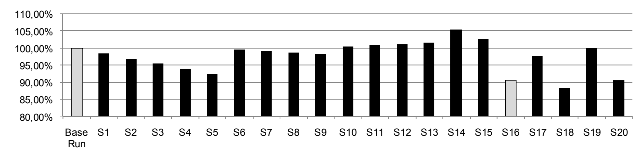

Figure 9: Total energy consumption per flawless part.

It is obvious that the reduction of casted material leads to a decrease of the energy consumption per part as the saved metal does not need to be smelted. In comparison to that the variation of cycle times does not lead to a strong increase or decrease of the energy consumption on process chain level. On the contrary a decrease of the quality rate leads to a significant increase of energy consumption as it is also connected with additional scrap material that needs to be smelted. Regarding that a decrease in the volume of casted metal often allows a decrease in the cycle time of the process it is shown with the results of S16 that this combination of varied parameters leads to a decrease in the energy consumption per flawless part of about 10% compared to the base simulation run. S17 and S18 show that the change to a batch production at the abrasive balsting process has an additional effect of only about 2%. The reduction of DCMs (S19 and S20) show only a marginal effect as the production load has to be transferred to the remaining DCMs in order to produce 40 flawless parts – but it shows that the investment in the third machine would not necessarily have been needed. Regarding the time per part (Figure 10) the simulation results demonstrate that none of the described parameter variations lead to a significant effect on process chain level. The throughput time is only affected by organizational measures like the batchwise production in the abrasive blasting process and the reduction of DCMs.

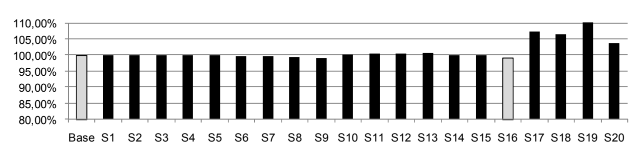

Figure 10: Production time per part.

Figure 11 illustrates the lever that single parameters have on the total energy consumption per part and the production time per part on process chain level. As the same parameters can be simulated in a detailed process simulation like Magmasoft® for the optimization of the die casting process the results of the process chain simulation can span an area of parametervariations in which a detailed and time-consuming process simulation can lead to promising results. Therefore this pre-evaluation of parameters can decrease the effort that is needed for a holistic improvement of processes and process chains.

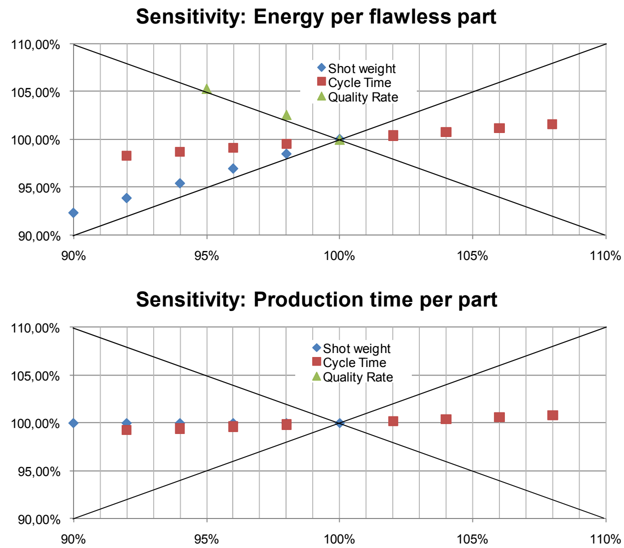

Figure 11: Sensitivity anlaysis of simulation results

5 SUMMARY / OUTLOOK

Against the background of the increasing relevance of considering energy and resource consumption in producing companies the paper introduces the aluminium die casting process chain as example for highly energy intensive process chains. Two simulation approaches are presented for the evaluation of parametervariations on process and on process chain level. Both simulation approaches are applied to case studies from the aluminium die casting industry. Within this case study the process chain simulation is used for a pre-evaluation of effects that occure on process chain level an are affected by variatons in the die casting process. Through this pre-evaluation the area of necessary parametervariations within the process simulation can be reduced in order to decrease the necessary computing capacity and to enable a more target oriented improvement of the process chain. As result of the process chain simulation a potential for decreasing the energy consumption per part by 10-15% seems to be possible. In upcoming research work the results of the process simulation have to be used as input on process chain level. By doing this the results of the detailed optimization on process level can be finally evaluated on process chain level for achieving a severe improvement in the observed production system.

6 ACKNOWLEDGMENTS

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