Evolutionary AI based algorithm for optimizing final mixing processes in the rubber industry

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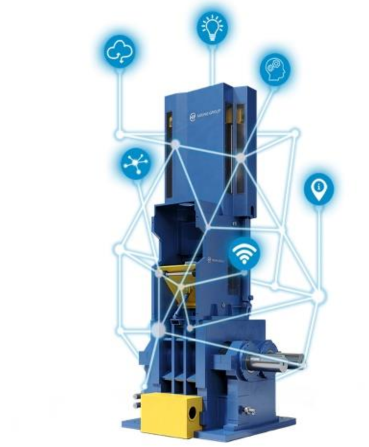

Companies are facing rising pressure to innovate, due to increasing international competition in combination with the requirements of a climate-friendly energy supply and rising electricity and energy costs. Especially in the last few years, energy prices have increased strongly, so that many companies are optimizing their processes to be able to continue producing under the changed framework conditions. The increased price pressure can also be seen in the rubber industry, so that procedures for increasing energy efficiency must be developed. One way to save energy in the rubber industry is to consider, analyse and optimize mixing processes. To optimize final mixing processes, the HF Mixing Group has developed a new tool called “Smart-Final-Mix-Tool”, which analyses and optimizes existing final mixing processes based on mathematical models and artificial intelligence. Within the algorithm, the batch temperature, the energy consumption, and the mixing quality are linked to each other and then optimized. From linking the different parameters, optimal process parameter settings, for example for the rotor speed, can be calculated that apply to the final mixing process. The new tool has already been used at several pilot customers since the beginning of this year with great success. By using the tool for optimizing industrial processes in the technical rubber goods (TRG) industry as well as at tire customers, energy savings of up to 29 % could be achieved.

1. Introduction

The production of technical rubber goods and tire compounds in internal mixers is state of the art today. Various components must be mixed to create a homogeneous batch. This requires mechanical power introduced to achieve this target, is largely frictional heat, resulting in an increase of the batch temperature. Since this is sometimes undesirable, the energy must be dissipated again at the same time. A great amount of energy could be saved, if only the minimum necessary amount of energy is introduced during the mixing process- this requires a clever mixing procedure. [1] [2]

In addition to reduce energy costs, the reduction of climate-damaging carbon dioxide emissions is another reason why companies are attaching importance to efficient and optimized processes. On the one hand, this allows economic advantages, but ecological aspects are also becoming a priority for companies, politics, and society more often. Since 196 countries and the EU agreed in the Paris Climate Agreement in 2016 to undertake far-reaching efforts to reduce greenhouse gas emissions, climate-damaging forms of energy will become significantly more expensive in the future [3]. In the European Union, foreseeable price increases have already been decided in the past as part of various decisions on emissions trading and as part of the "Green Deal". E.g., the CO_2-tax in Germany will rise from €30 per ton of CO_2 emitted in 2023 to minimum €60 per ton of CO_2 emitted in 2026 [4]. It is therefore becoming more and more important for manufacturing companies and plant manufacturers to optimize machines and processes to reduce energy costs. In addition, this also increases competitiveness and secures innovation leadership [5]. Furthermore, increasing energy efficiency in industry is part of several “energy efficiency strategies” of different countries, so that further efforts will have to be made in the future to reduce energy consumption [6].

Since the production of rubber in internal mixers is complex and various process parameters are partly dependent on another, the process engineering and evaluation are of particular importance. The analysis of mixing processes based on the empirical knowledge of the respective company and the responsible process engineer is widespread. Even if, for example, savings in energy, a reduction in mixing time and an increase in throughput are possible, the optimization is highly dependent on the personal background of the responsible process technicians. To optimize mixing processes, systematic considerations and modelling can provide support. This ensures that the procedure and the settings found are independent of the process engineer and show at the same time the maximum energy savings [7].

2. Modelling of final mixing processes

To describe the final mixing process, mathematical models and approaches have been developed to calculate the mixing quality, the batch temperature and link these to the energy consumption. Because the before named parameters are depending on the rotor speed, this process parameter is used for modelling the different parameters. The individual parameters are summarized in an overall model and used to describe and calculate the whole final mixing process. Based on this overall model, various calculation scenarios have been developed as part of the current research activities at the HF Mixing Group together with universities and research institutes to determine an optimal rotor speed curve for the final mixing process. The goal is to obtain a rotor speed curve that represents the minimum energy input to the compound on the one hand and the shortest possible mixing time on the other hand while maintaining the same mixing quality. By implementing this optimal rotor speed curve in the process control, the entire final mixing process can be optimized, and energy and process costs can be reduced. The Throughput can also be increased by reducing the mixing time.

In Order to use the Smart-Final-Mix-Tool, it must be possible to record data in the mixers process control. E.g., the power of the mixer, the rotor speed, the weight of the compound in the mixer or the setting of the temperature control units are required. These data are then used to optimize the process using the Smart-Final-Mix-Tool. The application of the Tool is divided into five different steps that are necessary for the calculation of an optimal final mixing process. The individual steps are as following:

1. Carrying out calibration trials
2. Calculation of heat transfer coefficients
3. Enter relevant parameters in the Smart-Final-Mix-Tool
4. Calculation of the optimal rotor speed curve
5. Implementation of the optimized process by carrying out validation trials

The different steps are necessary to precisely adapt the Smart-Final-Mix-Tool to the customers mixing process and mixing equipment, to calibrate the models and ensure that the results represent the maximum possible energy savings.

The three process parameters (mixing quality, batch temperature and energy input) are dependent on the rotor speed and the mixing time. To be able to also consider or model a change of the rotor speed during a mixing process, the calculation is carried out for individual time intervals (Δt). This means that a step-by-step calculation of the variables takes place dependent on the sampling rate, whereby the rotor speed in the overall model can change for each calculation step within predefined limits.

To optimize the entire final mixing process, an evolutionary algorithm is used to calculate different rotor speed curves for the final mixing process, taking into account various optimization criteria. The evolutionary optimization describes a procedure, which is used based on stochastic methods and under the specification of appropriate boundary conditions, to solve complex optimization problems. This approach is based on processes in nature, in which good properties are passed on and results that do not meet the objective are discarded. Evolutionary optimization algorithms have established themselves in practice since they are robust and do not require any knowledge about the structure or the problem to be optimized. The Smart-Final-Mix-Tool uses these advantages to optimize the mixing process regarding the energy input and the mixing time.

3. Optimization of final mixing processes in the laboratory

In Order to develop the models and the optimization algorithm, more than 500 trials were carried out at the HF Mixing Group's technical center in Freudenberg, Germany. The tests were needed on the one hand for the development of the models and on the other hand to validate the models as well as the calculated optimized final mixing processes and the savings. During the development, two rotor speed curves were elaborated by the evolutionary optimization that represent the lowest possible energy input and the shortest mixing time. The two scenarios are a constant rotor speed for the complete final mixing process and a linear increasing rotor speed curve. Both represent the respective optimal settings for the given scenario. The energy savings from optimization using the Smart-Final-Mix-Tool can thus be achieved through two main steps. These saving opportunities are structured as follows (Figure 11**Error! Reference source not found.**):

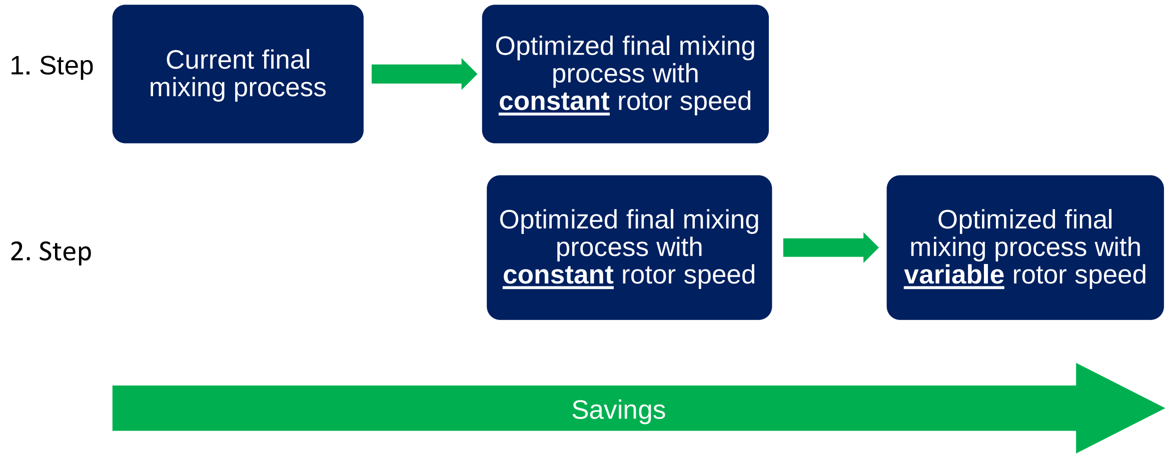

Figure 1: Two-step optimization of the final mixing process with different scenarios

Based on existing mixing processes, significant potential can already be exploited by optimizing the final mixing process with a constant rotor speed during the whole mixing process. The amount of savings always depend on how the respective current mixing process is carried out. In a further step, additional potential can then be developed by using a variable rotor speed instead of an already optimal constant rotor speed. So, the savings are even higher with a variable rotor speed than with a constant one.

During the development of the models in the laboratory of the HF Mixing Group, different final mixing processes have been considered. Therefore, final batches have been produced in a one-stage process as well as in a two-stage process on the GK5E with a PES5 rotor geometry. Even if the results are similar, in this publication the focus will be put on the two-stage mixing processes. For the test series, natural rubber (NR) of the type SVR CV60 from Viet Sing Joint Stock Company, Vietnam, is used. To produce the masterbatch, this rubber is masticated at a rotor speed of 50 rpm for 20 seconds. As filler, 30 phr (parts per hundred rubber) of the carbon black N550 from Orion Engineered Carbons GmbH, Frankfurt, Germany, are then added. The carbon black is incorporated at a speed of 50 rpm for 50 seconds. The ram pressure is set to 5 bar during the entire mixing process. After the masterbatch is produced, the compound is ejected, then temporarily stored, and cooled down to room temperature. In a second mixing stage the final mixing process is carried out. For all tests, 3 phr of sulphur of the type MIXLAND S 80 GA F500, mlpc international, France, and 1.5 phr of the vulcanization accelerator MIXLAND CBS 75-80 BA/GA of the same manufacturer are used. As activator the ZINC OXIDE SILOX ACTIF from Silox S.A., Belgium, is used with an amount of 5 phr.

In the Smart-Final-Mix-Tool, various functions are implemented for the mixing quality, which describe the dependence of the mixing quality on the rotor speed and mixing time. The mixing quality is described as a parameter for the homogeneity of the batch regarding the distribution of the curing system. For this purpose, samples were analysed during the validation with a rubber process analyser regarding crosslinking. The homogeneity of the batches can be determined from the statistical analysis of the maximum torque occurring during crosslinking. High homogeneity of the maximum torque of the samples means good mixing quality, whereas low homogeneity (= large scatter) means bad mixing quality. [7] [8]

3.1. Scenario with optimal constant rotor speed

For the recipe described in the previous chapter, the results for the constant optimal rotor speed are shown in Figure 22**Error! Reference source not found.**. The maximum batch temperature has been set to 100 °C and a mixing quality of 95 % must be achieved for this calculation.

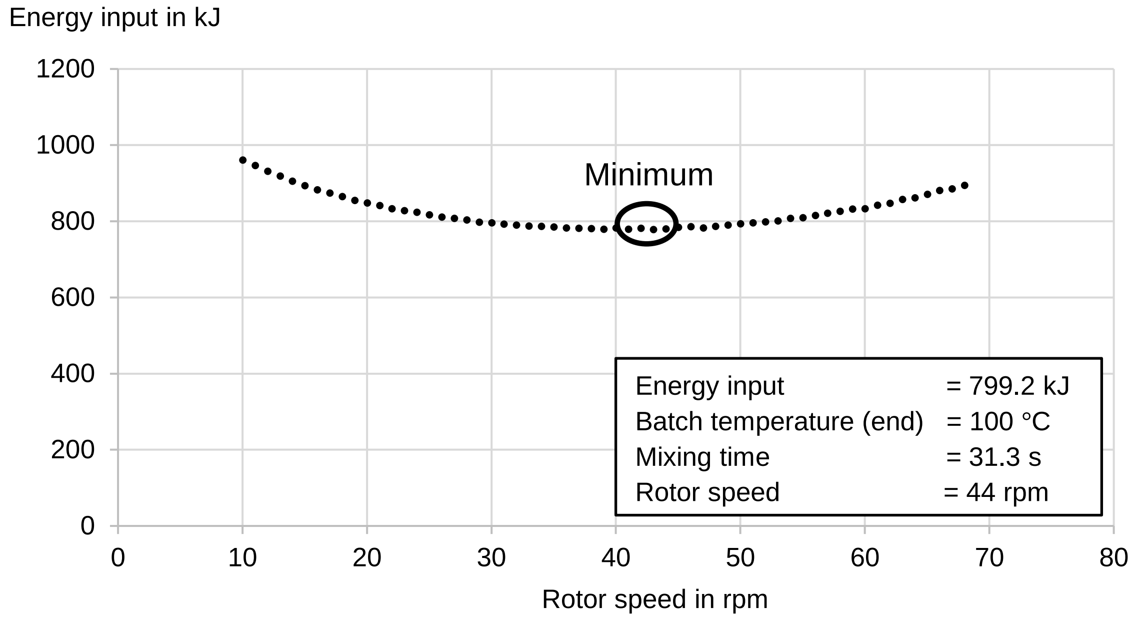

Figure 2: Optimal constant rotor speed scenario

As it can be seen, there is a minimum of energy input. The Smart-Final-Mix-Tool calculates an energy input of 799.2 kJ, a batch temperature at the end of the mixing process of 100 °C and a total mixing time of 31.3 s at an optimal constant rotor speed of 44 rpm. To validate the model and the results of the calculation, five batches for validation are produced at a constant speed of 44 rpm on the GK5E laboratory mixer. Therefore, the rotor speed and the mixing time have been set as recommended by the model. The energy input is calculated from the power data of the internal mixer after the production of the batches. The batch temperature is determined manually (pyrometer) after dropping the batch. To check whether a required mixing quality of 95 % is achieved, a total number of ten samples per batch are randomly selected from each batch and analysed with a rubber process analyser.

A comparison of the relevant parameters for the calculated optimal rotor speed scenario with the validation trials is shown in Table 1.

Table 1: Comparison of calculated scenario and validation trials for optimal constant rotor speed

Parameter	Smart-Final-Mix-Tool	Validation trials	Absolute Deviation	Deviation in %
Mixing quality in %	95	92	3	3
Batch temperature in °C	100	98	2	2
Energy input in kJ	799.2	755.1	44.1	5
Mixing time in s	31.3	31	0.3	1

As it can be seen in the previous table, there are small deviations between the calculation of the Smart-Final-Mix-Tool and the validation trials. The main reason for this is that only integer mixing times can be used for the practical validation trials. Other than that, the deviations are always less than 5%. Due to assumptions of the mathematical modelling as well as the fluctuation of the process and material parameters, an increase of the accuracy can only be realized with an uneconomic increased effort. The fundamental possibility of modelling and optimization based on the Smart-Final-Mix-Tool, the different models, the procedure, and the evolutionary algorithm can be seen.

3.2. Scenario with variable rotor speed (rotor speed curve)

As a second scenario, a variable rotor speed curve is considered in which the rotor speed changes during the final mixing process. Therefore, also the limits of the possible rotor speed of the mixer must be specified to the Smart-Final-Mix-Tool. Furthermore, a maximum batch temperature of 100°C and a necessary mixing quality of 95% are specified. These boundary conditions must be achieved within all calculations to reach a valid result. When calculating the modelled process parameters, the corresponding variables (mixing quality, batch temperature, mixing time and energy input) are calculated for different starting rotor speeds as well as for any positive changes in rotor speed during the mixing process. Using the evolutionary optimization algorithm, both the starting rotor speed and the change in rotor speed are changed in such a way that the minimum energy input and a reduction in mixing time are achieved under the given conditions (maximum batch temperature and minimum required mixing quality). The scenario for the minimum energy input is shown in Figure 3. The calculated energy input is 744.7 kJ and the batch temperature at the end of the mixing process is 100°C. At the beginning of the final mixing process, the rotor speed is calculated to be 39.4 rpm and increases linearly with a change of 1.63 rpm per second to 75.4 rpm after 22.1 seconds.

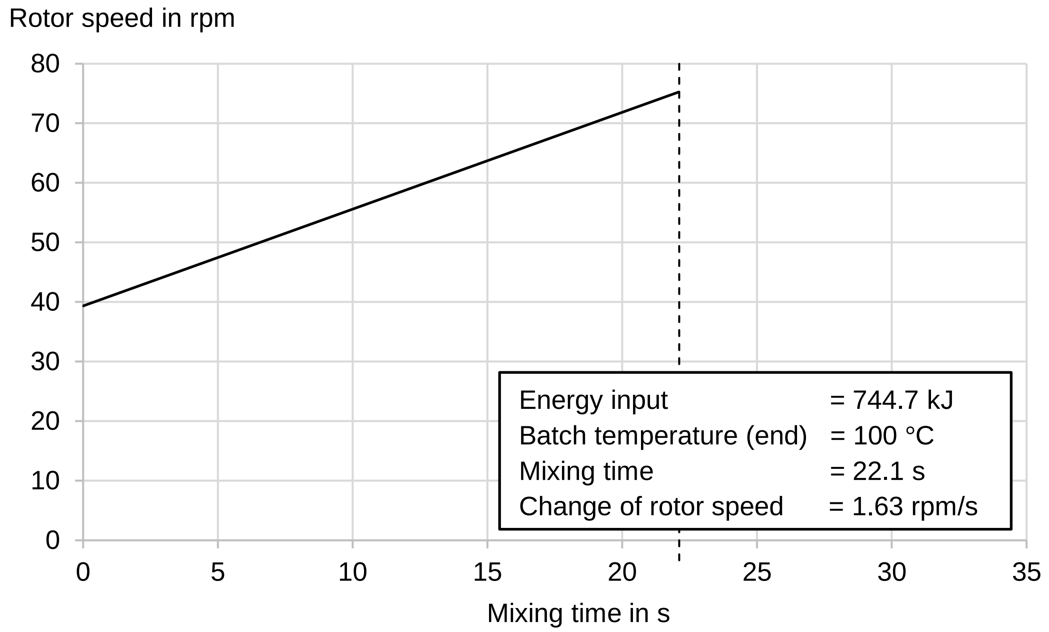

Figure 3: Variable rotor speed scenario

To validate the model and the results of the calculation, also five batches for validation are produced on the GK5E laboratory mixer. Therefore, the starting rotor speed, the change of rotor speed and the mixing time are specified. The energy input is calculated from the power data of the internal mixer after the production of the batches. The batch temperature is determined as described above. To check whether a required mixing quality of 95 % is achieved, a total number of ten samples per batch are randomly selected from each batch, analysed with a rubber process analyser.

A comparison of the most important parameters from the validation trials for the variable rotor speed scenario is shown in Table 2.

Table 2: Comparison of calculated scenario and validation trials for optimal variable rotor speed

Parameter	Smart-Final-Mix-Tool	Validation trials	Absolute Deviation	Deviation in %
Mixing quality in %	95	94	1	1
Batch temperature in °C	100	99	1	1
Energy input in kJ	744.7	748.1	-3.4	1
Mixing time in s	22.1	22	0.1	1

As it can be derived from the previous table, the calculation results can be confirmed based on the validation tests in the laboratory. The deviations between calculated and measured parameters, are low with around 1%. From the results it becomes clear that a description of the final mixing process as well as the evolutionary optimization itself is also possible with a variable rotor speed curve.

3.3. Comparison of optimal rotor speed scenarios

The comparison of the two scenarios shows the potential of the modelling and the evolutionary optimization of the final mixing process. Starting from the already optimal constant rotor speed, the values shown in Table 3 can be achieved using the variable rotor speed curve.

Table 3: Comparison of optimal constant and optimal variable rotor speed based on the calculation of the Smart-Final-Mix-Tool

Parameter	Constant rotor speed scenario	Variable rotor speed scenario	Absolute Savings	Savings in %
Energy input in kJ	799.2	744.7	54.5	7
Mixing time in s	31.3	22.1	9.2	30

As the table shows energy savings of up to 7% and a reduction in mixing time of 30% can be achieved. The comparison clearly shows the possibilities offered by the “second step” of the evolutionary optimization of the final mixing process. Savings are already possible through the “first step” of the optimization, in which the optimal constant rotor speed is calculated based on industrial processes. Since the savings are generally dependent on the existing final mixing processes of the different companies, it is difficult to estimate the savings for the “first step” of the optimization. Nevertheless, to illustrate the potential of the optimal constant rotor speed, the savings are presented and explained in the following chapter for different final mixing processes existing in the industry.

4. Optimization of mixing processes in the field with the Smart-Final-Mix-Tool

Following the development on a laboratory scale, the models were tested in an industrial environment. For this purpose, final mixing processes in the tire and TRG industry have been considered. Different mixers such as IM190E, GK160N, GK255N and IM320E with PES5, ZZ2 and PES6 rotors were used. In addition, various compounds such as EPDM with kaolin, SBR with carbon black and NR with carbon black were considered.

At the beginning of the optimization, calibration trials have been carried out to calibrate the models of the Smart-Final-Mix-Tool to the respective mixers. At the end of the mixing process, a temperature equilibrium needs to be reached at a constant rotor speed. This must be done with at least three different rotor speeds (Figure 4). All necessary mixer specific parameters for the optimization are automatically calculated by the tool based on these calibration trials.

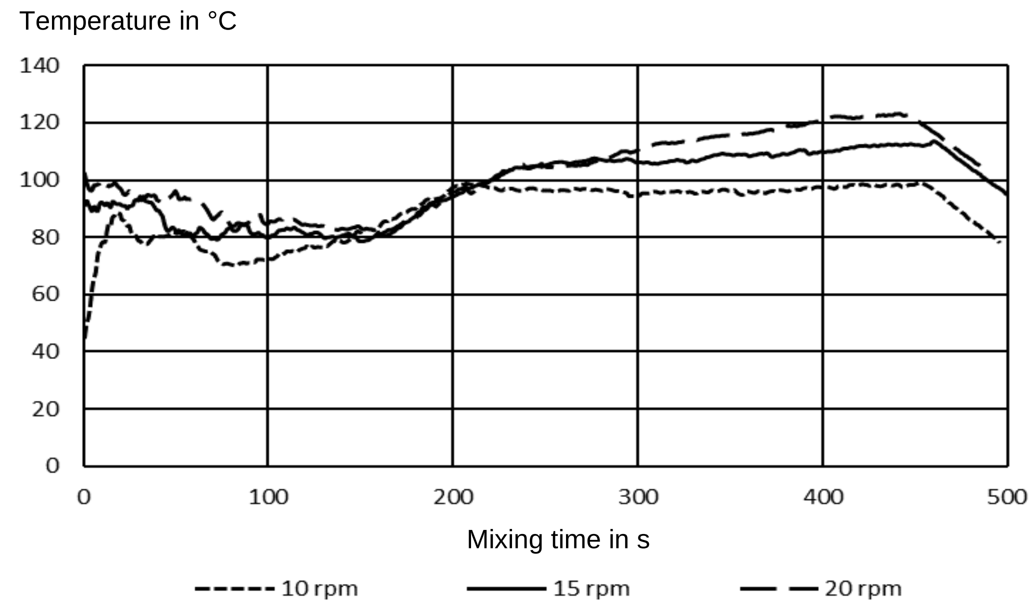

Figure 4: Batch temperature curves of calibration trials with rotor speed of 10, 15 and 20 rpm

After the calibration of the Smart-Final-Mix-Tool, the optimization of the mixing processes takes place. Due to limitations of the PLC and the main drives of the mixers, only an optimization for the constant rotor speed scenario described in 3.1 is calculated. Based on the feedback of the Smart-Final-Mix-Tool with an optimal rotor speed as well as an adjusted number of revolutions, an optimized mixing process is designed. In addition, the Smart-Final-Mix-Tool calculates an expected material drop temperature. Figure 55 shows the reduction of the mixing time and the specific energy input of the individual optimizations. The mixing quality of the optimized compounds is in the quality specifications of the

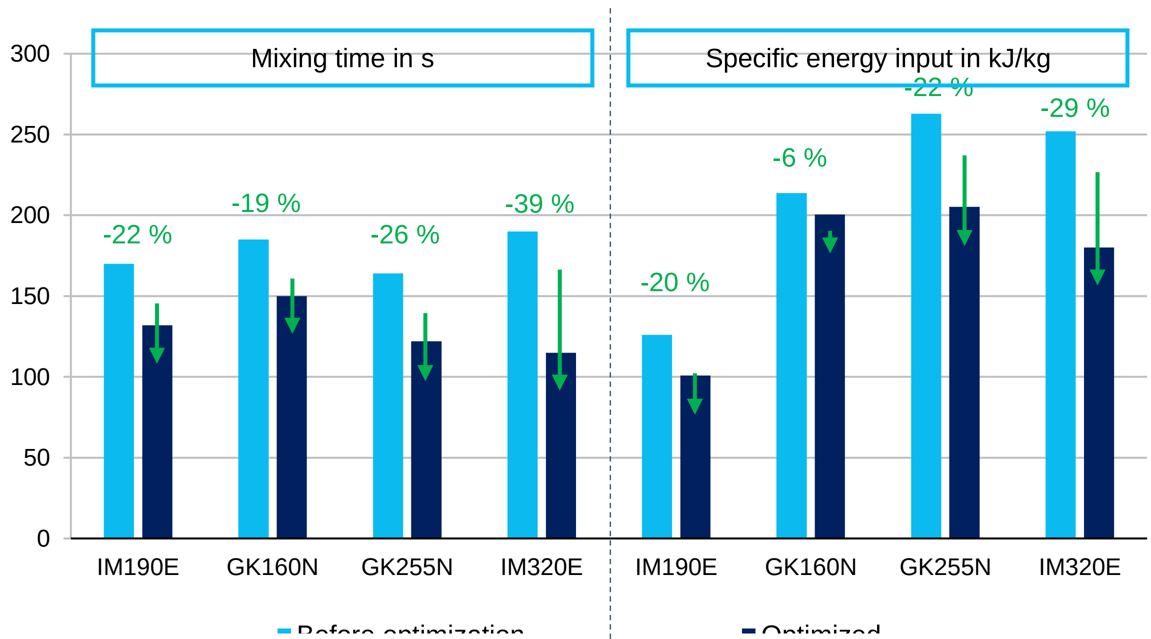

Figure 5: Reduction of mixing time and specific energy input with the Smart-Final-Mix-Tool for different compounds on different mixers

customer. All test formulations were approved by the respective quality laboratories (e.g., Mooney, rheometer, tensile strength).

Beside the energy saving the CO_2-reduction is also to be highlighted. With an annual production of 1350 t of the EPDM and Kaolin compound mixed on the IM190E mixer, a total of 4.100 kg of CO_2 emissions could be saved by using the tool (based on German power mix with 434 gCO2/kWh). This corresponds to a round trip flight from Frankfurt to Los Angeles. For a yearly production of around 4.000 t of the NR and carbon black compound on the IM320E mixer up to 34.000 kg CO_2 Emissions could be saved.

5. Summary

From the results it can be deduced that, on the one hand, it is possible to describe the final mixing process (in a laboratory scale as well as in the industry) with mathematical models. On the other hand, enormous savings potential in terms of mixing time, throughput, and energy can be realized by optimizing final mixing processes. During tests on industrial machines a mixing time saving of up to 39 % and an energy reduction of up to 29 % were achieved. The savings are of course dependent on the mixer type, the rotor and the compound.

The Smart-Final-Mix-Tool developed by the HF Mixing Group enables a simple and effective optimization of the final mixing processes and thus exploits the potential for energy savings. This makes it possible to reduce manufacturing costs, especially in countries with high energy costs, to lower CO_2 emissions and at the same time to increase competitiveness. In addition, the optimization becomes independent of the respective background of the responsible process engineer. This could be also one way to deal with the difficult situation of hiring experienced workers as well as the consider the rising requirements for efficiency in the mixing room. The tool can thus point a way to energy-optimized production processes and an ecologically sustainable rubber industry.

The newly developed and innovative Smart-Final-Mix-Tool will initially be supported by experienced process engineers of the HF Mixing Group, so that additional information and settings can be considered. This makes it possible to respond to individual customer wishes and needs. The results offer the opportunity to understand rubber mixing process. In further projects the HF Mixing Group is developing more models and optimization processes to consider also other phases e.g., the masterbatch process. With further additional optimization tools, the customers of the technical innovation leader HF Mixing Group are thus to be supported in optimizing their own processes and thus offering a direct benefit to them.

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