Article Identifier
DOI: 10.22032/dbt.58863
URN: urn:nbn:de:gbv:ilm1-2023isc-043:0

60th ILMENAU SCIENTIFIC COLLOQUIUM
Technische Universität Ilmenau, 4 – 8 September 2023
URN: urn:nbn:de:gbv:ilm1-2023isc:1

OPTIMIZING THE PROCESSING PERFORMANCE OF A SINGLE SCREW EXTRUDER USING LIVE SIMULATIONS BASED ON REAL TIME EXPERIMENTAL DATA

Jonas Köllermeier, Volker Schöppner

Paderborn University, Warburger Straße 100, 33098 Paderborn, Germany

ABSTRACT

This article aims to present a simulation system with an environment that enables live simulation of the process behavior of a single screw extruder based on real time experimental data. The simulated target variables such as pressure, temperature, throughput and melting behavior are visualized to the machine operator within an assistant system in a graphical form. The results can directly be assessed and furthermore, recommendations for process improvement can be carried out if the process behavior has to be optimized.
In a first step, current process parameters such as pressure and screw speed are read repetitively from the extrusion control. Next, this data is used to simulate the process behavior in real time and the results are sent to an assistant system. Afterwards, the results are visualized to the machine operator and based on the simulation results and expert know how potential for optimization can be generated.

1. INTRODUCTION

Injection molding and extrusion are the most important manufacturing processes in the field of plastics industry. Although 70 % of the companies related to plastics processors manufacture injection molded products [1], the extrusion process is the most important processing method in terms of quantity [2]. Concerning the distribution of manufacturing costs in the field of extrusion, the shares are as follows: With 70 % the material is the most relevant proportion followed by machine costs (14 %), personnel costs (11 %) and energy costs (5 %) [3]. Within the machine costs, nearly 25 % can be attributed to energy costs which is the single variable cost component to be influenced by the plastics processor since the energy consumption is mainly affected by the design of the extrusion process and its components [3]. In times of rising energy costs, operators have to set the focus on continuous improving of extruder and process design to reduce energy consumption. To quantify energy consumption, all components of the extrusion line have to require digital interfaces to a central assistant system to observe current energy consumption. In the last decades, many companies have carried out specific operations to improve energy efficiency [4]. Overall, the focus is to decrease material and energy consumption as these variables have the highest share on total costs.
Digitalization is often associated with the fourth industrial revolution which has been used for several applications and technology developments since its introduction in 2011 [5]. During the last decade many plastic processors introduced and developed digital operations with the aim to increase production efficiency. In the last few years, industry 4.0 has received a revolutionary meaning and does not longer describe the digitalization of products but the ability to connect technical systems in real time [6].

In this context, process monitoring systems are often used to receive an overview of the whole manufacturing process and to ensure quality assurance. There are different ways to measure process relevant parameters as shown in Figure 1.
The simplest but slowest monitoring solution with regard to the reaction time is the measurement away from production (1) where the measurement usually takes place for samples in separate measuring rooms. Systems near production (2) are placed directly next to the production process and often reveal full control. The response time can be improved by an inline measurement (3) with direct integration in the production line to enable full control after the process execution [7]. Furthermore, the categories contain in-situ (4) and in-process (5) measurements. The former record already machined component features and take place during the process or non-productive times such as a die change. The latter are performed during the process and monitor features currently being machined so that this category allows real time monitoring and control of the process [7].

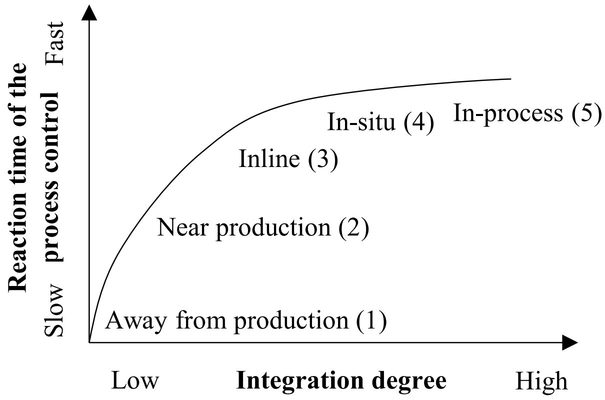

Figure 1: Categories of process quality assessment [7]

Elementary requirements to fulfill increasing demands to the products are data monitoring and evaluation systems to monitor current process conditions. These systems are also known as assistant systems and picture a characteristic feature of industry 4.0 [8]. The majority of companies in the plastics processing industry stated that the potential for efficiency has not been exhausted and could be improved by introducing digital technologies and services [9]. Today, the extrusion process generates a tremendous amount of data which is often only used in a small extent so that valuable resources and data-based benefits are wasted [10]. In a survey in behalf of the federal environment ministry of Germany, the potential savings in material and energy costs were estimated by 25 % [9].
Although these potentials represent meaningful reasons for the introduction of digital technologies and services, there are several barriers for their application for small and medium companies. The main reasons are missing resources such as expert know-how and time. In addition, supposed imponderables in terms of costs lead to uncertainties in the introduction. At last, the growing complexity of IT infrastructure and the thread of hacking attacks do not rise the readiness to invest in such technologies [11].
Referring to missing expert know-how, the plastics industry is affected by an immense lack of skilled workers as 87 % of the companies surveyed stated [12]. 52 % mentioned the shortage of plastics process mechanics followed by apprentices (37 %) and process engineers (24 %) [13]. Nevertheless, digitalization can be seen as a measure to reduce the shortage of skilled works whereas some limitations exist. On the one hand, the digitalization process will increasingly substitute workflows with repetitive work operations to automated processes. On the other hand, analyzation processes and optimizations will become more determinant to gain an edge over the competition. As a consequence, process engineers have to be educated in a

higher standard since the complexity of the tasks will extend to use the potentials of the digitalization process completely [14].

As already mentioned, extrusion lines are equipped with modern data monitoring systems to carry out process analyses and optimizations based on experimental data. For this purpose, communication interfaces have to be implemented to read the generated data. In 2015, the protocol Open Platform Communication Unified Architecture OPC-UA was developed by the OPC foundation and defines the communication language for data exchange between different devices [15]. This is a manufacturer independent protocol based on the client-server principle and enables communication between data sensors und actors to assistant systems [16].

The design of an extrusion process requires expert know-how with regard to the machine configuration and process parameters to manufacture a given product economically. The expertise needed can be achieved by material-intensive trial and error experiments. In the last decades, computer simulations have been applied to several industries and especially the plastics industry whereas these calculation tools can be seen as the state of the art in some branches [17]. The benefits of simulations are the process planning on the one hand and the problem analysis on the other hand. Today, several simulation systems along an extrusion line to simulate the process behavior exist. The calculations can be carried out for the different components of the extrusion line such as the extruder, die and cooling section. Nevertheless, these systems are based on experimental data based on previous studies so that the set of experimental data has to be present to carry out simulations. Moreover, the calculations have to be performed without interaction to the current process in real time so that there is not any inline simulation.

2. AIM OF THE WORK

The introduction above indicates that there is significant potential to design extrusion processes regarding digital methods and live assistant systems using simulation tools in real time. Consequently, there is a huge demand in simulation systems that are able to monitor the process behavior of an extrusion process based on real time experimental data.

The aim of this paper is to close this gap and to develop a solution that meets the requirements mentioned before. First, a simulation software is presented that is able to picture the live process behavior of a single-screw plasticizing unit for a given profile extrusion line based on real time experimental data. In this step, the status of the plasticizing unit is detected with regard to throughput, efficiency and melt quality. In a second step, the simulation results are preprocessed and transferred to a cyber physical assistant system to evaluate the given information. Lastly, the process behavior should be visualized for the machine operator and potential of optimization should be elaborated automatically.

A detailed workflow of the investigated approach is shown in Figure 2. At first, all digital available information generated in the extruder are provided by the extruder control and additional sensors. The process data is exported to an external database where the information is available as a digital twin. Thus, there is a digital data set with live information of the current extrusion process.

To determine further information, simulations based on the existing live data using the simulation software REX (Kunststofftechnik Paderborn, Paderborn University) are carried out. The software is able to calculate the whole operation behavior of the extruder using predominantly analytical equations [18-19]. The results are combined with expert know-how and transferred to the cyber physical assistant system. Here, assistant operations such as the visualization of potential for optimization and strategies to improve the current process behavior can be done.

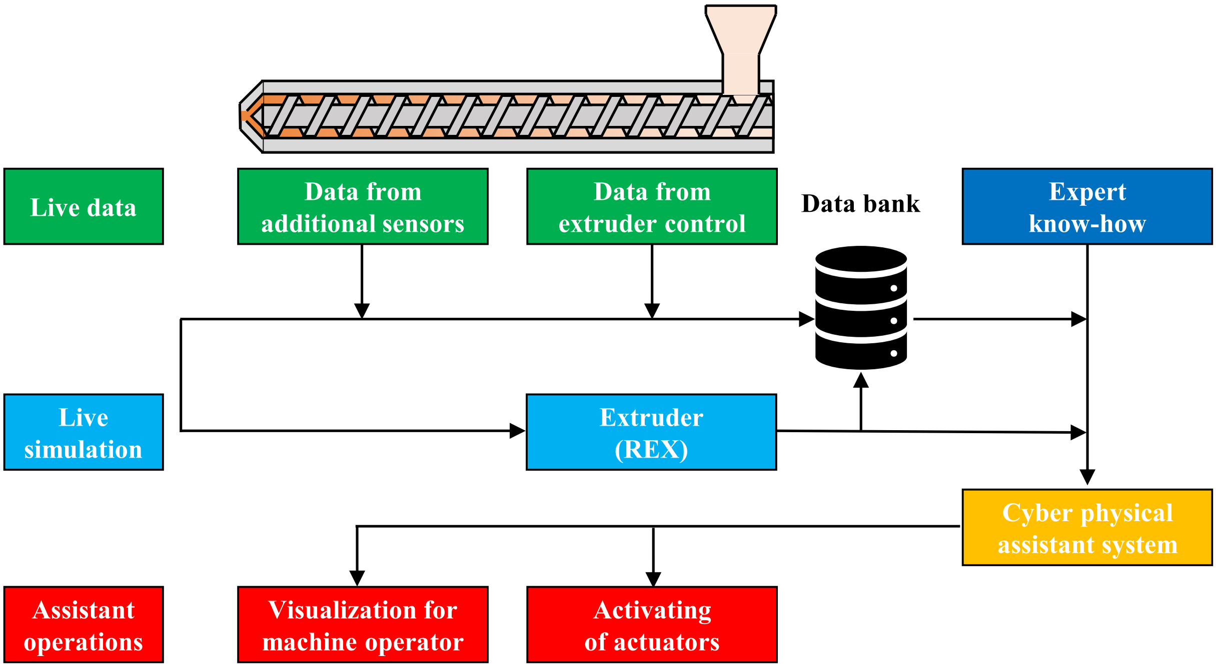

Figure 2: Methodical approach

3. EXTRUDER SIMULATION AND DIGITAL ASSISTANT SYSTEMS

To carry out live simulations, the operating principle and the calculation options of the simulation software REX is described in detail. Moreover, the functions of the digital assistant system Vipra (SHS plus GmbH) that is used as the cyber physical assistant system are outlined.

3.1 REX

Since 1980 the Kunststofftechnik Paderborn has been dealing with modeling of the process behavior of single screw plasticizing units [20]. The results have been implemented in the simulation software REX that is part of a joint research project of the Kunststofftechnik Paderborn and approximately 20 industrial companies of the plastics industry. The software is used to optimize existing extrusion processes as well as the design of completely new processes [20]. REX enables fast and complete assessment of the process behavior by dividing the whole screw length into 150 small intervals using predominantly analytical and closed-form equations with simplified assumptions [20].
The whole workflow of the calculation process in REX is pictured in Figure 3. Supported screw geometries are the common types such as feed, compression, metering, barrier and wave section as well as shearing and mixing elements [20]. Furthermore, common barrel designs such as smooth, degassing and grooved bush barrels can be simulated. There are several output values like throughput, pressure, temperature, residence time and melting behavior [20]. These results can be visualized graphically and in tabular form. Using the former output, the target values can be plotted over the screw length to evaluate the process behavior in individual screw sections.

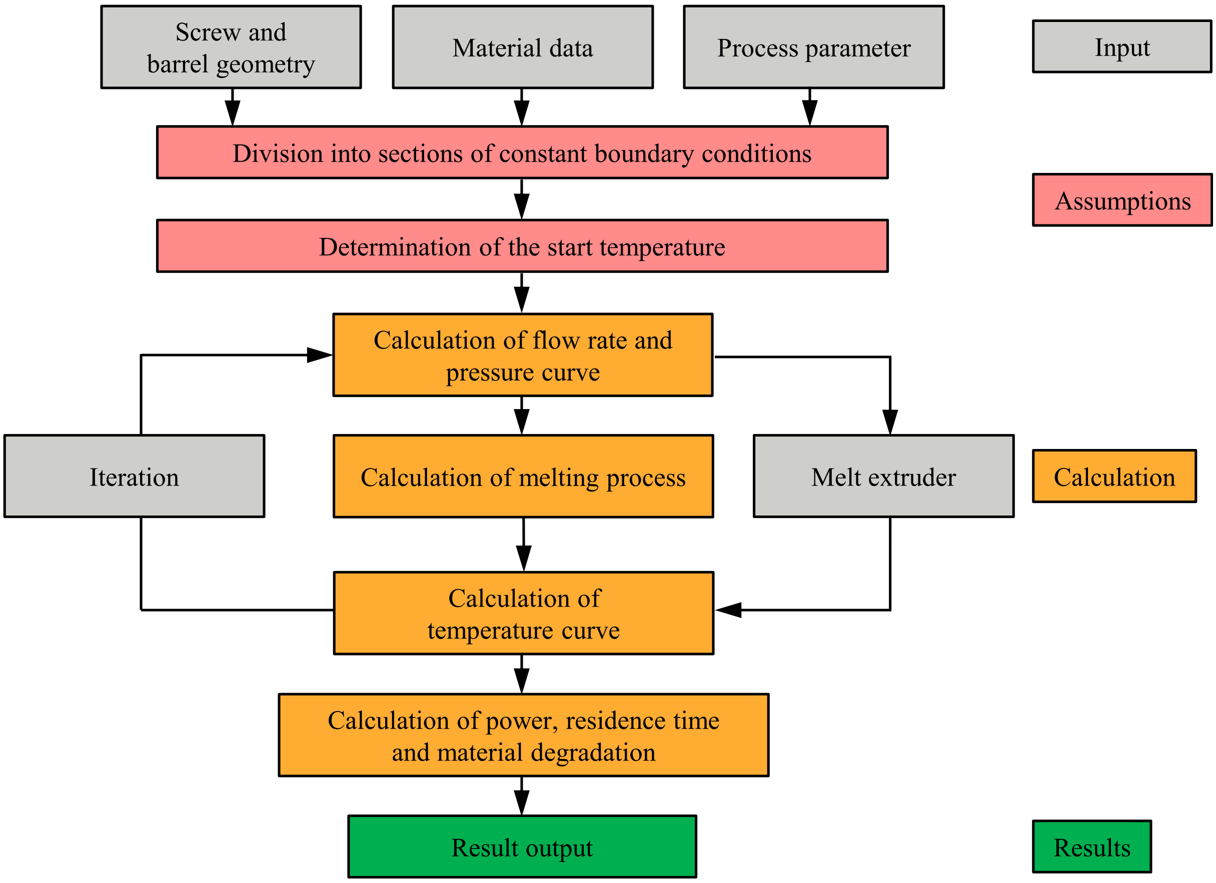

Figure 3: Workflow of the calculation process in REX

3.2 Vipra

Continuous digitalization for extrusion processes can be implemented by using digital assistant systems like Vipra (virtual productive assistant, SHS plus GmbH). Vipra was developed for the plastics processing industry and is able to support the machine operator by giving potential for optimization [21]. The fundament is the collection of live process data using sensors which are preprocessed in different modules in a first step and analyzed afterwards. Lastly, the results such as live data or calculated quality indicators can be visualized [21]. In addition, the system can be connected to several types of production systems such as injection molding machines and peripheral devices [22].
Furthermore, computer simulation systems of third parties can be connected to Vipra so that data processing and visualization between different systems can be carried out [21]. For extrusion processes, SHS plus GmbH offers the simulation system chillWARE that is able to simulate the cooling behavior of cooling sections and can be connected to Vipra [17]. Vipra can also be used as a data bank so that extern expert know-how can be added to carry out optimization potential based on a combination of live simulations and experimental expert know-how.

4. EXPERIMENTAL SETUP

The extruder simulations should be carried out based on real time experimental data. To generate this data, the extruder including additional measurement techniques is pictured in Figure 4. The extruder is a 45 mm single screw extruder (type Battenfeld BEX 1-45-30 B) with a three-section screw with a length of 32 D. The screw geometry is composed of a feed section with a length of 13 D and a channel depth of 9 mm, a compression section with a length of 11 D and a metering section with a length of 8 D and a channel depth of 3.5 mm. The channel depths result in a compression ratio of 2.5:1. The extruder consists of five barrel sections S1-S5 whereas the feed section S1 is a smooth bushing barrel. This section is thermally decoupled from the following sections and is cooled with a water temperature control and an inlet temperature of 15 °C. The sections S2-S5 consist of separate heating and cooling combinations with ceramic resistance heater bands and cooling fans to adjust individual section temperatures. To do so, each section is equipped with spring-loaded sensors to control the temperatures.

At the end of the metering section, a measuring flange (MF) is connected to measure melt pressure as well as radial melt temperatures across the melt channel simultaneously at the same axial position. For the pressure measurement, a strain gauge pressure transducer (type DA-250, Gneuss Kunststofftechnik GmbH) is used. The temperature is measured by five temperature sensors (type TF-CX, Gneuss Kunststofftechnik GmbH) in radial depths of 5, 10, 15, 20 and 22.5 mm. The fundamental approach of this temperature measurement is to calculate a single characteristic value named weighted melt temperatur based on multiple radial temperatures measured in different radial depths. The approach was developed by HÖRMANN [23] with the calculation of weighting factors that consider the partial volume flow rate depending on the flow cross-section and the amount of the shear-thinning velocity profile. Afterwards, the weighting factors are used to calculate the weighted melt temperature. The approach was successfully applied by KÖLLERMEIER and SCHÖPPNER in [24–27].

At the end of the extruder, a die with three sections D1-D3 is mounted to manufacture square hollow profiles with dimensions of 43 x 43 mm and a thickness of 3 mm. The sections are also equipped with heating bands and sensors to control the temperature.

Immediately after the die, the surface temperature measurement (STM) system is placed to measure the surface temperature of the product contactlessly. The system was developed by ELTZE [28] and consists of four infrared pyrometers (type CS LT 15, Optris GmbH) mounted on each side of the extruded profile. The pyrometers are used to measure the temperature on the profile within a diameter of 28 mm with averaging the temperature to a mean surface temperature subsequently. This approach was applied in investigations by KÖLLERMEIER and SCHÖPPNER published in [26].

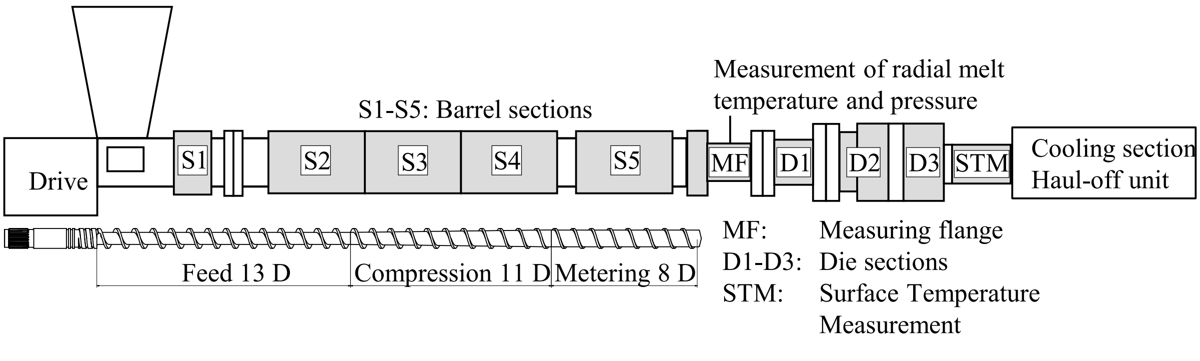

Figure 4: Schematic sketch of the extruder and measurement techniques

5. DEVELOPMENT OF LIVE EXTRUDER SIMULATIONS

The main objective of this paper is to develop a simulation system that is able to carry out calculations of the flow process in the plasticizing unit based on real time experimental data. Up to now, the calculations using the software REX are performed with experimental data that does not reflect current process conditions since the data set is not recorded simultaneously to the simulation. In other words, the software REX should be developed to a live environment. Another object is to implement interfaces between REX Live and the assistant system Vipra to enable data transfer.

In the following, the data model and information flow is described as schematically shown in Figure 5. There are two types of data within the model, namely static and dynamic data. Static data is provided once to REX Live and does not change during the process whereas dynamic data changes dependent on the process conditions. The latter including screw speed and barrel temperatures is provided by the extruder control. Melt pressure and melt temperature as well as surface temperature are measured by pressure sensors and the approaches described in the experimental setup. This data is transferred to Vipra via the communication language OPC-UA and is present as a digital twin in a central time series database. The data set of melt temperature, screw speed and melt pressure is used as dynamic input data for the simulation in REX Live. In combination with the input of the static, non-variable data, the simulations can be carried out.
REX Live as well as Vipra run in independent docker containers that enable quick and reliable execution of both systems. Data provision in Vipra is realized by extending the core application of Vipra called data dealer. It is responsible to connect data to different sources such as REX Live [29]. In a first step, the connection to the extruder via OPC-UA and in a second step, the connection to REX Live has to be established. To exchange data, an application programming interface (API) is added so that the user is able to export results from Vipra that have been acquired by physical sensors. Using this interface, the system is able to process the data, generate results and return them. The data transfer between Vipra and REX Live is conducted by implementing a representational state transfer (REST) interface.

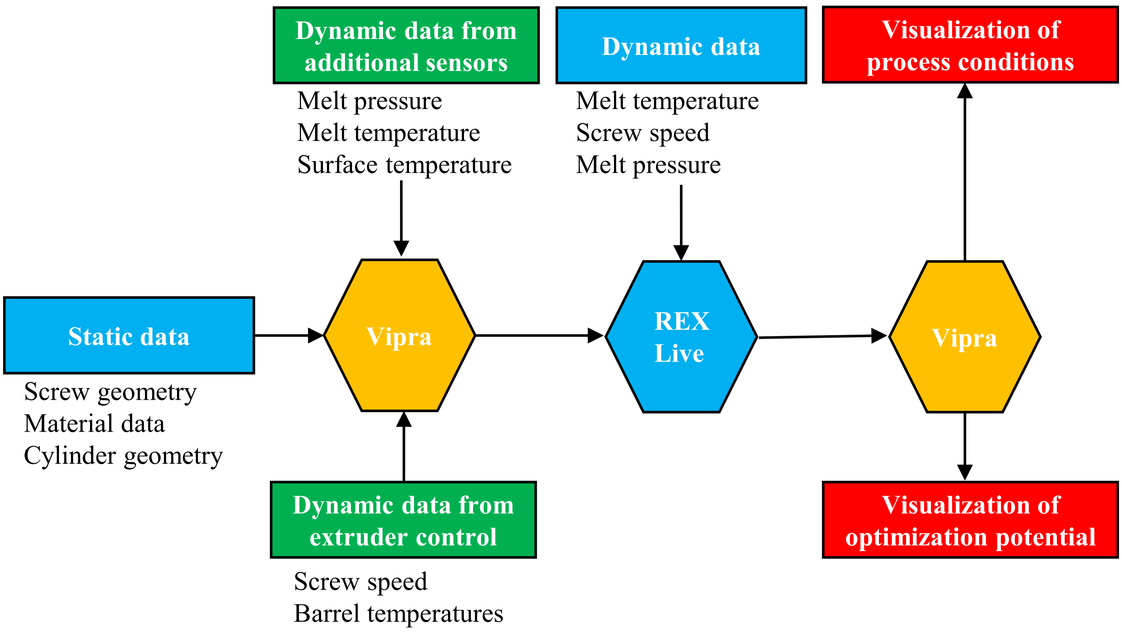

Figure 5: Data model and information flow

Based on static and dynamic live data, the calculation process is carried out in REX Live. Once the calculation has finished, the output data is transferred to Vipra as numerical values. The calculation procedure is repeated if the input data changes.
In a last step, Vipra is able to carry out two assistant operations. Since REX Live does not contain a graphical user interface, the visualization of target values is implemented in Vipra. The user can choose the values as well as calculated quality indicators to be visualized in different dashboards. Furthermore, optimization potential of the current process can be visualized if present.
The previous descriptions are based on the use case of live simulations based on real time experimental data to compare experimental to simulated process conditions. Another use case

of the developed system is the predication of process conditions using REX Live. Assuming there is a process with suboptimal process conditions such as insufficient melting behavior, REX Live can be used to predict the melting behavior including melt temperatures for changed process parameters. To do so, there can be a scenario where the user chooses increased barrel temperatures to improve the melting behavior. Afterwards, the simulations are conducted by REX Live using the given input data to calculate the target values within a short time. In a next step, the user is able to recognize the results in Vipra and can evaluate whether the enhanced melt temperatures have improved the melting behavior.

6. CONCLUSION AND FUTURE WORK

In this paper, the development of a cyber physical assistant system to carry out extruder simulations with the use of real time experimental data and subsequent assistant operations was presented. The simulations characterize current process conditions with the visualization of the results in the assistant system Vipra. Target values and quality indicators can be visualized and decision support for the machine operator can be given.
The technical basis for the presented assistant system has been fully implemented and the proof of concept could be shown. This includes the implementation of a live environment for REX Live as well as interfaces between Vipra and REX Live.
In future work, experimental investigations to validate the developed system have to be carried out. On the one hand, these investigations include the live extruder simulation with subsequent visualization of the process conditions and optimization potential if present. On the other hand, the scenario dealing with predictive simulations should be carried out.

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CONTACTS

Jonas Köllermeier email: jonas.koellermeier@ktp.upb.de

Prof. Dr.-Ing. Volker Schöppner email: volker.schöppner@ktp.upb.de