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High-quality sheet metal production using a model-based adaptive approach

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Abstract

Automatic panel benders of Salvagnini Maschinenbau GmbH enable high-quality and high-efficient production of sheet metal components. To achieve the steadily increasing requirements on precision, a model-based adaptive concept has been developed controlling the complete production process as a digital twin, from CAD data to the final sheet metal part. First, an overview of the underlying simulation models with different levels of detail is given. The models consider the elastoplastic deformation of the metal sheets as well as the elastic machine components and mechatronic models of the powertrain. Secondly, an overview is given of the adaptive production concept allowing the real-time adaption of the machine to changing process parameters like material properties. Finally, all production steps are controlled by a digital twin based on this model-based adaptive strategy. The paper demonstrates the successful transfer of scientific results to an industrial application.

Keywords: panel bender; elasto-plasticity; model-based adaptivity; digital twin

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1. Introduction

Nowadays, there are very high and continuously increasing requirements on production quality, e.g. precision, minimal cycle time, resource efficiency, versatility, adaptability, modularity, etc. These goals can only be reached utilizing advanced digital models representing the physical behavior of the production system.

This paper is a review on a two-decades lasting industrial research project as a cooperation of a research center (Linz Center of Mechatronics GmbH), two universities (Johannes Kepler University, University of Applied Sciences Upper Austria), and an industrial partner (Salvagnini Maschinenbau GmbH) in the framework of COMET-K2. In this project, digital methods have been successfully applied according to digital factory, industry 4.0, IoT, smart factory and lean manufacturing ([1-6]).

During the long duration of the project there was an impressive development of IT infrastructure concerning simulation software and hardware, as well as numerical methods and algorithms. However, many basic concepts, strategies, and decisions from the early days of the projects are still valid. This is possible because great importance was attached to a modularized extendable concept, making it simple to replace components with refined ones or to add new ones. In this paper, an overview of the main applied methods and models is given, as well as an outlook on future research topics.

To control high-quality precise production processes, we mainly differ two concepts: model-based and data-driven methods. If parameters are uncertain or change during the process, we need an adaptive concept which online identifies the relevant parameters. An overview has been given in [7]. For the model-based concept we need a reliable model representing all relevant physical effects as well as an identification strategy. In contrast, data-driven methods are based on the evaluation of large amounts of measured data and a learning concept like trial and error approaches, [8].

To implement a model-based adaptive concept, detailed knowledge about the process is necessary, and a high effort is needed to develop the physical models and identification strategies. Main advantage is that the underlying physical effects are well-known, so that the influence of parameters can be studied analytically, experimental validation of state variables is possible, and optimizations can be done with high efficiency. Simulations are possible, before a physical prototype exists at all. On the other hand, data-driven solutions need a high amount of measured process data. Once enough data is available, a data model can be derived within short time, and the behavior of the process can be represented with high precision. However, a physical prototype is necessary for the measurements, and the influence of parameters cannot be analyzed analytically. For parameter studies, appropriate measurements are necessary. Moreover, extrapolation is hardly possible. To combine the advantages of both concepts, they are frequently combined, [9-12].

In this paper, a successful example for an industrial application of a model-based adaptive concept is demonstrated. Object of consideration is an automatic panel bender of Salvagnini Maschinenbau GmbH, which enables a fully automatic production of sheet metal parts with lot-size one within minimal cycle times. Salvagnini offers a large portfolio of panel benders mainly differing with respect to the maximum dimensions of the produced parts. Exemplarily, Fig. 1 shows the machine type P4lean. Besides of the different machine types there are a lot of options, and customer-specific software and hardware features, so that each delivered machine is an individual and customer-specific product.

Fig. 1. Panel bender P4lean, Salvagnini [13]

The most essential requirements on the bending machine are:

- Product quality: It concerns precise geometric dimensions, as well as a high surface quality without tool imprints. To satisfy this requirement, a precise prediction of the tool trajectory is necessary, only possible with advanced simulation models.
- Minimal cycle times: First, setup-times for tools must be avoided. Secondly, the bending process must be performed without a feedback control of the bending angle. Instead, an adaptive strategy is followed by identifying characteristic material properties from measured process data and using a model-based approach to adapt the trajectories.
- Ultra-precise manufacturing: As an optional feature, very high precision can be achieved by feedback control of the bending angle. In this case, the machine is equipped with an angle sensor. Usually, angle measurements and a subsequent adaption of the trajectory are very time consuming. On the Salvagnini panel bender, the angle measurement is only necessary for the bends with highest tolerance requirements. With the information obtained from these measurements the trajectories of all other bends on the part can also be adapted. With this strategy, only a slight increase of the cycle time is obtained using the angle measurement feature.

To achieve all these requirements, a highly efficient production process has been developed in this research project using a model-based adaptive concept. This approach has been chosen because of the high number of variants (customer-specific machine) making it impossible to have a physical prototype for each instance. Therefore, in general measurement and test data are not available for the development of a new machine type or variant. However, the development is based on the digital model, also denoted as virtual prototype or digital twin, [6].

The complete digital twin of the production line consists of a high number of components. Here, only the components relevant to our research project are considered. Core parts are advanced simulation models representing essential physical effects like the elastoplastic deformation of the metal sheets very precisely by mathematical models. All these models have been validated and calibrated by experiments. Comparison to measurements show a very good coincidence, e.g. [14, 15]. However, the most critical limitation is the uncertainty of process parameters. This problem has been solved by an adaptive model-based strategy based on online and offline identification of relevant physical parameters from recorded sensor data, [16-20].

The following sections give an overview of the simulation models and the implemented adaptive procedure, controlling all process steps as a digital twin. The presented outcome demonstrates the successful transfer of scientific results to industrial application.

2. Model-based approach

The considered panel bender is a complex production system. As mentioned above, the high requirements on production quality can only be achieved with a very precise and robust simulation environment representing the complete system. In the following, the process parameters and physical effects are summarized.

2.1. Sheet parameters

Main part is the elastoplastic bending process. The material behavior is specified by the flow-curve which can be determined by a uniaxial tensile test. The flow-curve represents the relation of true stress σ (Cauchy stress) and true strain ε (Hencky strain), depending on the following parameters:

- The Young modulus E represents the flow curve for strains within the linear elastic domain according to Hooke's law $\sigma = E\varepsilon$. This linear relation holds for $\sigma < \sigma_Y$, i.e. stresses lower than the yield stress σ_Y.
- For higher stresses ($\sigma > \sigma_Y$) metals typically show hardening dependent on the specific crystal structure. There are many approaches to describe a flow-curve, [21]. In case of the considered panel bender, the strain rate $\dot{\varepsilon} = \mathrm{d}\varepsilon/\mathrm{dt}$ plays an essential role. This effect can be considered by the extended Hollomon equation

$$\sigma = a\varepsilon_p^n \dot{\varepsilon}_p^m, \tag{1}$$

where stress is a function of the plastic part of strain $\varepsilon_p = \varepsilon - \sigma/E$. In Eq. (1), a is the strength parameter, n the hardening exponent and m the rate sensitivity exponent, [22]. Note, that for the quasi-static case the strain rate is negligible, i.e. $\dot{\varepsilon}_p \cong 0$, yielding the original formulation of Hollomon [23], $\sigma = a\varepsilon_p^n$.

- Anisotropy also has an important influence on the bending of cold-rolled sheet metal. This effect is described by the Lankford coefficients r_0 and r_{90} [24]. The coefficients are determined by tensile tests in two directions, longitudinal (0°) and transversal (90°) to the rolling direction. The Lankford coefficient is the relation of strain in lateral and thickness direction of the specimen. Finally, in our simulation models, the effect of anisotropy is considered by Hill's yield criterion [25]. Investigations on the influence of anisotropy on the considered panel bender have been presented in [26].

Besides of these material properties, the geometric dimensions of the metal sheets, i.e. length L, width B and thickness s are essential.

2.2. Process parameters

In the considered machine, the sheet is deformed by a free bending process as schematically shown in Fig. 2. The sheet is clamped between the upper and lower clamping tool by the clamping force F_C. The bending process is controlled by the motion of the bending tool. The shape of the tool path (trajectory) has an essential influence on the contact force between bending tool and sheet, in the following denoted as bending force F_B. Depending on the position of the bending tool relative to the sheet, we differ between sharp bend (high forces) and wide bend (low forces). On the considered machines, there are mainly two types of trajectories implemented: Rolling contact with minimum friction forces and line contact, in which the tool touches the sheet on the same location during the complete bend.

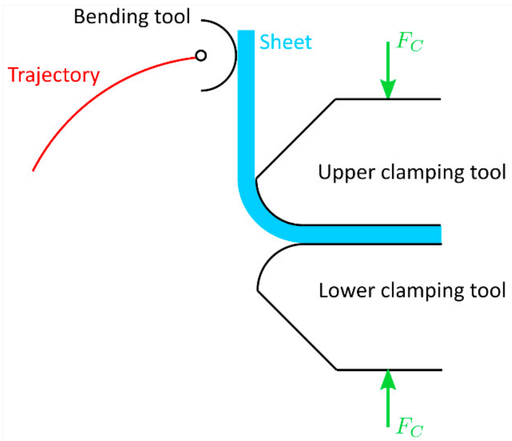

Fig. 2: Bending process

After unloading by removing tool and clamping force, the bending angle reduces by the springback angle ρ because of the elastic reversible strains. This effect must also be compensated by an appropriate trajectory.

Finally, the essential geometric parameters of the bent profile are the angle and the side lengths. Only the bending angle can be directly controlled by the trajectory. The shape of the latter also has an influence on the side lengths, but it is not possible to control these dimensions by the trajectory. This must be done by an appropriately developed sheet, i.e. the cut layout of the raw plane sheet. Depending on trajectory, bending force, and clamping force the initially straight clamped and free side lengths change during the bending process. These longitudinal effects must be considered to achieve the required tolerances, and therefore are an important outcome of the simulations.

2.3. Modularized model of the bending machine

As obvious in the previous sections, many parameters influence the bending process. Goal of our model-based approach is a consistent, numerically efficient, and robust representation of the relevant physical effects. During the long duration of the project, several cycles of refinements have been done which were possible because of the rapid evolution of algorithms, modeling techniques and hardware. Using a modularized concept as described in the following, it is possible to efficiently replace components by refined ones or to add new components.

2.3.1. 2D-Finite Element model

The Finite Element Method (FEM) is very powerful for modelling and simulating an elastoplastic bending process with multiple contact between the tools and the workpiece. It is possible to consider large elastoplastic deformations of the sheet as well as elastic deformations of the tools and machine frames.

It has turned out that the most relevant effects can be represented by a two-dimensional Finite Element model based on the assumption of plane strains. This assumption holds because the sheet thickness typically is small compared to the longitudinal and lateral dimension. The advantage of a 2D-model is a low computational effort compared to a 3D-model.

Figure 3a exemplarily shows the deformed configuration for a high bending angle, and the contour plot visualizes the von Mises stress distribution. The grey regions refer to stresses exceeding the yield stress σ_Y, i.e. this should only be the case in the sheet metal. Because of the numerical efficiency of the 2D model, many effects can be studied within a short time, and the influence of many process parameters can be analyzed like bending forces, trajectories for rolling mode and line contact mode, contact pressures, length change of the sides and springback angle.

As main drawback of the 2D-model influences in longitudinal direction of the machine as well as the machine length itself are not represented. E.g., the maximum total bending force depends on the machine length. To consider these effects, a 3D model has been implemented.

2.3.2. 3D-Finite Element mode

All effects depending on the longitudinal coordinate are considered by a 3D Finite Element model of the complete machine. The complexity of the used mechanical model is demonstrated in Fig. 3b.

Also, with the 3D model the complete elasto-plastic bending process is simulated. Additional considered effects are, e.g., the longitudinal curvature of the sheet and distribution of the contact pressure on the surfaces of the sheet which has an essential influence on the surface quality of the final product. The results of the 3D Finite Element model show a very good coincidence with measurements. However, the computation time is quite high, and it is not practicable to simulate a high number of parameter combinations.

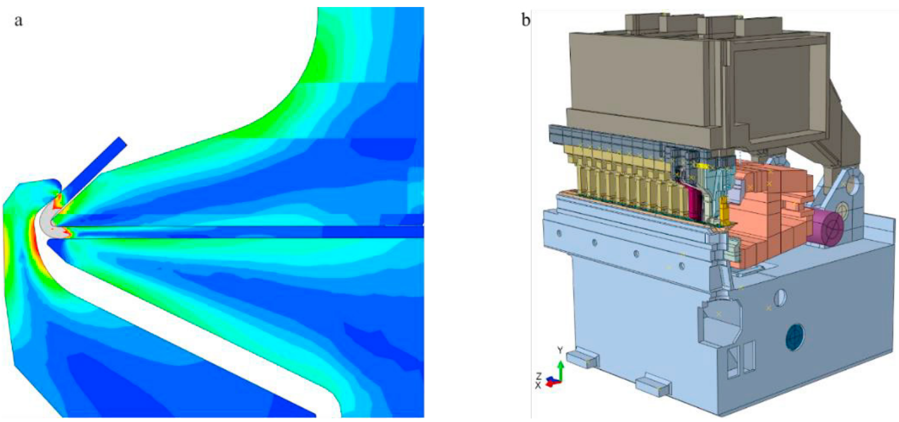

Fig. 3. (a) Results of the 2D simulation model; (b) 3D-model

2.3.3. Analytic formulations

Both, 2D and 3D Finite Element models are very reliable tools for many important engineering tasks, but not directly applicable in an online adaptive bending process, because the latter requires information in real-time. For this sake, simplified analytic formulations still representing the physical effects have been derived from the FEM results. This kind of model-reduction enables the real-time capability.Several efficient methods have been applied in this project within two decades. Two of them are:

- Substructuring: Subsystems of elastic machine parts can be represented by substructures, expressing the vector of elastic displacements $\boldsymbol{u}$ as product of the compliance matrix $\boldsymbol{C}$ with the load vector $\boldsymbol{f}$:

$$\boldsymbol{u} = \boldsymbol{C}\boldsymbol{f} \tag{2}$$

  Computation time is minimized by reducing the dimension of the vectors $\boldsymbol{u}$ and $\boldsymbol{f}$ as far as possible without loss of precision. The substructure compliance $\boldsymbol{C}$ is derived from 2D and 3D Finite Element results. Longitudinal effects can be considered by a compliance matrix which is a function of the longitudinal coordinate z, i.e. $\boldsymbol{C} = \boldsymbol{C}(\boldsymbol{z})$, such that $\boldsymbol{u} = \boldsymbol{u}(\boldsymbol{z})$.

- Similarity considerations: It is well-known that physical processes depend on non-dimensional relations of parameters. In [27] and [28] several examples confirm this behavior. An application to the bending of a cantilever beam, as it is the principle of the Salvagnini panel bender has been shown in [18,19].The great advantage of using similarity relations is the reduction of the number of influence factors. For instance, in case of bending a cantilever beam, the bending force is a nonlinear function of the relation of sheet thickness and an effective trajectory length. It has been shown in [18] that this result found in the framework of first order beam theory also holds for a nonlinear bending process including large deformation. Figure 4 demonstrates the reduction of influence parameters: Figure 4a shows the bending force per sheet length for four materials (indicated by color) with several combinations of sheet thickness and trajectory parameters. There is a high variance of the bending force, but the curves of each material show similar shapes. On the other hand, Fig. 4b shows the non-dimensional bending force in grey color. Four clusters of non-dimensional forces are obtained, each one corresponds to one of the four materials. An experimental validation of this strategy has been shown in [19]. This normalization of the bending force is the basis for identifying flow-curve properties.

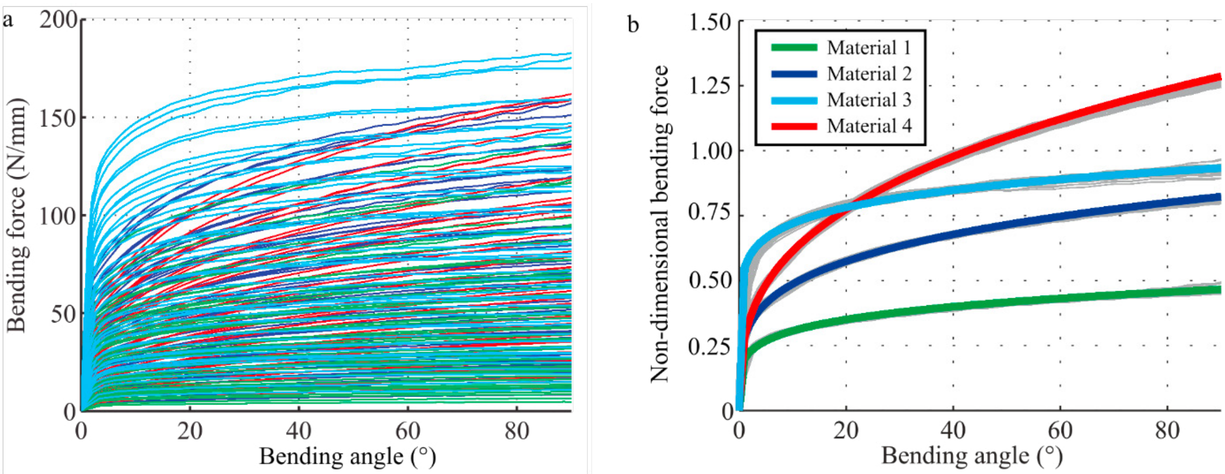

Fig. 4. (a) Bending force for many parameter combinations: similar shapes; (b) Reduction of complexity by normalization of the bending force

Using substructuring combined with the similarity formulation, the computational effort can be reduced to a very low level. To determine the compliance matrices of the elastic subsystems, only few time-consuming Finite Element computations are necessary.

3. Adaptive production process

The simulation models presented so far are very powerful tools representing the physical behavior like elastic deformation of the machine and elastoplastic deformation of the sheet metal. Moreover, there are a lot of parameters that can be precisely considered in a Finite Element model, but because of uncertainties they are not precisely known. Examples are the specific material properties of the sheet, the friction coefficients at the contact pairs or part tolerances. Therefore, each machine and bending process behaves slightly different. Although these differences are low, it is not possible to achieve the required product tolerances without an adaptive strategy as described in the following. The implemented adaptive concept is also based on the models presented above. Adaptivity is achieved by an identification of the unknown uncertain parameters. Offline and online identification is performed as follows.

3.1. Offline identification

This concerns machine parameters which do not change during the production of a specific sheet, like joint stiffnesses, joint clearances and part tolerances in general. Such parameters are identified during the startup-procedure of a machine by some few measurements. Additionally, this process can also be used to compensate lifetime effects like abrasion. E.g. during a standard service procedure, the machine can be re-calibrated. For the example of the sliding joints the physical model and identification strategy has been presented in [17]. Furthermore, investigations on efficient optimization algorithms have been presented by in [20]. Thanks to the model-based approach, only a low number of measurements is necessary to calibrate the machine.

3.2. Online identification

This concerns uncertain sheet parameters like geometric dimensions and material properties. Even, if high quality material is used, high variances of the parameters in Eq. (1) can occur. For example, according to DIN standard, the ultimate stress of the frequently used material DC01 is 270-410 N/mm² and for DC06 the range is 270-330 N/mm². Since these parameters are not known in advance, and because this high variance can occur from one part to the next, the sheet parameters must be identified online during the bending process. With the obtained parameters, the trajectories can be adapted immediately. Note, that this identification process must be real-time capable to avoid an increase of the cycle time.

3.3. Workflow of the adaptive process

The geometric dimensions of the sheet are measured by appropriate sensors on the machine. Especially, the sheet thickness has a high, i.e. over-linear, influence on the bending forces. For identifying relevant material properties, a hybrid strategy has been developed. First, the crystal structure of the sheet is determined by an eddy-current sensor. This sensor allows a coarse classification of the material, e.g. stainless steel can be differed from mild steel or aluminum. A fine classification is based on the measurement of actuation forces. The main idea is to first transform the measurement results to a non-dimensional representation as shown in Fig. 4, cf. [18, 19], and then extract the parameters of Hollomon's equation (1).

3.4. Experimental validation

Figure 5a shows measurement results performed on the panel bender P4lean. Several steel sheets with different material properties have been bent with and without the material adaption. On the abscissa the strength parameter a has been related to a_{ref} of the reference material. The ordinate shows the relative angle deviation, related to the reference angle. Without material adaption, the maximum deviation of the bending angle is 6% of the reference angle. Switching on material adaption, the error can be significantly reduced to values less than 1%. Thus, the product tolerances are satisfied in all considered cases.

Figure 5b shows the housing of a lamp as a typical example for very high requirements on precision. To avoid scattered light, no gaps are allowed at the edges. If the gap is small enough, the edges are closed by coating, so that expensive additional process steps like welding can be avoided. With the presented adaptive strategy this is possible even if the material properties show a high variation. Figure 5b shows the differences with and without material adaption.

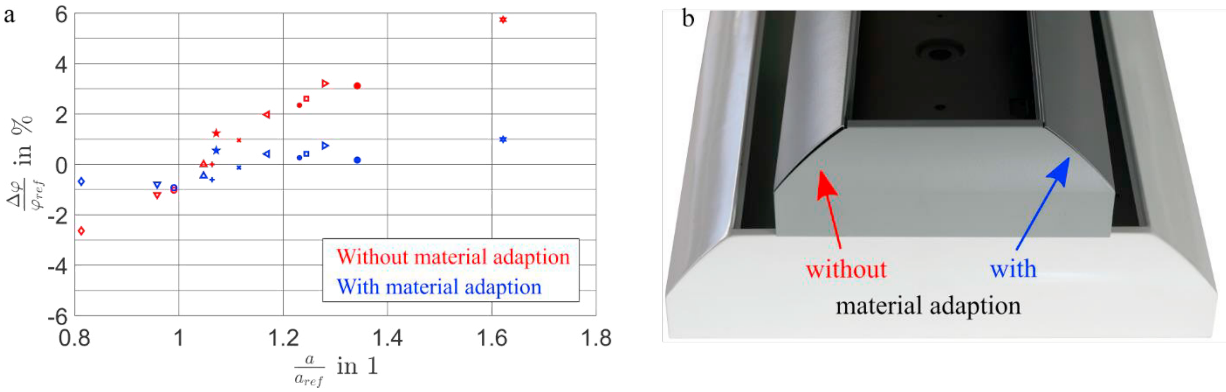

Fig. 5. (a) Deviation of the bending angle with and without the adaptive strategy; (b) Example for a product with high accuracy requirements

3.5. Time efficiency

The adaptive process has been integrated in the production process very efficiently, since there are no additional bending steps required. The measurement is done with a standard bending trajectory. At the beginning of the trajectory, i.e. for small angles, the material properties are identified, so that the end point of the trajectory already is adapted.

Moreover, this identification only needs to be done once on a part, since material parameters can be assumed to be almost constant within one raw sheet. Consider the light housing in Fig. 5b: Many bends are necessary to obtain such a panel. Since the identification is only done once during the first bending, the increase of the cycle time for the complete product can be neglected.

Note that this identification method can also be applied if the material properties are not homogeneous. This has been observed for low quality raw sheets. Depending on the specific case, the identification can be performed on each side or even for each single bending step.

3.6. Digital twin

The adaptive model-based strategy is fully integrated into the production process of the panel bender, controlling the essential steps of the production chain as a digital twin. Note that the software implementation is not part of this research project, and thus not discussed here.

Figure 6 shows an overview of the main components. The process starts with CAD data of the panel (final product). The first step is the computation of the developed sheet. Here all the length changes of the sides during bending must be considered. Next step is punching and cutting of this layout. Salvagnini Group offers laser cutting and punching machines for this task. Subsequently, the optimal trajectory and clamping force are computed by the digital twin. Finally, the adaptive bending process including identification of material parameters (feature MAC 2.0) is completely controlled by the digital twin.

With the above described modularized modelling concept it is possible to adapt the digital twin to all machines of the product portfolio, as well as to customer-specific machine settings.

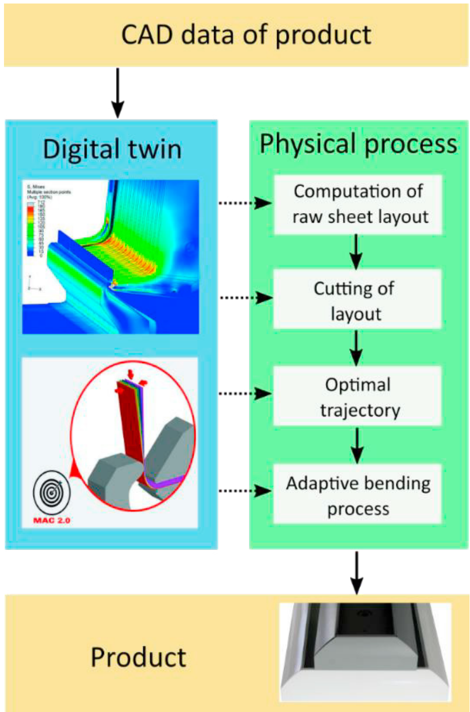

Fig. 6. Production process and digital twin

3.7. Conclusions

This paper gives a brief review on a successful industrial research project, already lasting two decades. With the model-based adaptive approach implemented as digital twin the high requirements of a modern production process are satisfied.

However, further refinements and optimization of the digital twin will be necessary in the future. The experience so far shows that still improvements of the models are possible, considering physics in more detail. Also, the adaptive approach has high potential for extension, considering more parameters. However, such extensions and improvements require an increasing effort.

An alternative would be to apply data-driven methods. Recently, feasibility studies have been done in this project, and data analysis has already been started. To utilize all the available knowledge, only a combination of the existing model-based components with new data-driven ones seems to make sense for the considered production system and portfolio of the company. Goal is to combine the best of these two paradigms by a Data-driven and Model-based Design (DMD) according to [12]. First, advanced model-based methods are used to describe physics. Additionally, data-driven methods can be used for analysing production data, and handling parameter uncertainties. Parameters of the model-based components can be adapted, also changes of parameters of the production line due to lifetime effects. Also, health monitoring and predictive maintenance features are planned to be realized by combining model-based and data-driven methods ([10, 11]).

Acknowledgements

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