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PRODUCTION MACHINES

Modeling machine-side influences on the Z-Folding process of battery cells

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Abstract
The modeling of stacking machines for battery cell production offers potentials for quantifying interdependencies and thus optimizing development and commissioning processes against the background of a targeted efficient production. This paper presents a methodology to develop a model for quantifying machine-side influences using the example of a Z-Folding machine. The components and aspects of the machine to be modeled and their level of detail are systematically derived. Subsequently, it is shown how to parameterize the derived aspects. The components and aspects of the machine are modeled and connected through a multi-physics simulation. This makes it possible to predict the effects on the separator material to be processed depending on the selected setting parameters on the machine. This opens up potentials, for example, to identify optimal setting parameters in a risk-free and model-based manner, depending on the materials to be processed. As a result, material waste can be reduced by eliminating previous "trial and error" approaches.

Keywords Battery production · Machine simulation · Stacking · Digital twin

1 Introduction

In the context of the transition to electromobility, lithium-ion batteries continue to be recognized as key technology for mobile energy storage systems [1]. Consequently, a significant increase in demand for lithium-ion batteries is projected in the near future [2]. This fact is confirmed by various sources. So also in [3]. In addition to the overall rapid growth in cell capacity, further trends in battery development can be observed. There are ongoing efforts to optimize battery cell characteristics in terms of energy and power densities, safety, and aging. These efforts primarily result in the advancement and innovation of material systems, cell designs, and production processes [4].

In the context of lithium-ion battery production, the stacking process is of great importance, mainly due to the transition from continuous to discrete manufacturing that usually takes place at this stage [5]. Therefore, it is crucial to ensure that the stacking machines are correctly designed and operated with high efficiency [6]. A key challenge is the reduction of separator thickness to increase energy density [7]. However, this reduction poses a significant challenge, as it is still associated with high scrap rates [8]. One reason for this is a lack of understanding of the underlying causal relationships. For instance, it is assumed that the presumed optimal machine settings must be determined by trial and error approaches [9]. Intensive efforts can be observed from both research and industry to quantify the causal relationships of battery production processes through appropriate models [10]. To obtain a comprehensive representation of battery production, it is essential to develop and integrate appropriate models at different scales, ranging from the particle level to the production system level [11]. This is illustrated in [12]. Here, an intensive analysis of current modelling approaches highlights the need for cross-scale modelling. This also includes the modelling of the production machine. The current research focus is primarily on modeling the material-related influences on the production process. [13] deals with the modelling of material-side influences on the mixing process. In [14], approaches are presented for modeling the filling process, while [15] focuses on modeling the coating process. The influence of the material on the calendering process is modelled in [16]. In [17], a similar approach is followed with the use of DEM simulation. [18]

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focuses on the modelling of SEI formation in the completed battery cell.

Approaches to model the stacking process are described as follows. In [19], the modelling of the material behaviour of individual electrode sheets during their handling in a high-throughput process is explained. [20] deals, among other things, with the modelling of the material behaviour of electrode-separator composites in a new continuous operating process. In [21] an approach to model the effects of calendered electrode sheets on the stacking process is presented. Since the stacking process is characterized by a wide variety of machine concepts, particularly with regards to its mechanical process characteristics, there is a need to model the influence of machine behavior on the process. First approaches to model the influence of machine components, control, and regulatory structure are presented in [22]. The studies primarily focus on simulating a machine for flexible singulation and stacking. Within the scope of these studies, an additional contribution is aimed at modeling the machine-related influences on the stacking process. In the following, a method for developing corresponding machine models is presented. The method is demonstrated using the example of a Z-Folding machine.

2 Methodology and approach

Figure 1 illustrates the approach for the development of the stacking machine model. The approach consists of a total of four steps. These steps include system analysis (Step I), definition of modeling aspects (Step II), model parameterization (Step III) and model formalization (Step IV).

In the system analysis (Step I), the machine and the concrete problems as well as the target variable to be modeled are initially outlined. This is followed by a systematic top-down analysis of the machine technology. During the definition of the modeling aspects (Step II), the machine components and aspects to be modeled are identified and the level of detail is determined. The model parameterization (Step III) includes the determination of the necessary characteristic values for the identified parameters. In the model formalization (Step IV), the model is built using an appropriate software tool.

2.1 System analysis

The following section provides an initial elucidation of the machine's operating mechanism. Subsequently, the fundamental issues and the target variable to be modeled are derived. Finally, a comprehensive analysis of the machine technology is conducted. Figure 2 illustrates the initial operating mechanism of the machine.

Essentially, the process involves feeding individual electrode sheets and a continuous separator web. In view A, the path of the separator is depicted. The material is unwound and guided through a roller system, including a dancer for tension adjustment. The tension is adjusted by a pneumatic cylinder. Finally, the separator is guided to the stacking table. On the stacking table, the electrode sheets (cathode and anode) are alternately placed using a gripper. The stack is held in position using the clamping fingers. The stacking table is then moved horizontally, causing the separator to fold over. View B shows the flow of the anode sheets. The sheets are fed from a magazine to the alignment table and placed. Mechanical stops are used to position the electrode sheet on the alignment table. Finally, the sheet is placed on the stack.

The stack accuracy is often used as a quality measure for the stacking process. It primarily refers to the precision of the individual electrode sheets in relation to each other. However, the main factor influencing stack accuracy cannot be directly attributed to the stacking machine itself [6]. Instead, stack accuracy is mainly influenced by the characteristics of the electrode sheets. In particular, the dimensional accuracy during the previous singulation process plays a crucial role. The inaccuracies caused by the gripper systems, their actuators and dynamics have only a very minor effect on the stacking accuracy in comparison and are therefore not focused on in the following analysis [6]. The main influence on the qualitative aspects of the cell stack in the depicted machine lies in the processing of the separator. It is essential that the separator is processed with a homogeneous and low web tension. Significant errors that may occur

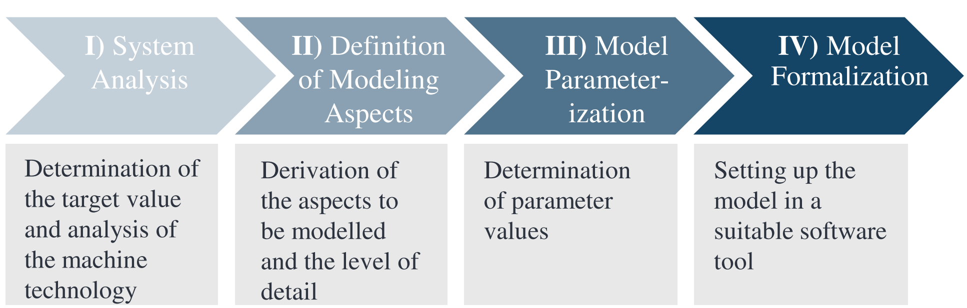

Fig. 1 Approach for the development of the stacking machine model

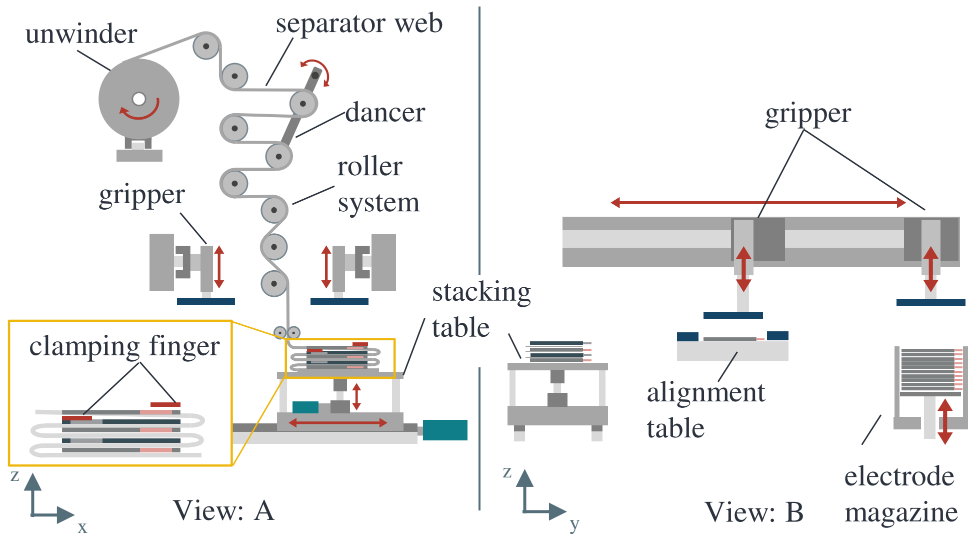

Fig. 2 Illustration of the stacking machine

include plastic deformation of the separator or web tearing. Damage to the separator can lead to an electrical short in the cell stack and subsequently affect its performance. Therefore, the target variable to be modeled is the web tension influenced by the machine behavior.

In order to understand the system in its entirety, a top-down analysis is carried out, which is illustrated in Fig. 3. In particular, the mechanical relationships of the system, material and information flows and all existing components are shown. The components shown are only a part of the whole system. Individual components can be further subdivided, such as a servomotor into stator and rotor. However, this subdivision is not useful, because the function of an electric motor to transmit torque, is already shown in sufficient detail as a single component.

2.2 Definition of the modeling aspects

To accurately model a system, the key components must be digitally represented and mechanically, electrically, or pneumatically connected according to the kinematic chain. As the level of detail increases, the implementation effort also increases, so it is advisable to only model the components in detail only if they have a significant influence on the objective of the simulation. Another advantage of a limited simulation is the computation time, which increases with the level of detail. In case of the investigated use case of the stacking process of a Z-Folder, components that affect the web tension of the separator are particularly relevant. To quantitatively select the relevant system components, those that have a major influence on the overall system and influence other components with respect to the optimization goal are of particular importance.

For this purpose, a Design Structure Matrix (DSM) is used first to analyze and visualize the relationships and dependencies between the elements of a system. Components are evaluated according to their impact on three criteria: Mechanical stress of the separator, stacking accuracy in the x-axis direction, and stacking speed. Based on the top-down analysis, it is possible to better understand the functioning of the system through the mapped relationships. As described in [23], components of the model are evaluated against each other in a matrix to assess the extent to which they influence each other. As shown in the upper part of Fig. 4, the matrix is not symmetric. To assign higher weights to components that have a strong impact on other parts, a scale is used, ranging from 0 (no dependency) to 1 (low dependency), and up to 3 (strong dependency). After pairwise comparisons of each row and column in the matrix, the sums for each row are calculated. Therefore, components with a high degree of interconnectivity within the system have a high sum.

However, certain parts of the system may have a significant impact on others, but they are not relevant to the target variable being modeled. For instance, the environment has an influence on a lot of components, resulting in a high overall score. On the other hand, its impact on web tension is not as strong as other aspects of the system, such as the handling of the separator. Therefore, a utility analysis is conducted to evaluate and compare the components based on their influence on the main system. Subsequently, a decision can be made regarding which components should be represented in detail in the system simulation using a ranking list. The evaluation scale for the utility analysis is identical to that of the DSM. The bottom right corner of Fig. 4 shows the final rankings based on both methods. Based on this, the first ten components are represented in detail, with various examples such as different friction coefficients, deformation under load, or respective moments of inertia. The next ten components are also implemented but with less detail. Any

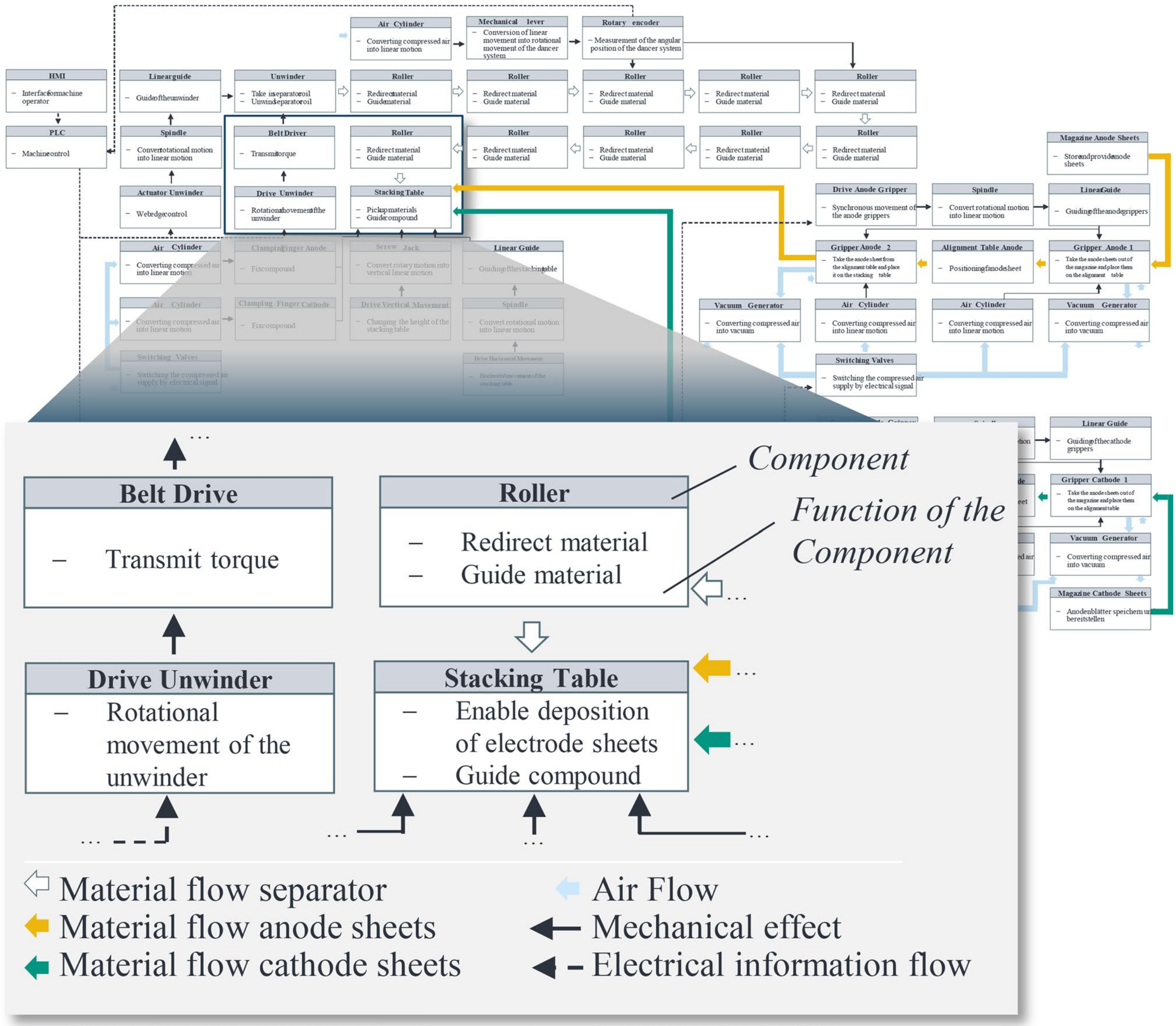

Fig. 3 Excerpt of the top-down analysis

additional components will be implemented minimally if needed.

The separator was given the highest score in the analysis. This may be surprising at first, as the focus of the work is on the machine. The separator functions at this point as a component on which the various components have an effect. Therefore, it is necessary to present it as well. Since a large part of the machine's behavior affects the separator, it is given the highest score in the analysis. But the drive motors for the individual axes, as well as the guide rolls, unwinder and dancer, are also important. By combining DSM and utility analysis, a more comprehensive basis for decision making is obtained, considering both the structural aspects of the system and the evaluation criteria. This can aid in making informed decisions that take into account both the relationships between individual elements and the overarching objectives. In the presented case of a Z-folder system simulation, this approach significantly reduces the implementation effort.

2.3 Model parameterization

After identifying the key components for the system simulation, the individual parameter values are determined. First, the coordinates of the components are measured to capture the spatial arrangement of the system in the model. Additionally, specific values can be approximated through a literature review and data sheets. Masses, moments of inertia, and geometries are determined based on the corresponding CAD models. Further relevant parameters, such as the

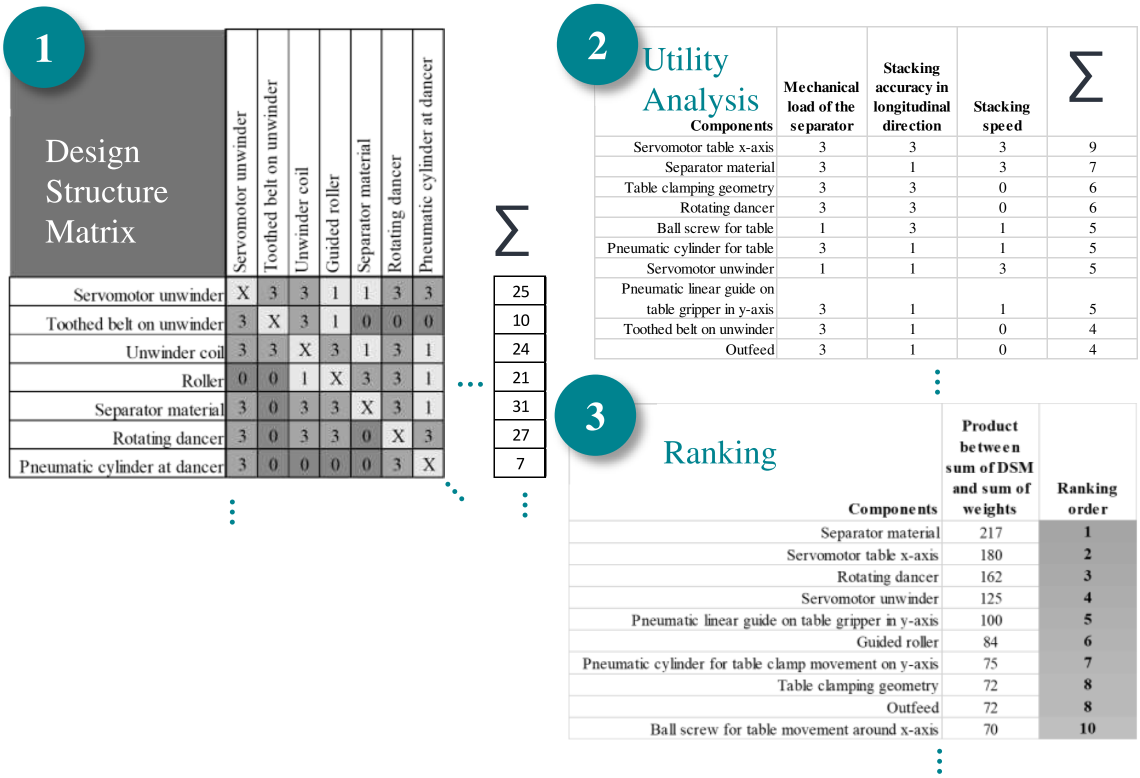

Fig. 4 Excerpt of the DSM and the utility analysis

material parameters of the separator, are determined through experimental methods. Table 1 illustrates the sources of parameterization used for this modeling task. The experimental determination of the parameter values is discussed below.

The behavior of the separator under uniaxial tensile stress is investigated using a tensile test according to ISO 527-3. The rollers and the table surface are made of carbon fiber reinforced plastic (CFRP). Therefore, the coefficients of friction between the separator and the CFRP are determined by a coefficient of friction test according to ISO 8295. The results of the experimental parameterization are illustrated in Fig. 5. For the measurements, a ceramic-coated nonwoven separator and an uncoated polymer separator were used. On the left side of the figure, the average static and dynamic friction values are depicted. It can be observed that the static friction value is higher and the dynamic friction value is lower compared to the polymer separator. The likely cause for this difference is the particle behavior of the ceramic coating.

On the right side, the Young's Modulus resulting from the tensile tests is presented. It is evident that, on average, the nonwoven fabric separator exhibits a higher Young's Modulus than the polymer separator. The determined average values are subsequently used in the model.

Table 1 Sources of parametrization

Literature review and data sheets	CAD construction	Experiments
Friction values bearings	Position of components	Young's modulus separator
Friction pneumatic cylinders	Masses	Friction between separator and rollers
Moments of inertia (drives)	Moments of inertia (rollers) Geometries	

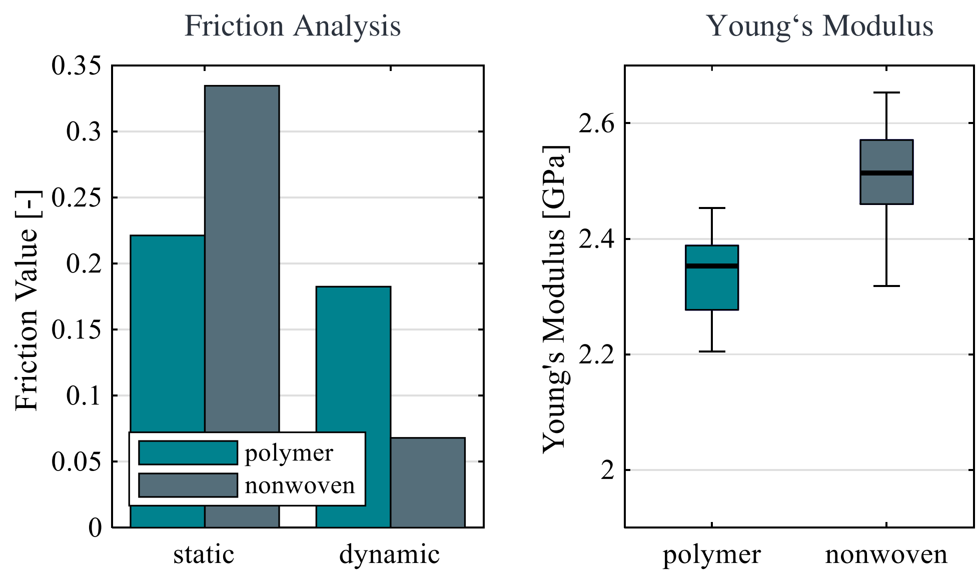

Fig. 5 Results of experimental parameterization

2.4 Model formalization

A multiphysics simulation using *Siemens Simcenter Amesim* is performed for the model formalization. The system is constructed using individual model-building-blocks. Various elements from the two dimensional mechanical library were utilized for handling the separator. Signal elements were used for controlling the axes and process parameters. One notable aspect is the modeling of the table along with the clamping fingers for the separator. These movements are programmed using state charts, position and speed control elements, allowing the optimal determination of movement speeds, start and end time points depending on the settings. The main model without submodels including the input, internal and output parameters, is shown in Fig. 6. The input parameters can be varied by the user and are divided into material and machine parameters. For the internal parameters, an excerpt has been provided. This includes,

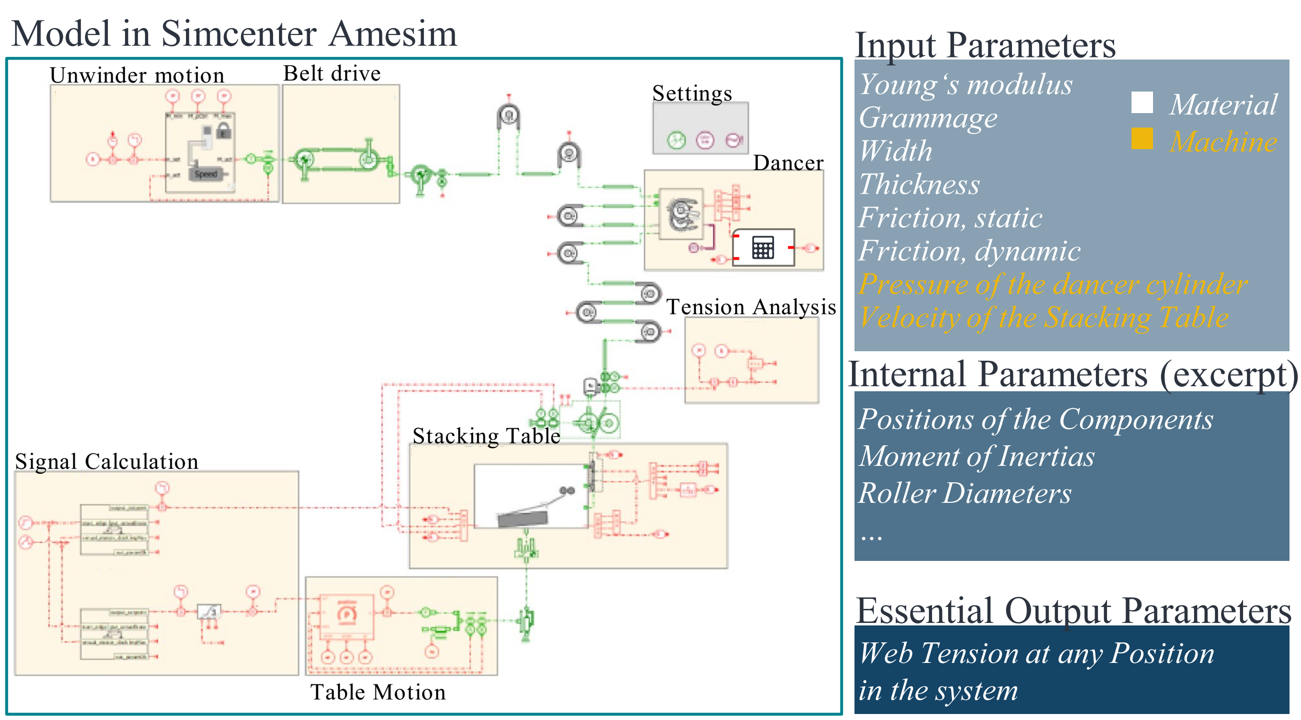

Fig. 6 Model of the Z-Folding machine in *Simcenter Amesim* and its parameters

for example, the inertias and positions of the components. The essential output variable includes the web tension at any position in the system. In the model, the identified aspects and levels of detail from the previous analysis steps are implemented. Additionally, the parameters in the individual sub-models have been populated with the required values. The individual calculations are based on physical relationships, which will not be discussed in detail in this context. It should be mentioned at this point that the description of the web tension based on a mass conservation equation, which will be explained in more detail in [24]. The effects of rollers are explained in [25].

3 Model-based analysis

In the context of this study, a model-based analysis of machine-side influences on material stress is conducted. The main focus is on using the two aforementioned separators, considering their average determined friction values and Young's modulus. Another important aspect of this investigation is the examination of three different table velocities. The pressure in the cylinder of the dancer system is kept constant during this analysis to exclusively study the effects of table velocity on material loading. To include as many machine-side influences as possible, the web tension is analyzed after the last roller. The selected parameters, namely the two separators with their specific friction and modulus values, as well as the three table velocities, are illustrated in Table 2.

First, the influence of the materials on its load under velocity 2 is investigated. The results are shown in Fig. 7. As shown here, the tension profile in the system exhibits a significant dependency on the system's kinematics. The first peak occurs when the clamping finger makes initial contact with the separator. Subsequently, the web tension relaxes as the table moves to the right side.

Table 2 Material and machine parameters

Material parameters			Machine parameters	
	Nonwoven	Polymer		
Young's modulus [GPa]	2.44	2.34	Pressure of the dancer cylinder [MPa]	0.2
Grammage [10^{-5}*g/mm^2]	4.077	1.166	Velocity 1 [mm/s]	32
Width [mm]	143	145	Velocity 2 [mm/s]	80
Thickness [µm]	30	20	Velocity 3 [mm/s]	128
Friction, static [–]	0.335	0.221		
Friction, dynamic [–]	0.068	0.182		

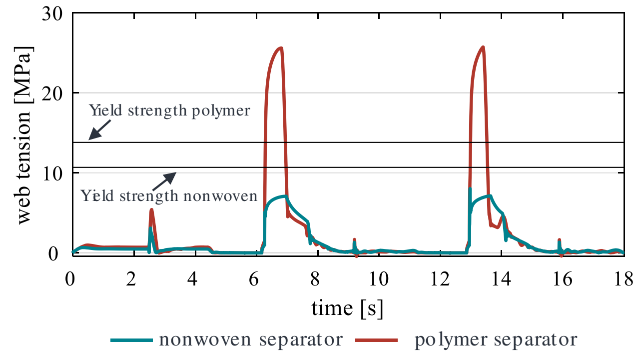

Fig. 7 Comparison of web tensions for different materials at velocity 2

Once the table aligns directly under the outfeed rollers, reaching the central position, the separator experiences a sudden tensile stress, leading to the second peak. This deflects the dancer enough to activate the unwinder, which unwinds the material, first limiting and then reducing the web tension. As the table moves towards the right end position, the material continues to unwind. The second gripping of the separator, evident in the third, smaller peak. Following a brief waiting period, this process is repeated periodically.

Both materials share an identical machine parameter configuration, which results in the simultaneous progression of the stress profiles. The only variation lies in the previously determined material parameters. In the case of the polymer separator, it is evident that the peaks of the web stresses are significantly increased. Therefore, it is not suitable for the given kinematics. Adjustments in the table speed or in the dancer cylinder pressure would be necessary to reduce the web tension and prevent material damage.

Second, the process is simulated at three different table velocities. As depicted in Fig. 8, web tension correlates with velocity. While high speed provides faster production cycle times, it also increases stress peaks. At velocity 3, the separator exceeded the yield strength, thereby diminishing the

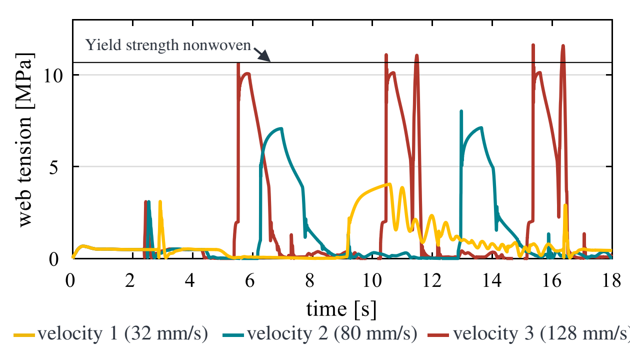

Fig. 8 Comparison of web tensions at different velocities for the nonwoven separator

quality of cell stacking by plastic deformation. Conversely, employing the lower velocity 1 mitigates stress peaks. However, it causes vibration due to the slower pace and subsequent delayed material discharging. The model helps determining the suitability of the system for elevated materials and different machine-side parameters without causing plastic stresses, suggesting potential adjustments for optimal performance. In particular, the model ensures that valuable material is not wasted by providing a sufficiently digital representation of the Z-folding process.

4 Summary and outlook

This work focuses on the modeling of machine-related influences on the stack assembly process and their significance for optimization, particularly during the ramp-up phase. The objective of this study was to present a generalizable methodology for developing a machine model for a Z-Folding machine. To create the model, the components to be modeled and the desired level of detail were initially determined. Subsequently, a parameterization was performed, with the sources used for parameterization being described. Experimental determination was necessary for the coefficients of friction between the rollers and separator, as well as for the Young's Modulus. The modeling itself was carried out using *Simcenter Amesim* software. This made it possible to quantify and analyze the influence of different machine and setting parameters on the quality-relevant web tension. Virtual identification of possible process boundaries can thus be achieved prior to actual implementation. In comparison to other modeling approaches, such as data-driven methods, the following advantages and disadvantages can be noted. One advantage of this approach is that initially, no real datasets are required. For example, in the early development phase of a machine or during the early ramp-up phase, relationships between machine and material parameters can be quantified. The disadvantage is that, for model creation, it is necessary to know which parameters should be considered. Through the use of data-driven approaches, such as employing artificial intelligence, relationships can be identified that may have been overlooked in the development of the multiphysical model.

The outlook includes the validation of the model. Here, a measuring roller is integrated into the system and all parameters are varied via a statistical test series and web tension is measured. The measured values are then compared with the simulation data using, for example, the root-mean-squared error. Furthermore, it is possible to integrate additional models that focus on the material-side influences.

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Data availability The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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