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Simulation Model for Digital Twins of Pneumatic Vacuum Ejectors

Increasing productivity, as well as flexibility, is required for the industrial production sector. To meet these challenges, concepts in the field of "Industry 4.0" are arising, such as the concept of Digital Twins. Vacuum handling systems are a widespread technology for material handling in industry and face the same challenges and opportunities. In this field, a key issue is the lack of Digital Twins containing behavior models for vacuum handling systems and their components in different applications and use cases. A novel concept for modeling and simulating the fluidic behavior of pneumatic vacuum ejectors as key components of vacuum handling systems is proposed. In order to increase the simulation accuracy, the concept can access instance-specific data of the used asset instead of object-specific data. The model and the data are part of the Digital Twins of pneumatic vacuum ejectors, which shall be able to be combined with other components to represent a Digital Twin of entire vacuum handling systems. The proposed model is validated in an experimental test setup and in an industrial application delivering sufficiently accurate results.

Keywords: Digital Twin, Behavior model, Pneumatic vacuum ejector, Simulation model

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1 Introduction

The industrial production sector is required to increase productivity and flexibility due to shorter product lifecycles, mass customization, and global competition leading to an increased price pressure [1–3]. To meet these challenges, new information and communication technologies are supposed to contribute. These are often summarized in terms such as "Digitalization", "Industrial Internet of Things (IIoT)" or "Industry 4.0" [2]. This often includes simulation techniques in early phases of engineering, virtual commissioning, predictive maintenance or condition monitoring. For the realization of such uses cases, detailed digital representations, often called models, of the used components and objects together with relevant data is needed. Generating the models and data manually takes a vast amount of time, decreasing the benefit of the use cases and the productivity of the entire object or process.

An alternative option is to employ a concept that has been gaining importance lately, the so-called Digital Twin. In literature, a variety of different definitions for Digital Twins exist, due to its novelty and high popularity [2,4]. In this article, a definition is used in which a Digital Twin is a virtual representation of an object, very often referred to as asset, enabling to represent its static and dynamic behavior [5]. It contains all models of the represented object and includes all data from the different phases of the lifecycle, enables the simulation of the physical behavior in the virtual space and is always synchronous with the asset. Using Digital Twins in the various named use cases of "Industry 4.0" increases their efficiency significantly. Therefore, the Digital Twin is often seen as an enabler for a successful realization of "Industry 4.0" [2].

Besides the use cases of "Industry 4.0", the mentioned challenges lead to the fact that more and more components which used to be mechanical are becoming mechatronic components by integrating computing units and communication technology [6].

A domain influenced by both, the digitalization as well as the trend to more and more mechatronic systems, are material handling systems using vacuum. These vacuum handling systems are widely used in production systems and automated handling tasks due to their robustness and easy implementation compared to competing technologies [7,8]. Throughout their ability to grip the object just from one side, they can easily adapt to different forms, sizes, and weights of objects with only little or no modifications [9]. This makes vacuum handling systems an interesting solution for future flexible production

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systems. In general, they consist of components of six major categories, which are vacuum generators, connections, fastening elements, switches and system monitoring elements, valves and of course vacuum suction cups [10].

Pneumatic vacuum ejectors as representatives of pneumatically driven vacuum generators are key components of high dynamic vacuum handling systems. They combine many advantages such as fast and wear-free operation, as well as lightweight construction which allows mounting them directly on end-of-arm toolings for robots and handling systems leading to vacuum handling systems as functional all-in-one and ready-to-use-devices, as shown on the left of Fig. 1 [8, 11].

Core component of a pneumatic vacuum ejector is its nozzle technology consisting of one or more drive and receiver nozzles working in combination following the principle of jet pumps. Using compressed air flowing through the ejector the static pressure according to the principle of Bernoulli drops, which leads to a measurable pressure difference to the atmospheric pressure often described as the vacuum level [10, 12].

In addition, pneumatic vacuum ejectors may comprise valves, control units, and silencers, and are then, referred to as compact ejectors, seen in the middle of Fig. 1. The fluidic scheme of such a compact ejector is presented on the right of Fig. 1. A crucial issue using these pneumatic vacuum ejectors in "Industry 4.0" use cases is the lack of models describing their physical-technical behavior in terms of fluidic and control relevant aspects.

Beginning with the identification of relevant parameters for vacuum handling systems, existing approaches to model pneumatic vacuum ejectors besides solutions from other domains are presented and conclusions for the rest of this contribution are drawn (Sect. 2). Afterwards, a representative evacuation process is analyzed using a pneumatic vacuum ejector (Sect. 3). The proposed phase model is then used to create a model concept for the behavior of pneumatic vacuum ejectors (Sect. 4). This model is realized and validated in a typical industrial application in addition to an experimental test setup (Sect. 5). The article ends up with a summary, a conclusion, and a brief outlook (Sect. 6).

2 Initial Situation

Stating relevant parameters in vacuum handling systems is followed by approaches for pneumatic vacuum ejectors and those of other domains.

2.1 Relevant Parameters in Vacuum Handling Systems

Most of the relevant parameters of a vacuum handling system such as the gripping force, the time needed to evacuate the system, mostly relevant for the cycle time, as well as the energy consumption can be directly calculated from the current vacuum level in the system. Relevant components influencing the vacuum level in the system are vacuum generators, connections and vacuum suction cups [9, 14].

2.2 State of the Art

Existing approaches to model relevant parameters for pneumatic vacuum ejectors and solutions from other domains for behavior modeling are presented in the following.

2.2.1 Concepts to Model the Evacuation Behavior of Pneumatic Vacuum Ejectors

A nearby way to model the pressure behavior of pneumatic vacuum ejectors connected to a vacuum system can be derived from the ideal gas equation. Under the conditions of a leakage free system and a linear suction capacity of the vacuum generator the actual pressure can be calculated as follows [9, 14, 15].

$$p(t) = [p_0 - p_{\mathrm{end}}]\exp\left(-\frac{S_{\mathrm{N}}}{V}t\right) + p_{\mathrm{end}} \tag{1}$$

Herein, the actual pressure depends on the ambient pressure $p_0$1), the minimum achievable absolute pressure of the vacuum

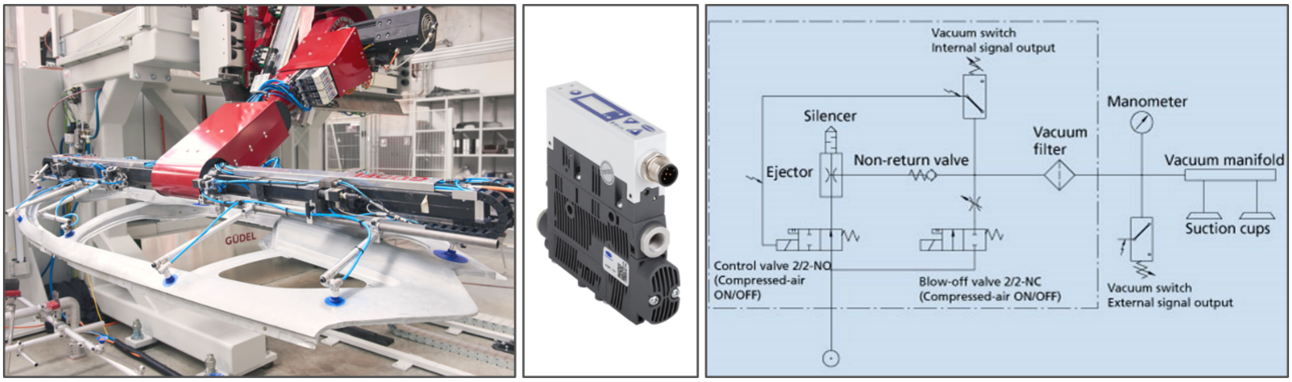

Figure 1. Representative industrial setup of a high dynamic vacuum handling system using compact ejectors (left), example of a widespread compact ejector (middle) [13], and fluidic scheme of a pneumatic vacuum ejector with pneumatic control (right) [13].

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1) List of symbols at the end of the paper.

generator p_{end}, the nominal suction power of the vacuum generator S_{N}, the systems volume V, and the evacuation time. Under the condition of a constant suction capacity of the vacuum generator over the complete vacuum range, Eq. (1) can be simplified. Using the following equation, the time to reach a specific vacuum level can be calculated directly.

$$t = \frac{V}{S_{\mathrm{N}}} \ln\left(\frac{p_0}{p_{\mathrm{v}}}\right) \tag{2}$$

Therein, the evacuation time t depends, besides the already known parameters, on the desired absolute final pressure p_{v}. In practical applications, a safety factor of 1.2 or higher is used by multiplication [9].

In addition to these basic calculation methods, two- or three-dimensional numerical simulation methods are often used in the field of pneumatic vacuum ejectors to simulate specific parts, mostly focusing on the venturi nozzle as it is the core component and mainly influencing the behavior of the whole component. A widespread method of numerical modeling is computational fluid dynamics (CFD) [10].

For cross-domain simulations of complex mechatronic systems with multiple components, as needed in many Digital Twin use cases, system simulations form a good solution. As such models for system simulations of pneumatic vacuum ejectors are not commonly accessible so far, existing concepts from other domains will be viewed at in the following.

2.2.2 Modeling Concept from Other Domains

Most of the machines used in production, pneumatic vacuum ejectors are installed in, consist of different components realizing the different functionalities of the machines. This abstraction is also applied for behavior models. On the different abstraction levels, the corresponding components are implemented as virtual behavior models with their inputs and outputs [16, 17].

2.3 Conclusions from the Introduction and the Initial Situation

Based on the initial situation and the state of the art, the following conclusions can be drawn for the scope of this article:

- Pneumatic vacuum ejectors are key components of high dynamic vacuum handling systems. The availability of Digital Twins and models describing them is therefore a crucial issue.
- Most of the relevant key performance indicators of vacuum handling systems can be derived from the vacuum level in the gipping system. It is the most important parameter.
- A large number of use cases of the Digital Twin require behavior models for the mapped assets.
- As such models are not commonly accessible for pneumatic vacuum ejectors so far, a novel model concept is proposed.
- To be able to set up a model concept, the influence of pneumatic vacuum ejectors on the vacuum level of vacuum handling systems needs to be analyzed at first.

3 Phase Model of a Representative Evacuation Process

Analyzing the influence of pneumatic vacuum generators on the vacuum level, a typical evacuation process of a pneumatic vacuum ejector, as schematically displayed in Fig. 1, connected to a stainless-steel tank with a preset leakage, is presented in Fig. 2. This simplified test setup is used to avoid other influences on the vacuum level than those of the pneumatic vacuum ejector.

The vacuum in mbar relative (mbar,rel) is indicated on the left y-axis and the time is presented on the x-axis. The right y-axis shows the Boolean signal for starting the evacuation process and the Boolean signal to start the blow-off process over time to analyze the vacuum level not only over time but also in relation to the signals received from the system the pneumatic vacuum ejector is connected to.

Fig. 2 shows different phases of the vacuum level over time for controlled pneumatic vacuum ejectors. The blue areas represent the time slots with an active nozzle. During this time, the vacuum level of the system increases. In contrast, the red areas show the timeslots where the nozzle is inactive due to the air-saving function of the pneumatic vacuum ejector. The air-saving function is applied to reduce the compressed air consumption using a two-point control with an upper threshold (H1) and a lower threshold (H2). During the time of the air-saving function, no compressed air flows through the nozzle, which leads to a decrease of the vacuum level of the system mostly caused by leakage. Furthermore, the green area shows the time slot where the blow-off function of the pneumatic vacuum ejector is active to destroy the vacuum in the system, which leads to an object release.

The blue phases are all very similar in their qualitative course. They are mainly influenced by the suction capacity of the pneumatic vacuum ejector together with the volume of the

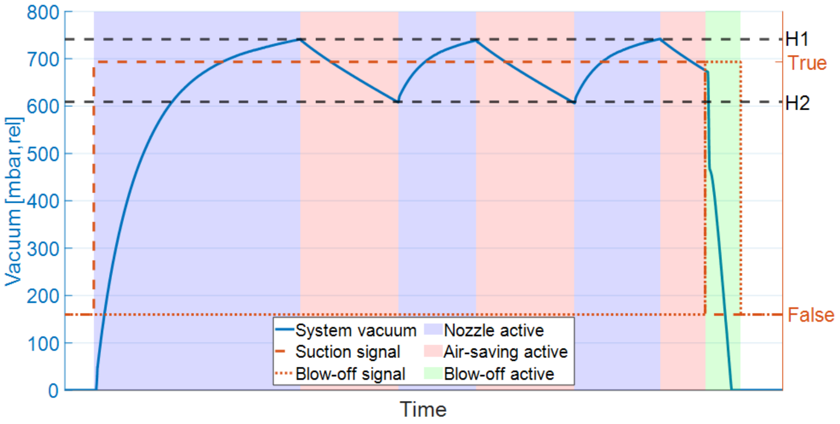

Figure 2. Vacuum over time of a typical evacuation process.

connected vacuum system. These phases show the impact of the pneumatic vacuum ejector with an active nozzle to the vacuum level of the system and will therefore be analyzed more in detail in Fig. 3.

It presents a section of the first blue area from the left side, with the same information on all three axis. In difference to Fig. 2, Fig. 3 represents an increase of the system vacuum from environmental pressure at the beginning of the evacuation process to a vacuum level just over 500 mbar,rel. Furthermore, due to the shorter time shown in the figure, the start of the evacuation process can be analyzed more in detail. Expanding the sole evacuation phase, colored in red, Fig. 3 also depicts two more preceding phases, i.e., a response phase, colored in green, as well as a ramp-up phase, colored in blue.

The response phase describes the time range the pneumatic vacuum ejector needs to start the evacuation process beginning with the suction signal coming from a controller, for example. It is mainly determined by the reaction time of the control elements of the pneumatic vacuum ejector. After this response phase, the ramp-up phase begins. This ramp-up phase represents the time needed by the pneumatic jet to ramp up after the valve opens up. After the suction capacity reaches its full potential, the ramp-up phase is over and the regular evacuation phase comes into operation.

Analyzing a relevant evacuation process leads to the following three phases needed to enable a technical physical behavior modeling of the most relevant parameters for the evacuation process of pneumatic vacuum ejectors:

- response phase,
- ramp-up phase and
- evacuation phase.

4 Conception of a Model for Pneumatic Vacuum Ejectors

The concept to model the behavior of a pneumatic vacuum ejector is based on the newly presented three relevant phases. The basic behavior of the pneumatic vacuum ejector is modeled using a controlled mass stream source. The mass stream of pneumatic vacuum ejectors is strongly dependent on the current vacuum level at the suction port and the operating pressure with which the pneumatic vacuum ejector is operated [14]. This is realized with the help of a characteristic diagram that depends on the current vacuum level and the operating pressure feeding the controlled mass stream source. This mass stream source as the center of the model besides all peripheral components is depicted in Fig. 4.

To increase the transparency, the different parts of the concept are clustered in six major blocks. Starting on the left-hand side of Fig. 4, the input parameters needed to model are listed. These input parameters contain information about the pressure supply of the pneumatic vacuum ejector, due to its impact on the suction capacity [14]. Furthermore, the type and ID are listed for further usage of object or instance-specific data. Thereby object-specific data contain general information about all assets of a certain type while instance-specific data contain individual information about one individual asset.

The start signal is used to start the evacuation process and the further information below contain values for peripheral functionality, which is not the main scope of this paper. This peripheral functionality is modeled in the additional functionality block to the right of the input parameters block. Herein, functionality such as the two-point control can be modeled. More relevant is the time-delay block realizing the reaction phase described in Fig. 3. This time-delay is specific for different types of pneumatic vacuum ejectors and part of the object-specific data stored in the Digital Twin. This data is accessed via the data access block in Fig. 4. Therefore, a get function uses the information from the parameter input to access the relevant data via the database connection. This information is employed in the additional functionality block and in the central functionality block, too. Therein, this information is processed in the data set block to provide it to the mass stream source.

Furthermore, the data set receives the actual system pressure from a pressure sensor as the mass stream of a pneumatic vacuum ejector is dependent on the actual pressure [14]. Besides that, the system pressure and the information from the database, the data set also gets control information from the additional functionality block such as the delayed start signal or signal from the two-point control. Using all these information, the data set provides the mass stream source with the actual relevant mass stream the pneumatic vacuum ejector is able to evacuate from the connected vacuum system to the environment.

The connection to the mentioned vacuum system relevant for the modeled pneumatic vacuum ejector is realized in the access vacuum system box shown in Fig. 4. Other components of the system, the vacuum handling system with the modeled pneumatic vacuum ejector is connected to, make decisions in dependence of the actual vacuum level of the system. Therefore, this information is provided. This can be done by just making the actual system pressure available or by defining switching thresholds to trigger digital signals.

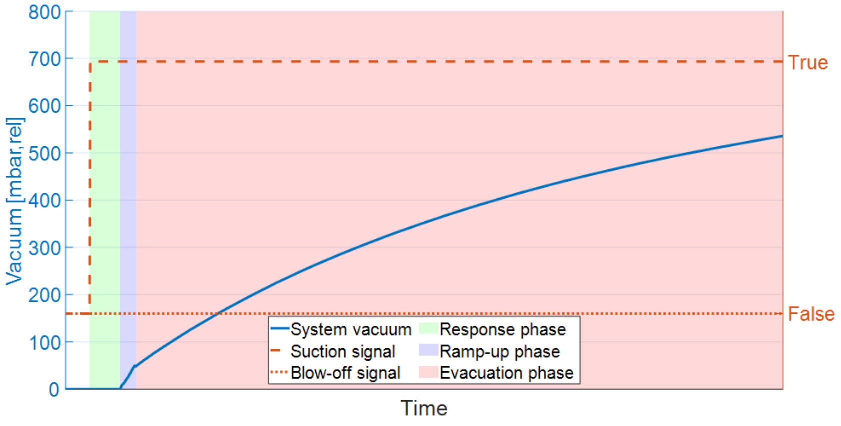

Figure 3. Start of the vacuum over time of a typical evacuation process.

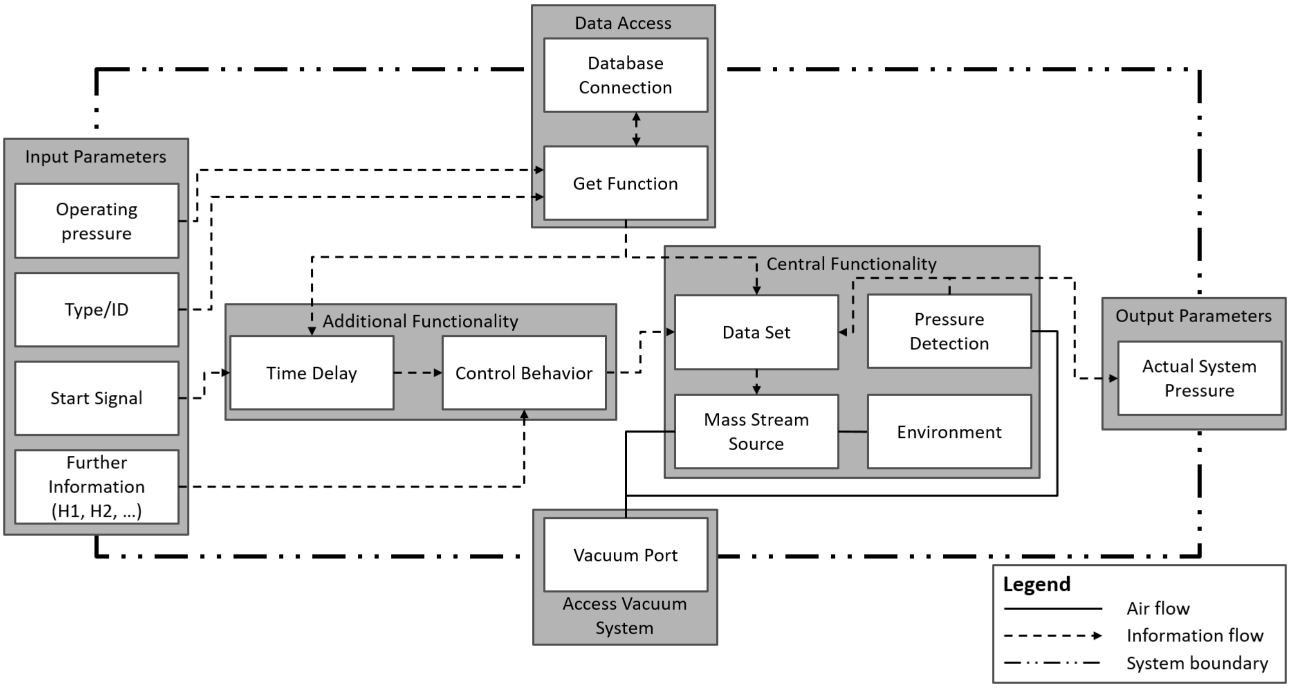

Figure 4. Functional model for pneumatic vacuum ejectors.

5 Realization and Validation Based on a Test Setup and an Industrial Application

The realization of the presented model concept will be implemented using a common system simulation environment and validated afterwards against an experimental test setup plus an industrial application.

5.1 Simulation Model

To decrease the complexity for the validation, a reduced version of the model presented before will be used. Thereby the basic functionality of the vacuum modeling is retained, omitting only those parts of the model that are responsible for peripheral functions. This reduced model concept is realized with the commonly used system simulation environment Matlab Simscape, taking advantage of predefined building blocks for the model of the pneumatic vacuum ejector as well as for other components of the system as indicated in Fig. 5. Therein the model of the pneumatic vacuum ejector with the mass stream source in the middle plus the data set which controls the mass stream dependent on the type and the actual pressure of the connected vacuum system is displayed on the top. The actual pressure is captured using a pressure sensor, shown on the right side in the pneumatic vacuum ejector box.

For the validation, further components are also modeled completing the system such as pipes, further pressure sensors, a constant volume tank, and a solver. This setup will be explained further in detail in the following section.

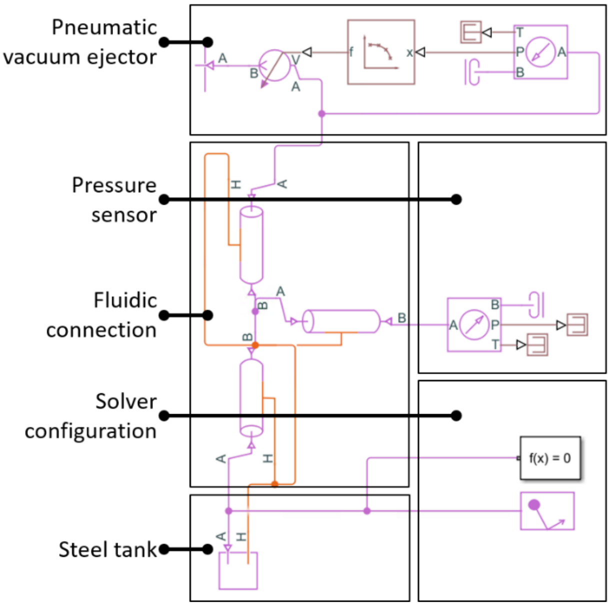

Figure 5. Simscape model of the test setup.

5.2 Experimental Test Setup

The experimental test setup used to validate the model involves a pneumatic vacuum ejector with the needed periphery consisting of a pneumatic pressure supply besides the environment where the outlet of the pneumatic vacuum ejector is connected to. The fluidic part of the test setup is illustrated in Fig. 6.

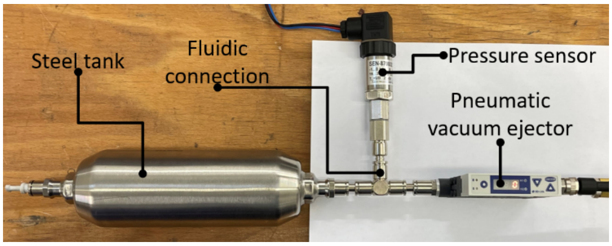

Figure 6. Fluidic part of the used test setup.

The vacuum system connected to the vacuum port of the pneumatic vacuum ejector consists of a fluidic T-connector connecting a stainless-steel tank with a volume of 0.75 l as well as a pressure sensor. The pressure sensor is connected to a programmable logic control (PLC) which enables a live tracking of the pressure values in the cycle time of 1 ms plus the control of the pneumatic vacuum ejector. To start the evacuation process via the PLC a laptop is used. This laptop has also access to the tracked pressure values.

For the test setup the parameters from Tab. 1 as well as standard conditions according to ISO 8778 are employed [18]. The used object-specific suction capacity is the average of the suction capacity of ten pneumatic vacuum ejectors from different manufacturing dates and batches.

Table 1. Parameters of the test setup.

Parameter	Value
Instance-specific suction capacity	35.0 sl min^{-1}
Object-specific suction capacity	33.4 sl min^{-1}
Tube length from tank to t-connection	50 mm
Tube length from t-connection to pneumatic vacuum ejector	50 mm
Tube length from t-connection to pressure sensor	65 mm
Inner diameter of tubes	6 mm
Tank volume	750 ml
System volume	755 ml
Minimum pressure reachable for pneumatic vacuum ejector	150 mbar,abs

5.3 Results for the Test Setup

The results comparing the presented models with the measurements generated with the test setup is depicted in Fig. 7. The y-axis displays the difference pressure in mbar,rel and the x-axis the time. The measured pressure over time is shown in blue while the dashed curves in yellow and orange demonstrate the simulated behavior with the presented model using instance and object-specific data, respectively. Furthermore, the purple and green dotted curves denote the evacuation process using the state-of-the-art equations (1) and (2).

Comparing the existing equations and the simulated behavior with the measurement indicates a significant improvement in the qualitative as well as quantitative course using the presented behavior model. A more detailed examination of the presented pressure over time is done in Tab. 2. It displays the maximum deviation between the measured and the calculated curves using the different calculations depicted in Fig. 7. The deviations to the measurement are presented in absolute and percentage figures in the first two columns. Concentrating on the percentage values, the improvement from the state-of-the-art equations to the newly presented model can be clearly seen.

As already mentioned, a typical key performance indicator for vacuum handling systems is the evacuation time mostly influencing the cycle time directly. A typical target value for the vacuum level is 600 mbar,rel [19]. Using this value, Tab. 2 presents the time needed to reach a vacuum level of 600 mbar,rel for the test setup using the different sources.

Columns four and five demonstrate the absolute and percentage deviation to the measured time. The analysis of the cycle time, highly relevant for the process the vacuum handling is used in, also confirms the statements already made that the newly presented behavior model is significantly more accurate than the previous equations presented in the state of the art. Furthermore, the already high accuracy of the behavior model can be even further increased by using instance-specific data instead of object-specific data. Since the analysis of the evacuation time gives a similar result as the analysis of the pressure over time, the evacuation time can be used as a relevant parameter to compare different models in the future.

Table 2. Analysis of the evacuation process of the test setup.

Source	Maximum deviation to measurement in Fig. 7	Percentage deviation to measurement in Fig. 7	Evacuation time to reach 600 mbar,rel	Deviation to measured evacuation time
Measurement presented in Fig. 7	–	–	1091 ms	–
State-of-the-art equation (1)	126 mbar	14.8 %	1569 ms	43.8 %
State-of-the-art equation (2) using a safety factor of 1.2	128 mbar	13.9 %	1403 ms	28.6 %
New behavior model using object-specific data according to Fig. 5	29 mbar	3.4 %	1164 ms	6.7 %
New behavior model using instance-specific data according to Fig. 5	17 mbar	2 %	1113 ms	2.0 %

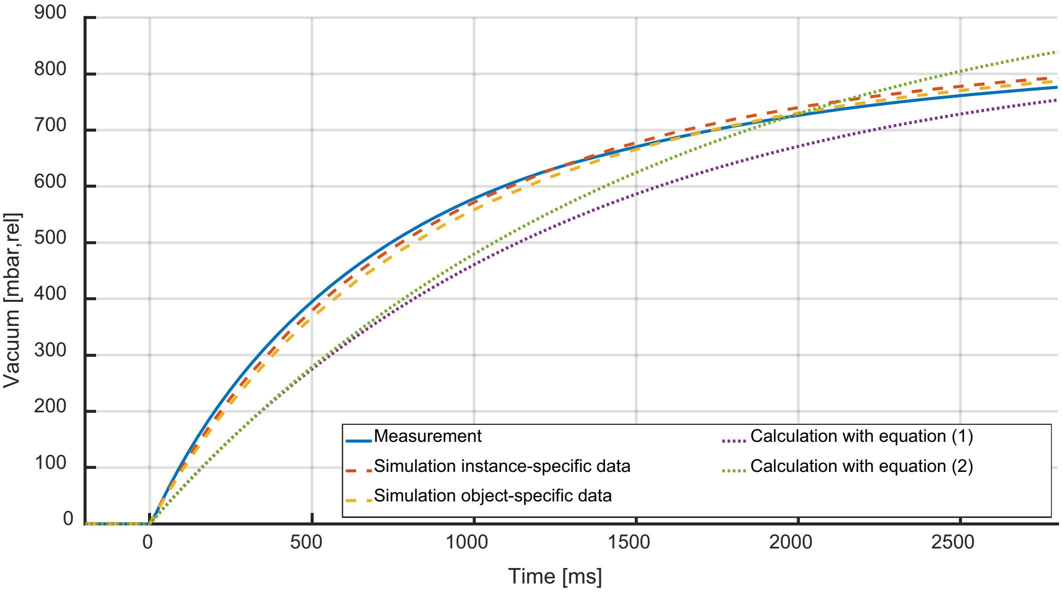

Figure 7. Comparison of simulated and measured pressure over time.

5.4 Industrial Application

To further illustrate the accuracy of the introduced model, the evacuation of a typical industrial application of a vacuum handling system for metal sheet handling in the automotive body shop is used. The parameters of the system are presented in Tab. 3.

Furthermore, the instance-specific suction capacity from the test setup specified in Tab. 1 along with the standard conditions according to ISO 8778 are employed [18]. The presented application example extending the presented model is built in Matlab Simscape resulting in the model presented in Fig. 8.

The calculated and measured times to reach the desired 400 mbar,abs (corresponds to 600 mbar,rel at standard conditions) together with the absolute deviation between the measured and the calculated or simulated time are given in Tab. 4.

The analysis of the presented evacuation times clearly show again the significant improvement in modeling the evacuation time using the new behavior model compared to existing calculation models. The deviation using existing calculations ranges from 42 % to 58 % applying Eq. (2) with the mostly used safety factor of 1.2 [9]. Compared to this, the deviation can be reduced to 15 % using the presented behavior model of the pneumatic vacuum ejector with object-specific data. A further reduction of the deviation to 10 % can be achieved by using instance-specific data.

Table 3. Description of the parameters from the industrial application [19].

Parameter	Value
Length of tubes	2 m
Inner diameter of tubes	4 mm
Volume of suction cups and periphery	125 ml
System volume	150 ml
Target system pressure	400 mbar,abs

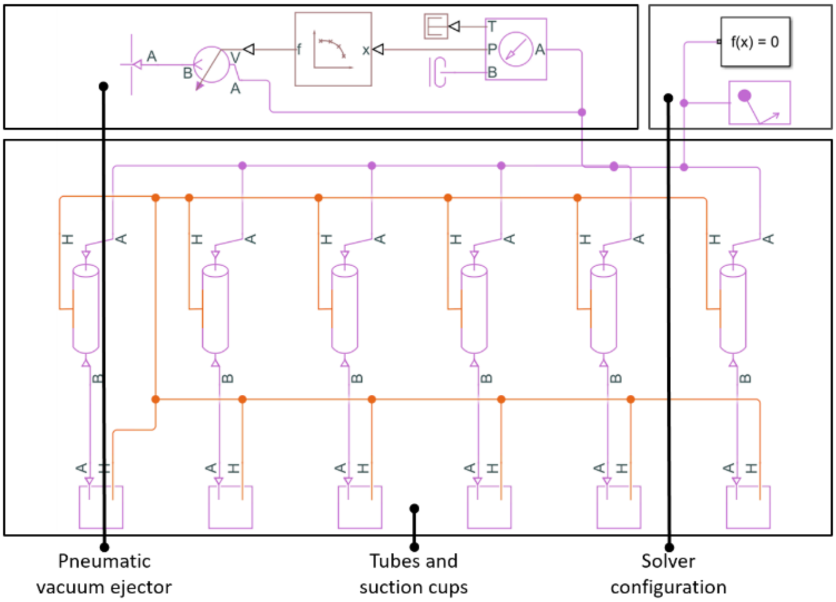

Figure 8. Simscape model of the industrial application.

Table 4. Evacuation times for the industrial application using the presented models.

Source	Evacuation time	Deviation to measured evacuation time
Measurement [19]	200 ms	–
State-of-the-art equation (1)	315 ms	58 %
State-of-the-art equation (2) using a safety factor of 1.2	283 ms	42 %
New behavior model using object-specific data	230 ms	15 %
New behavior model using instance-specific data	220 ms	10 %

6 Summary and Conclusion

The presented contribution mentions current challenges of the producing industry as well as for vacuum handling systems and therefore pneumatic vacuum ejectors leading to the need of digitized models with special emphasis on behavior models. Beginning with the presentation of existing modeling concepts for pneumatic vacuum ejectors plus concepts from the domain of machines in production lines, such behavior models used in production machines are not consistently available for pneumatic vacuum ejectors. Therefore, a representative vacuum process is analyzed first in a macroscopic and afterwards in a more detailed way to present a novel phase model of the evacuation process and identify the relevant modelling aspects. These aspects are picked up in the presented concept model enabling the first time behavior modeling of the evacuation process for pneumatic vacuum ejectors connected to a vacuum system, mostly vacuum handling systems, with a flexible accuracy depending on the used data set describing the physical component.

Validating the proposed concept, implementation is done using a widespread system simulation tool to compare the simulated behavior with the measured behavior for a test setup and a typical industrial application. With both scenarios, the functionality of the presented model could be impressively demonstrated and is now available for further development for industrial application. To further increase the already high accuracy of the model, an instance-specific data set instead of an object-specific data set is examined and shows even further improvements in accuracy.

Future work will focus on the modeling of the ramp-up phase of the pneumatic vacuum ejector as well as the blow-off process to destroy the vacuum in the connected system. At the system level, behavior modeling of vacuum suction cups will be a focus for further contribution as these are mostly influencing the behavior of vacuum handling systems besides the vacuum generators.

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Symbols used

$p(t)$	[bar]	Pressure at time t
p_0	[bar]	Ambient pressure
p_{end}	[bar]	Minimum achievable absolute pressure of the vacuum generator
p_{v}	[bar]	Desired absolute final pressure
S_{N}	[$\mathrm{m^3s^{-1}}$]	Nominal suction power of the vacuum generator
t	[s]	Time
V	[$\mathrm{m^3}$]	Volume

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