NOVEL ENGINEERING AND PRODUCT SOLUTIONS TOWARDS DIGITALIZATION AND SUSTAINABILITY IN VACUUM HANDLING AUTOMATION

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ABSTRACT

This paper outlines new digital services for vacuum handling automation as well as new fluidic system concepts and products. Due to the large number of applications and different objects to be gripped, as well as the large product portfolio, the design process is heavily based on experience and testing. A digital engineering platform for vacuum gripping systems can help to rapidly provide optimal solutions. With a view to greater sustainability, new or previously little-used fluidic system concepts and innovative components are presented. These include, in particular, system concepts with controllable pumps, grippers with venting function, or the reduction of energy consumption. More efficient cups seal better to the surface of the object being gripped and therefore have less leakage. Simulation and test results are used to demonstrate the potential of the solutions in terms of energy efficiency.

Keywords: Digitalization, Energy Efficiency, Vacuum Handling, Vacuum Grippers

1. INTRODUCTION

Current trends such as demographic change, the shortage of skilled workers, digitalization, fragile supply chains, the need for greater sustainability and, last but not least, increased competitive pressure require new solutions and products in and for industrial production technology. Digital support for the product development process, modular systems and energy-efficient components and system concepts can help here. This article presents suitable concepts and products from the field of vacuum handling technology.

2. VACUUM HANDLING TECHNOLOGY AND KEY ISSUES

As a world market leader in vacuum handling technology, the J. Schmalz GmbH covers a product spectrum ranging from small suction cups with a diameter of 1 mm to layer grippers for intralogistics with a load capacity of 300 kg and vacuum lifting systems for the wind power industry with a load capacity of up to 40 tons [1]. In the area of vacuum components, there are more than 10,500 active sales items, of which over 4,000 are suction cups and over 1,500 are vacuum generators. Many advantages of vacuum handling technology are the reason for its widespread use: coverage of a wide range of requirements and applications, gentle handling and good accessibility from above, high process safety and flexibility, high process speed, energy efficient components and concepts, digitalization based on integrated sensors and therefore high IIOT readiness. The range of applications can be extended even further by combining several gripping principles [2, 3].

Vacuum gripping systems are made up of suitable support structures and vacuum components from six main groups: 1. vacuum generators, 2. connectors, distributors and filters, 3. fastening elements, 4. suction cups or suction modules, 5. valve technology, 6. sensors and switches for system monitoring [1, 2]. The product development process for vacuum gripping systems begins with a force calculation that takes into account the object properties and the handling process [1, 5]. The attainable suction force, which must be greater than the theoretical holding force with a safety factor, depends on the actual vacuum achieved. This in turn depends on the vacuum generator used and the properties of the object, which can lead to leakage. The leakage can be caused by the object-suction pairing, the air permeability of the object or by system defects. The calculation of the required holding force and the achievable vacuum results in the required suction area, which in turn is used to determine the number and type of suction cups or suction modules, taking into account the object geometry and properties. Vacuum generators and the valve technology interacting with them must be matched to the required cycle time.

The calculation of forces and the design of vacuum components when using suction cups is based on a proven scheme [1]. It contains degrees of freedom due to the large solution portfolio, which are designed in consultation with the customers or with knowledge of their wishes and objectives by the employees in sales and engineering for customer-optimised solutions. This is where the respective experience of the people involved comes into play. Such objectives or design priorities may be a fast process, high energy efficiency, little noise, cost effectiveness or short delivery time. The design process by experienced and competent personnel can therefore lead to different solutions due to the existing degrees of freedom. In view of demographic change and the shortage of skilled labour, it will become more difficult in future to provide customer-optimised solutions in this way. The product development process is therefore characterised by an iterative design calculation and a subsequent engineering phase in which the remaining degrees of freedom of the solution are designed depending on the personnel involved.

The energy efficiency and therefore the sustainability of vacuum gripping systems is significantly influenced by three system features and characteristics:

- operating energy: pneumatic or electric,
- fluidic concept of the vacuum supply: centralised or decentralised,
- type of object release: blow-off or ventilation.

Modular product kits can shorten the development time through the use of digital configurators, according to the motto "configuring instead of designing", and contribute to the circular economy and thus to sustainability through good feasibility of so-called R-strategies [6]. In addition to defined vacuum components, modular kits for vacuum gripping systems include in particular the elements for building the mechanical support structure. Due to the large number of applications for vacuum handling technology, it is advantageous to define gripper kits on an application-specific basis. Examples of product kits for gripping systems are the SLG lightweight gripper with a 3D-printed support structure, the PXT and the SXT gripper construction kits with a support structure made of tubular elements, the VacuMaster and SSP-HD construction kits for higher object weights, and the SPZ-M-C layer gripper with a combination of several gripping principles [1, 2]. Some digital configurators are already available online, planned or in use within the company as a preliminary stage of configurators.

Pure product configurators are characterised by the fact that the customers subsequently selects the design features of the solution, guided by the software and with knowledge of their application, and thus reach the definition of the overall solution. With pure application configurators, the system solution is automatically generated without user input based on the requirements from the application.

Currently available configurators for vacuum gripping systems can be mixed forms, e.g. if the geometry is uploaded as a data file in a product configurator or can at least be defined by manual input, such as in the configurator for the SLG gripping system.

3. DIGITAL ENGINEERING PLATFORM FOR VACUUM GRIPPING SYSTEMS

The visionary concept of a digital engineering platform for vacuum gripping systems as an application configurator shows **Figure 1**. The input variables are requirements that can be more or less structured. Possible mechanical configurations and fluidic solutions are generated and evaluated based on these requirements. The result should be directly usable files, e.g. the CAD data, the parts list of the gripping system, the dynamic behavior model, possibly as part of a digital twin, the offer to the customer or, for example, a production order. Standardized exchange formats for behavior models and digital twins are for example the Functional Mock-up Interface FMI and the Asset Administration Shell Format AASX, i.e. as digital components Functional Mock-up Units FMU and Asset Administration Shells AAS [7, 8] respectively.

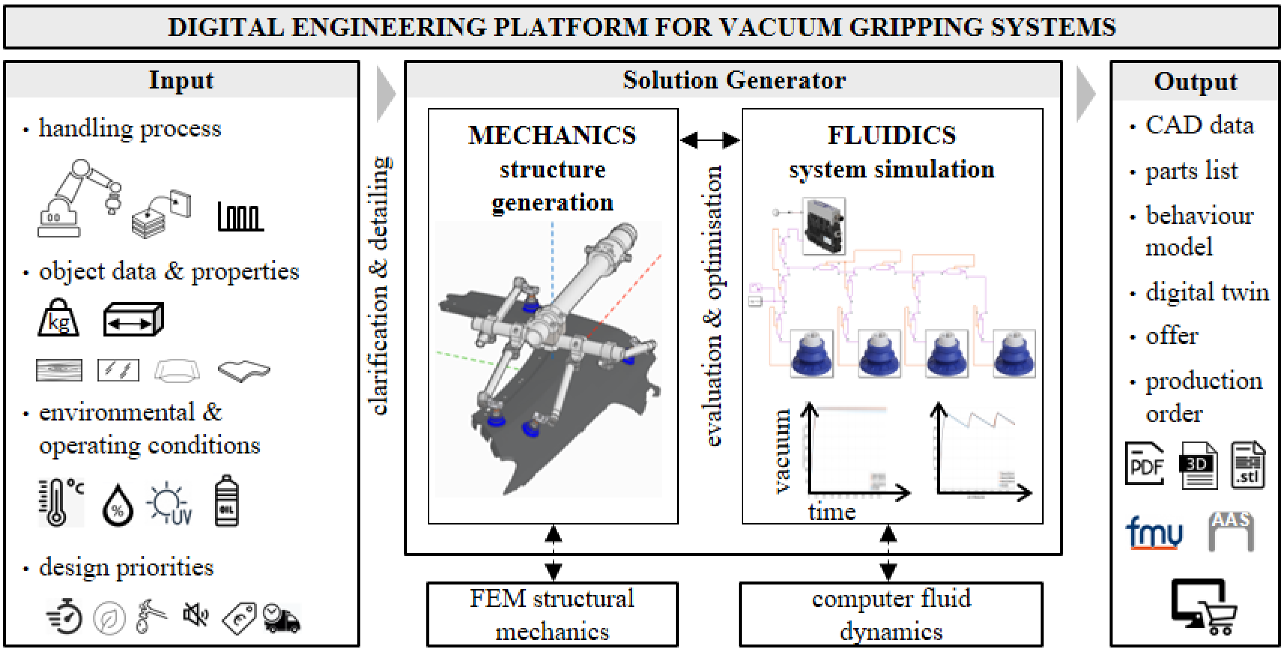


Figure 1: Visionary concept of a Digital Engineering Platform for vacuum gripping systems

Scientific results show that digital behavior models for vacuum generators and suction cups can be created and that they provide sufficiently accurate results in system models [9, 10, 11]. The modelling depth can be taken into account for balancing accuracy and computing time [12]. For the efficient creation of system models, so-called graphs can be used [13], which serve as a transfer interface between the mechanical and fluid subsystems, e.g. for hose lengths. An FEM calculation of the structural mechanics or a flow simulation can be coupled to evaluate the mechanical and fluidic partial solutions. For example, it is known that FEM analyses can be used to determine optimum gripping points on thin objects that are prone to deflection [14].

Such a digital engineering platform was implemented as a prototype on a workstation for the SXT gripper construction kit and initial tests were carried out for shaped air-tight objects of sheet metal which are typical for the automotive industry [15]. For the orchestration of the platform and the generation of the mechanical structure from modular elements the software Synera is used [16]. A system simulation realised with Matlab Simulink and the Simscape fluid library is used to calculate the the fluid system [17]. The implemented process of generating the mechanical support structure is shown in **Figure 2**.

Based on the geometry data, a surface analysis is carried out to select suitable areas on the sheet metal for the placement of suction cups. At the same time, suitable sets of suction cups are generated based on the dimensions and other geometric features of the gripping object as well as the required total suction surface determined in the force calculation. A suction cup set contains a number of suction cups, possibly of different dimensions and types, which fulfil the requirements. Gripping points are then defined within the selected areas. Based on this, the skeleton of the mechanical support structure is then generated, taking into account the bar elements available in the respective modular system, and the 3D CAD model is created. This is followed by the generation of the fluid distributors and hoses. The result is the complete CAD model, which consists of valid components from the modular gripper system.

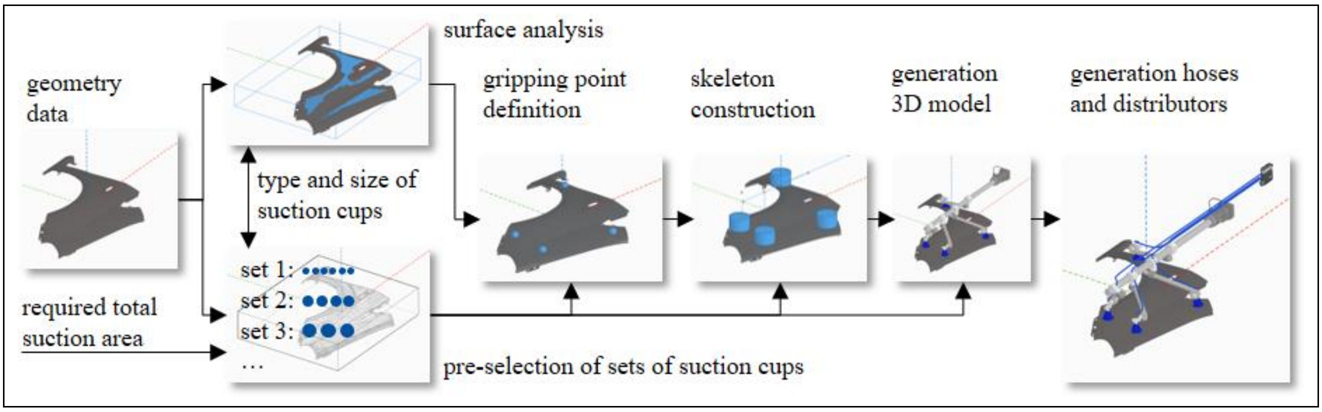
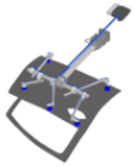
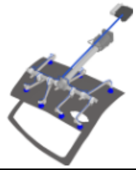
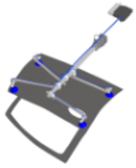
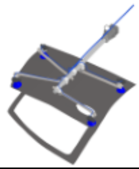


Figure 2: Procedure to generate the mechanical structure of the SXT gripper construction kit

Table 1 shows four different gripper solutions and the calculation results for the "side door" gripping object. Three different sets of suction cups are supplied centrally with a controllable SCPSi15 compact ejector and the third set of suction cups with four controllable decentralised ejectors SEAC10RP. The calculation times were less than one minute for the variants with a central ejector and slightly over 10 minutes for the variant with four decentralised ejectors. The operating pressure was set to 5 bar,rel. The blow-off time was determined by calculating the release time using the system simulation plus a safety reserve of 20 %. The internal volumes of the hoses were taken into account in the simulation. The hoses to the suction cups have an inner diameter of 6 mm and lengths in the range of 700-780 mm. They are combined to a hose with an inner diameter of 9 mm and a length of 1120 mm, neglecting a distributor.

The variants with the different number of suction cups show that the price increases with the number of suction cups. This is due to the fact that the number of mechanical components required also increases. As expected, the evacuation and release time is shortest for the system with the decentralised ejectors. However, the system costs are then the highest because four ejectors used. The energy consumption for evacuation in this system is within the range of the other variants, whereas the energy consumption for blow-off is significantly higher here, although blow-off takes place directly at the suction point. This is due to the fact that the simulation takes into account the hoses that have to be filled with pressurized air. If decentralised ejectors with a venting function were used, the energy for blow-off would be omitted and the total energy required would then be the lowest in this comparison. In this case, 44.4 % of the energy could be saved by venting instead of blow-off. The displayed variants can be presented to the user for selection or subjected to an automatic selection process.

Table 1: Comparison of different gripping systems based on mechanical and fluidic characteristics

alternative vacuum gripping system				
computing time	42 s	56 s	35 s	10 min 15 s
suction cup set	5x SAXB 60	7x SAXB 60	4x SAXB 80	4x SAXB 80
dimensions [mm]	1159 x 841 x 273	1147 x 864 x 273	1077 x 972 x 213	1095 x 991 x 213
price mechanical system	100.0 %	117.1 %	71.5 %	71.9 %
ejector and fluid concept vacuum supply	1x SCPSi 15 central	1x SCPSi 15 central	1x SCPSi 15 central	4x SEAC 10 RP decentralised
vacuum	650-750 mbar	650-750 mbar	650-750 mbar	650-750 mbar
threshold “part presence”	600 mbar	600 mbar	600 mbar	600 mbar
suction force (safety factor)	918.6 N (1.0)	1285.8 N (1.5)	1307.4 N (1.5)	1307.4 N (1.5)
evacuation time to 600 mbar	358 ms	473 ms	433 ms	158 ms
evacuation time to 750 mbar	640 ms	828 ms	639 ms	199 ms
blow-off time / release time	185 ms /154 ms	244 ms / 203 ms	197 ms / 164 ms	42 ms / 35 ms
energy consumption per cycle for evacuation to 750 mbar	645.3 J	835.4 J	644.3 J	771.2 J
energy consumption per cycle for blow-off	153.0 J	202.3 J	163.0 J	615.0 J
price fluidic system	100.0 %	108.6%	96.6%	197.7%
energy consumption per cycle: evacuation + blow-off	798.3 J	1037.7 J	807.3 J	1386.2 J
gripper weight	14.97 kg	16.68 kg	7.28 kg	8.14 kg
price mech. + fluidic system	100.0 %	115.4 %	76.5 %	96.8 %

4. NEW ENERGY-EFFICIENT VACUUM GENERATORS AND FLUID CONCEPTS

Industry accounts for around 44 % of electricity consumption in Germany, of which 7 % is used to generate compressed air [18]. It is estimated that around 20 % of the compressed air produced is used for pneumatic drives [18] and around 5-20 % for pneumatic vacuum generation with ejectors [19]. Compressed air is often referred to as the "most expensive form of industrial energy" for several reasons. Up to 30 % of the compressed air produced is lost through leakage [18]. Due to conversion and distribution losses, only 15-18 % of the energy is available at the pneumatic component in compressed air applications [20, 21]. In a typical compressed air application, approx. 75 % alone is necessary for energy provision and distribution [22]. Although the losses in compressed air distribution are ideally less than 10 %, they can be up to 50 % in industrial practice [22]. Added to this is the pressure drop in the distribution system, which is often up to 0.5 bar [22]. The costs of compressed air have risen from 0.015-0.02 €/sm³ about a decade ago to 0.03-0.054 €/sm³ nowadays, depending on the electricity price used as a basis [18, 23]. Due to the disadvantages, the scenario of the "compressed air-free factory" was established [24]. Nevertheless, pneumatic components have important advantages: robustness, long-life operation, compact design due to high power density, comparatively low price and, particularly important in terms of energy savings, the ability to switch on and off very quickly and thus realise two-point control.

There are a number of approaches to increase energy efficiency in vacuum handling technology. For drive technology, it has been shown that up to 93 % of energy can be saved by electrifying pneumatic solutions [24]. In the evacuation process in vacuum handling technology, savings of 82-99 % are possible for typical applications with air-tight objects, depending on the internal volume and vacuum level, by using electrically controllable pumps [25]. Electric vacuum generators can also score points with a higher efficiency compared to ejector nozzles, which was stated in a study to be max. 18.2 % [26]. For the energy comparison of pneumatic and electric solutions, 0.12 kWh/sm³ can be assumed for well-designed large compressor stations with optimum compressed air distribution without leaks [18]. In the following, however, the distribution with leaks is taken into account using a higher conversion factor of 0.15 kWh/sm³, i.e. 9 W/(sl/min).

However, vacuum-based handling processes with pneumatic ejectors can also be designed to be energy-efficient. In particular, controlled compact ejectors with an air-saving function save up to 90 % energy compared to basic ejectors when handling air-tight objects. Multi-stage nozzles in compact ejectors reduce the evacuation time for air-tight objects and therefore also the air consumption. If operating points of ejector nozzles have to be adapted to specific conditions, the nozzle geometry can be optimised by means of flow simulation, for example at the transition from motive nozzle to receiver nozzle [4]. Using models to predict suction cup-object leakage and grip stability, compressed air savings of up to 30 % are estimated to be feasible [27]. Internal analyses and feedback from customers revealed that when using compact ejectors, an average of 50 % of the energy is used for blowing off. This percentage can therefore be saved by atmospheric ventilation. The principle of demand-based power provision realised with the air-saving function in compact ejectors cannot simply be transferred to electric pumps. For example, the rotary vane pumps often used have a very low permissible switch-on frequency of typically 10/hour and are therefore used uncontrolled in constant operation [28]. Until some time ago, no controllable electric vacuum generators were available below the typical sizes of rotary vane pumps [24].

Important approaches for increasing energy efficiency in vacuum handling technology are therefore: electric vacuum generators that can be controlled over the entire speed range, enabling the "passive vacuum" principle in automation, lightweight, fully electric ventilation valves with large nominal sizes and the use of system simulation for alternative fluid concepts in order to analyse their energy efficiency before they are actually installed. Accordingly, **Table 2** shows new energy-efficient controllable vacuum generators with venting function and **Table 3** venting valves for the use in vacuum handling technology.

Table 2: New energy-efficient controllable vacuum generators with ventilation function

				
product	GCPi50	ECBPi	ECBPMi	EcoGripper
dimensions	220 x 236 x 102 mm	Ø152 x 89 mm	Ø63 x 61 mm	Ø75 x 40 mm
energy type „primary“ vacuum	active	active	active	passive
weight	3220 g	775 g	230 g	282 g
max. vacuum	800 mbar	750 mbar	600 mbar	400 mbar
suction rate	46 sl/min	12 sl/min	1.6 sl/min	0.33 sl/min
rated electrical power	75 W	13 W	7,2 W	0,3 W
venting diameter	3.5 mm	2.5 mm	0.8 mm	0.8 mm

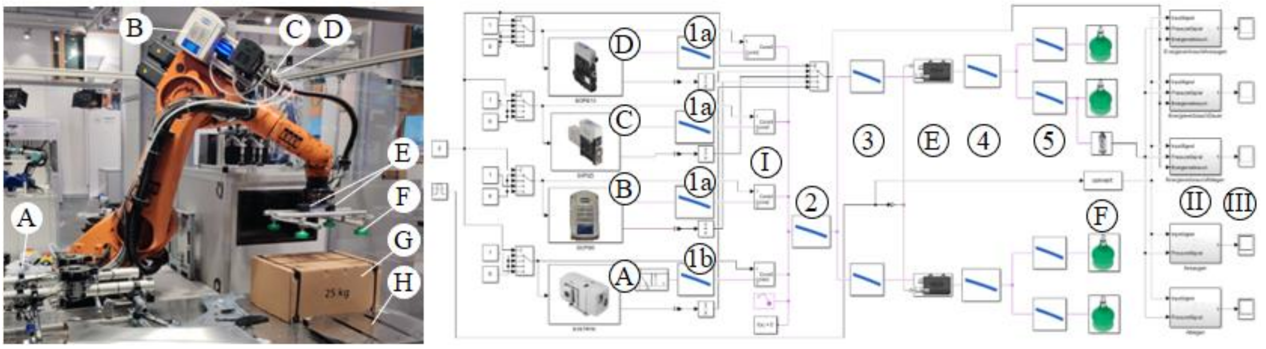
The new venting valve LQE is in the same range as the EMV10 and EMVO12 in terms of venting volume flow of 300-350 l/min. However, it stands out in this class due to its low weight and low power consumption. Of the electric valves shown, it has the best ratio of weight to venting capacity. The valve LQE and the Inline Valve IV are particularly suitable for electric gripper systems due to their low weight and the associated possibility of positioning them on the gripper as close as possible to the suction cups.

Table 3: Venting valves for use in vacuum handling technology

product	 EMV10 24V	 EMVO12 24V	 LQE	 Inline Valve IV	 SEV	 SEAC10 ECO
actuation energy	electrical	electrical	electrical	electrical	pneumatical	pneumatical
type	3/2 way valve	3/2 way valve	3/2 way valve	3/2 way valve	fast venting valve	ejector with venting
weight	2510 g	1200 g	399 g	70 g	24 g	95 g
rated electrical power	32 W	18.3 W	3.2 W	4.5 W	-	-
valve nominal diameter	Ø 10 mm	Ø 12 mm	Ø 8 mm	Ø 3 mm	Ø 4.6 mm	Ø 6 mm
venting rate	333 sl/min	350 sl/min	300 sl/min	21 sl/min	82 sl/min	39 sl/min
ratio weight/venting	7.5 g/(sl/min)	3.4 g/(sl/min)	1.3 g/(sl/min)	3.3 g/(sl/min)	0.3 g/(sl/min)	2.4 g/(sl/min)

To investigate different concepts for vacuum supply in various application scenarios, a robot cell and a digital behavior model for system simulation with defined parameters were set up, shown in **Figure 3**. The results of the system simulation for the evacuation and release process in a handling cycle in terms of energy consumption, evacuation and release time for the air-tight sheet metal without or with two LQE valves installed close to the gripper are shown in **Figure 4** and are in line with expectations. It is confirmed that around half of the energy consumption can be saved if object release is realised by venting instead of blowing off. As expected, the electrically controllable vacuum generator GCPi50 with venting function has the lowest energy consumption. This can be reduced even further by using the LQE valves close to the suction cups. The constantly operated electric rotary vane pump requires the most energy. It can be seen that the controlled pneumatic compact ejectors are significantly more energy-efficient in this case of handling air-tight parts.

The energy consumption of the variant with a rotary vane pump is slightly higher in conjunction with the two LQEs and the aim of achieving the shortest possible evacuation time by pre-tensioning the vacuum system, because the pump has to work longer against a higher vacuum. This shows that the simulation model works correctly with the stored characteristic curve of the pump. In the "sealed object and no leakage" scenario, the vacuum generators that can be switched off do not absorb any energy on the return stroke in a cycle. In contrast, the constantly running rotary vane pump also absorbs energy on the return stroke in a cycle, at least in idle mode or against vacuum, depending on whether the return stroke takes place with the venting valve open or closed. The evacuation time is shortest with the SXMPi25 compact ejector. Overall, the evacuation time was reduced for all four concepts when using the LQE valves. The deposition time is longer for the electrical concepts with integrated ventilation function than for the ejectors with blow-off function. Here too, the LQEs installed on the gripper can bring about a significant reduction.



Vacuum components and test objects: (A) EVE-TR10 + EMV10 24V, (B) GCPi50, (C) SXMPi25, (D) SCPSi10, (E) 2x LQE, (F) 4x suction cups SPB1 80, (G) air-permeable cardboard box, (H) air-tight sheet metal. **Hoses:** (1a) VSL12-9/L500, (1b) VSL12-9/L4000, (2) VSL12-9/L1100, (3) 2x VSL8-6/L180, (4) 2x VSL8-6/L200, (5) 4x VSL8-6/L250. **Vacuum generators**: air consumption suction SCPSi10 46 sl/min, SXMPi25 290 sl/min; conversion factor 9 W/(sl/min); electrical power consumption: GCPi50 0-74.4 W depending on speed; EVE-TR10 370-430 W depending on vacuum; max. suction capacity SCPSi10 36 sl/min, SXMPi25 185 sl/min, GCPi50 50 sl/min, EVE-TR10 167 sl/min; max. vacuum SCPSi10 850 mbar, SXMPi25 850 mbar, GCPi50 800 mbar:, EVE-TR10 850 mbar; blow-off flow rate SCPSi10 120 sl/min, SXMPi25 320 sl/min; operating mode: SCPSi10 / SXMPi25 air saving function two-point control, GCPi50 speed-controlled, EVE-TR10 uncontrolled. **Building blocks for simulation control:** (I) selection valves for vacuum generators (II) calculations (III) outputs. **Boundary conditions:** pressure sensor in each vacuum generator; connectors and push-in fittings neglected; suction cups pressed down before evacuation by 8 mm; switching threshold vacuum part presence 400 mbar, air saving function two-point control vacuum 450-550 mbar; release criteria: rest vacuum ≤ 10 mbar and max. release time 0.5 s; cycle: vacuum active 2s, no return stroke.

Figure 3: Robot cell and simulation model for analysing different fluid concepts

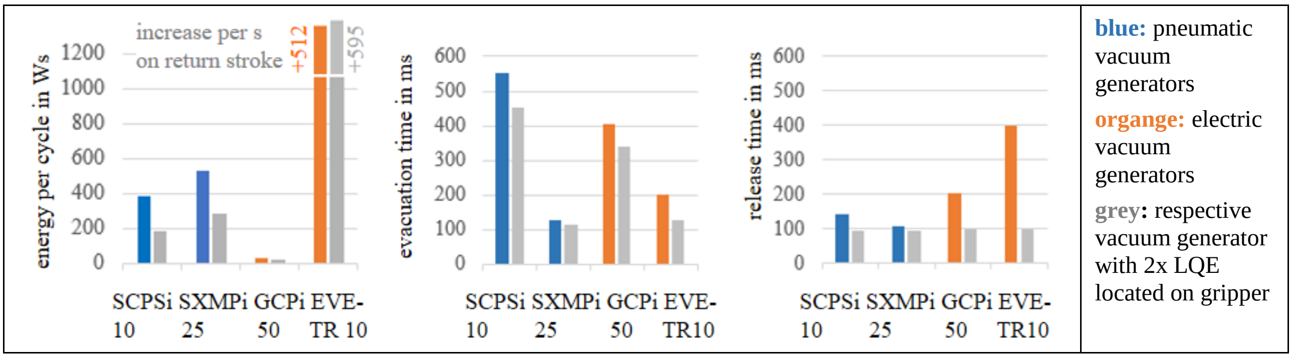


Figure 4: Results of the system simulation for the application scenario with air-tight sheet metal

5. NEW ENERGY-EFFICIENT CONCEPTS FOR SUCTION CUPS

Suction cups can contribute to the energy efficiency of vacuum gripping systems by having a low internal volume and good sealing to the gripped object. This enables shorter evacuation times and therefore shorter switch-on times for controllable vacuum generators and reduces leakage [29]. Both lead to lower energy consumption for the vacuum generators and enable concepts with passive vacuum without active vacuum generation.

Various concepts for passive vacuum with diaphragm suction cups are known, which have a diaphragm that is closed towards the object to be gripped. In addition to the effect of the weight of the object during lifting, the lifting of this diaphragm can also be achieved by actuators: mechanically by levers, fluidically by a vacuum [30], by an actuator made of shape memory alloy [31], by a preloaded spring [32] or by a magnetic coil. This lifting can be equipped with a "lifting reserve" to compensate for any leakage that occurs for a certain period of time. However, this does not ensure process safety, e.g. if a gripper has to wait for an event for an indefinite period of time while the object is gripped. Due to the requirement for process safety in automation, a passively generated vacuum without an active vacuum generator is therefore only suitable to a limited extent. For this reason, suction cups should be used for this purpose that enable suction to compensate for leaks. A scientific study has also shown that objects can be held for up to several hours with standard suction cups, depending on the level of the starting vacuum, the surface roughness and the weight of the gripped object and the Shore hardness of the suction cup material [33]. To reduce leakage between the suction cup and the gripping object, two basic approaches can be derived from scientific research [34]: Increasing the sealing surface, i.e. widening the sealing lip, and the use of soft sealing lip materials. The approaches for achieving process safety and leakage reduction were realised in the EcoGripper shown in **Table 2**. It has already been shown that soft sealing lips bonded to various standard suction cups can improve the sealing behavior on differently structured surfaces [29, 35].

In order to rule out the influence of different suction cup types and sealing lip widths on the sealing behavior, additional silicone sealing rings were applied to standard suction cups FSGA 53 SI-55 by casting and their Shore hardness was measured. For the test, the suction cups were lightly pressed as in an automated process, suction was applied with ejectors of different nozzle sizes and thus different air consumption in continuous suction mode and the vacuum value achieved was determined. The suction cups and samples used as well as the test results are shown in **Figure 5**.

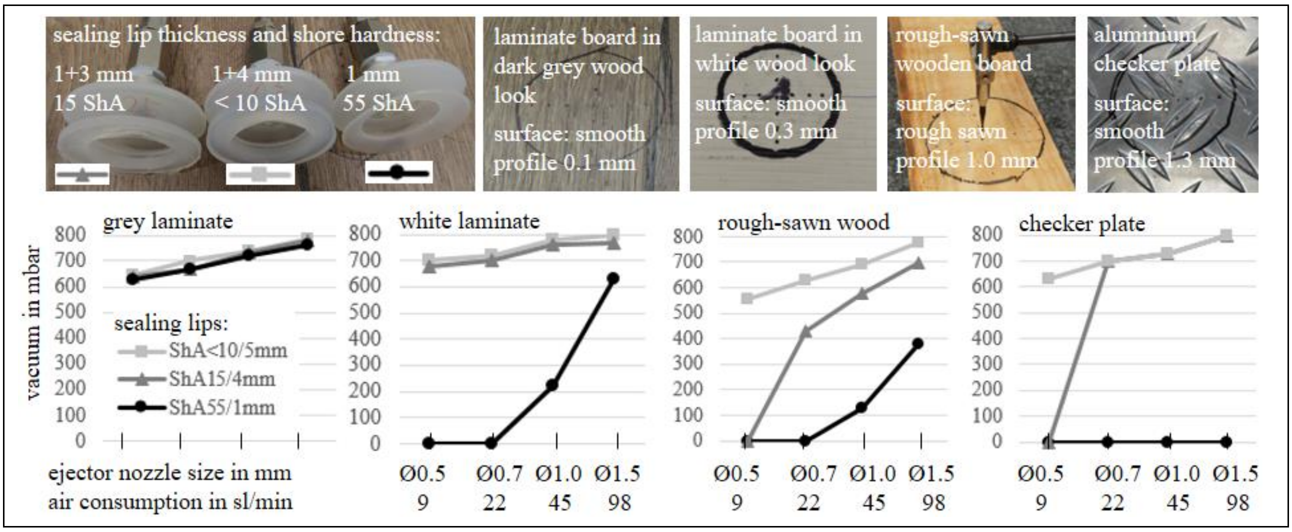


Figure 5: Results of the investigation of the sealing behavior of soft sealing lips

First of all, the known correlation is confirmed that with increasing nozzle size and the associated higher suction volume flow, leakage that occurs can be better compensated and therefore the available vacuum increases. Furthermore, the expectation that sealing lips seal better the softer they are is confirmed for all samples. The coarser the surface structure of the object to be gripped, the more soft materials contribute to the gripping success. The checker plate can only be gripped with the two softer materials. So compared to harder materials, softer sealing lip materials achieve a desired target vacuum level with a smaller ejector nozzle and therefore with less operating energy. This shows that soft sealing materials can contribute to the energy efficiency of vacuum gripping systems.

6. SUMMARY AND OUTLOOK

New contributions towards digitalization and sustainability for vacuum handling technology were presented. The visionary concept of a digital engineering platform for vacuum gripping systems was outlined in order to shorten development times and provide customer-optimised solutions. An initial implementation has shown that it is possible to automatically create the mechanical gripper structure from predefined mechanical structural elements using generative engineering in conjunction with fluidic system simulation. For the case of air-tight gripping objects, new components and concepts were described that increase energy efficiency and thus sustainability. It was shown that controllable vacuum generators, in particular electrical ones, as well as releasing by ventilation have great saving potential. System simulation can be used to analyse the energy efficiency of different fluid concepts in advance. Another contribution to sustainability is to reduce the surface leakage that occurs by using soft suction cup sealing lips.

With regard to the visionary concept of a digital engineering platform for vacuum gripping systems, further work must be carried out to determine how incomplete requirement data can be clarified and detailed automatically, e.g. by using rule-based methods or machine learning approaches. An extensive taxonomy for vacuum handling technology can form the basis for this. Time- and resource-efficient algorithms are required to generate optimised system concepts. For the system simulation of the fluid concepts, behavior models of all relevant vacuum components are required with sufficient accuracy to build up a complete library. Particularly in the case of hose interfaces and distributors, the modelling should not only take into account the geometric cross-sections, but also the fluidic inflow effects which were already investigated in the field of hydraulics [36]. The system simulation could be integrated into simulation environments that model the dynamics in order to take masses and torsional torques into account.

Energy efficiency in vacuum handling technology can be further increased. With regard to the contribution of vacuum generators and fluid concepts, the solution space of only three basic concept decisions - electrical versus pneumatic, centralised versus decentralised and blow-off versus ventilation - already leads to an optimisation problem that should be scientifically investigated with simulation for representative application scenarios, i.e. also objects with different air permeability. The utilisation of process-safe passive vacuum for automation should be further advanced. The sealing behavior of soft sealing lips of suction cups should be further investigated and economical processes for their manufacture developed. At the same time, the wear behavior must also be quantified in order to estimate the break-even points of reduced energy consumption during operation due to reduced leakage and earlier replacement of the component due to increased wear.

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