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Engineering Based Approach To Optimize Electrolyzer Production Plant Planning

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Abstract

Climate change and its consequences are forcing us to rethink energy production. Therefore, the German government strives to establish hydrogen as a new energy carrier. It will be produced from sustainable energy to replace fossil fuels. As a result, there is a growing need for electrolyzers and, thus, a need for fast production. Nowadays, electrolyzers are produced in a manufactory-like operation because of the high variance in size and technology used. A production plant can be built for a single type electrolyzer, but since the future of hydrogen technology is highly volatile, general solutions must be developed that help build an automated production for any electrolyzer cost-effective and efficient. Therefore, the research program FertiRob is creating universal methods to significantly accelerate the set-up, planning and commissioning of electrolyzer productions. The difficulty lies in the absence of established automation concepts for electrolyzer production, requiring the simultaneous conceptualization of production facilities alongside a diverse array of undefined electrolyzer products. Although there is a wide range of electrolyzers, components and processes are similar. These need to be identified to prepare production planning and automated assembly in the best possible way. This paper aims to illustrate how a detailed system analysis on a specific electrolyzer and market research on electrolyzers can identify such characteristics and translate them as an approach to increase an efficient plant engineering process and the degree of automation within the assembly.

Keywords

Production modules; scalable production plant; electrolyzers; design for automation; flexible production

1. Introduction

The escalating global climate crisis is exerting a growing influence on society, scientific endeavors, and the economy. The onset of 2022 witnessed the emergence of an energy crisis in Europe, prompting a comprehensive reevaluation across various societal and economic sectors [1]. In Germany there is mainly a resounding call for energy independence and a concerted push for expanding renewable energy sources in both political and social realms. Location-independent experiences can be gained at different levels and user-specific difficulty levels. The significant surge in the proportion of renewable energies integrated into the national power grid has led to an increasingly volatile energy landscape [2]. Expanding storage power plants can help stabilize fluctuations, especially given Germany's geographical conditions, where hydrogen emerges as a promising storage medium. With the projected surge in hydrogen demand, water electrolyzers become vital for hydrogen production. Germany is expected to see a hundredfold increase in electrolyzer demand by 2030, requiring mass production of hundreds of thousands of units annually. Current electrolyzers are manually crafted due to low volume demand, but automating production processes presents a challenge because they are designed for manual assembly. The FertiRob research initiative is working on

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the series production of electrolyzers. It aims to develop a mass production line for automated electrolyzer assembly to make green hydrogen competitive and meet future demands efficiently [3].

The existing challenge in the development of automation for scalable electrolyzer production is that the solutions must be developed to be as universal as possible to be used for as many types and technologies of electrolyzers as possible. When deciding which automation is best suited to a given assembly problem, there is still no complete knowledge of the final shape of the electrolyzer components to be assembled. Given the uncertainty surrounding the prevailing electrolysis technology [5], there is a pressing need for a versatile production concept that can adapt to emerging advancements in the field. Furthermore, manufacturers are careful not to disclose any information about their products to remain competitive. The momentum in investment is growing, as evidenced by the announcement of over 500 large-scale projects globally. In the foreseeable future, conventional industrial applications and transportation are anticipated to emerge as the principal drivers of demand for clean hydrogen. [4] Due to the expected investment sums and the associated economic opportunities on the market, it is understandable that companies keep their technical development status secret. However, this makes the targeted development of automation solutions a challenge.

This paper shows a methodical approach and challenges in the development of automation solutions for the series production of electrolyzers. Based on market research and a procured electrolyzer, reference components that occur in different scales in every electrolyzer system are identified. Regarding the automation solutions to be developed, the procured electrolyzer is analyzed and subjected to a design-for-automation process. Finally, the results are used to show how generally valid, scalable solutions can be derived using the example of a gripper which can be used as universally as possible through targeted design changes. In addition, this paper is intended to show that the assessment of automation feasibility with subsequent adjustments is a necessary step towards replacing manual assembly with automated solutions that require further development.

2. Necessity of a reference system and mandatory subsequent procedure

This chapter explains the basics of electrolyzer systems and their main components. It also presents the FertiRob research project and explains its status to help readers understand the problem this paper is addressing. In addition, input is given on the methodologies used to circumvent the challenges.

2.1 FertiRob configurator

The current predominantly manual production is time-consuming, cost-intensive, and prone to errors. To produce electrolyzers more cost-effectively and make the production of green hydrogen more economical, automation solutions must be found quickly. In the FertiRob project, production planning is modularized and digitalized for this purpose focuses on a modular production system that is efficient and flexible to use and can be easily scaled, which can be created in a configurator based on the electrolyzer to be produced [5].

The primary objective is to plants planning and the construction process, expediting market time. In the context of the FertiRob project, user stories were developed to envision a future plant configurator, considering three key stakeholders: the plant builder, the electrolyzer builder, and the end customer. The methodology progresses from defining stakeholders to presenting electrolyzer dimensions, outlining a flexible plant concept, and simplifying the automated configuration workflow. The plant builder is key in aligning the production plant with the future operator's needs. The operator, guided by customer specifications, determines electrolysis output, technology, and performance. Order quantity dictates plant cycle time, allowing flexibility for adjustments. The pre-configured production line accommodates various product dimensions and order quantities, meeting diverse customer needs. The operator defines desired parameters during configuration, simulating restrictions to ensure alignment with envisioned outcomes. [6] To provide automation solutions for this configuration process, these must be developed before information about the system developed by the electrolyzer manufacturer is available as mentioned.

2.2 Electrolyzers and procured reference system

Hydrogen generation within a water electrolyzer occurs through the electrochemical splitting of water molecules using electricity. The electrolysis stack is central to this process, where the electrolysis transpires. Although various electrolysis techniques exist (e.g., proton exchange membrane electrolysis (PEM), alkaline electrolysis (AEL), anion exchange membrane (AEM) and solid oxide electrolysis (SOEC)), the components typically exhibit a similar structure across these methods, with assembly techniques remaining largely consistent. [7]

Electrolyzers span various power classes and sizes, from small-scale units in the single-digit kW range for residential use to larger industrial units surpassing 100 kW. Presently, automated serial production concepts for electrolyzers are lacking, contrasting with the mass production of similar fuel cells, notably in the automotive sector, where rigid automation prevails. This research, endeavors to adopt more flexible manufacturing solutions inspired by existing fuel cell production methods and leveraging robotics. Despite the limited focus on automated electrolyzer production in current research, most still rely on manual processes. Hence, adapting proven approaches from fuel cell production is advisable due to the nascent stage of automated electrolyzer manufacturing. While various automated plant configuration methods exist, developing a comprehensive concept applicable to diverse electrolyzer designs remains ongoing. [6]

Based on the challenges described in chapter 1 and accompanied by the results of the market research, an electrolyzer was procured. The Erredue G2 Alkaline Electrolyzer has been manufactured for producing hydrogen through electrolysis with the nominal flow rate of 1,33 m^3 per hour and 0,66 m^3 oxygen simultaneously. The procurement status can be seen in Figure 1.

(a) (b) (c)

Figure 1: Procured electrolyzer

The system shown is 1330 mm deep, 840 mm wide and 1800 mm high. According to market research, these dimensions are very close to the average dimension of all electrolyzers on the market. In automated production, factors such as product size, component weights, and assembly processes are crucial considerations. Despite variations in electrolyzer types, assembly processes tend to be similar. Interestingly, the footprint of the product influences the production system design more significantly than component weights. The market study presents a diagram categorizing electrolyzers by size, which shows most electrolyzers on the market have a footprint ranging from 1 to 5 m^2. Consequently, the procured electrolyzer falls within this size range. [8]. This ensures that the solutions derived are as broadly applicable and universally valid as possible. This, in turn, means that as many electrolyzer manufacturers as possible can use the solutions developed in the research project, thereby accelerating the market ramp-up of cheaper systems to reach the required hydrogen output.

2.3 Detailed analysis and Design for Automation

A detailed analysis of the construction of the assembled system and the associated chemical process must be used here, as no digital image of the procured electrolyze is available. Step by step, all parts, connections and technical components of the system are analyzed, documented, and digitized in terms of size, weight and shape This type of system analysis is often referred to as reverse engineering. It represents a multidisciplinary approach with broad applicability across various industrial sectors. Its engineering is the systematic analysis of the components of an existing product to understand its structure and functionality. In addition, reverse engineering is of value in cases where technical products or technologies are malfunctioning, and deconstructive analysis is required to identify flaws or defects in their design or operation. The term "reverse" signifies the bi-directional exchange of data between digital and physical realms. [9]. However, to optimize the design and then simulative tests for assembly, a Computer-Aided Design (CAD) model is essential. Once a digital image of the electrolyzer is available, it can be improved in terms of automation-friendly assembly. Therefore, a design-for-automation process is used. This method emphasizes the design of products and systems that are inherently compatible with automation technologies, aiming to enhance efficiency and reduce costs. [10]

3. Workflow

This chapter shows how the procured electrolyzer is processed based on the market research results. A detailed analysis of the construction of the assembled system is used to generate a digital image to carry out a methodical Design for Automation process. The aim of this is to be able to develop suitable automation solutions for electrolyzer assembly. This should enable individual production modules to be developed within the FertiRob concept.

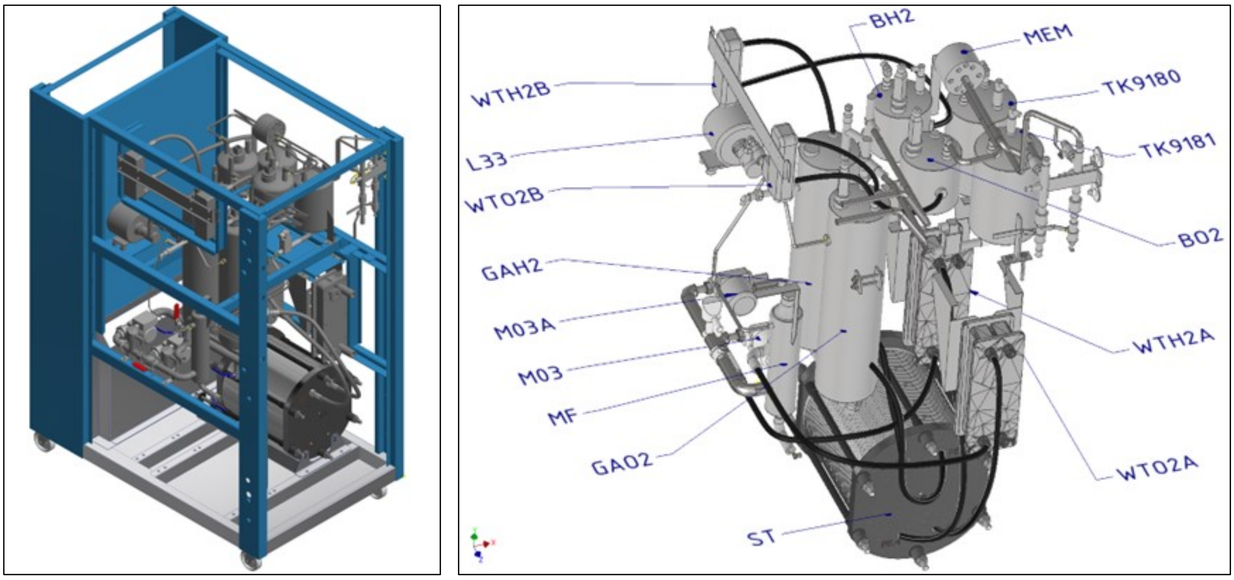
3.1 Result and derivation of improvement potential

The entire system was analyzed and counted component by component. For this purpose, all mechanical connections of assemblies and hoses or pipes were listed. The result is a complete list of parts of the system. By analyzing the system, individual assemblies can be identified, each performing separate process engineering tasks within the electrolysis process. In addition to the electrolysis stack, there are assemblies such as gas separators, in which the hydrogen produced from the process fluid and the oxygen produced on the other side are removed. Some pumps provide the system pressure, heat exchangers for heat regulation, a magnetic filter system and container tanks for the hydrogen produced. Therefore, it makes sense to divide the assemblies according to the tasks in the process. The resulting division can be seen in Table 1.

Table 1: Results of the assembly classification

No.	Technical component	Kind of part	Labeling	Part description
1	Stack	AEL electrolysis stack	ST	Chemical arrangement for electrolysis
2	Magnetic filter	Tank	MF	Filters impurities from the electrolysis process
3	Heat exchangers	Technical unit	WTH2A/ WTO2A	Cooling tanks
4	Condenser tanks	Tank	TK9181/9180	Condensing fluid gases
5	Storage tanks	Tank	BH2/O2	Storing the gases
6	Gas separator	Tank	GAO2/H2	Separating gaseous and fluid mixture
7	Pressure equalization diaphragm	Technical unit	MEM	Pressure equalization in the process
8	Second heat exchangers	Technical unit	WTH2A/WTH2B	Cooling condensed gases
9	Pump	Technical unit	L33	Pumps fresh water into the process
10	Water storage tanks	Tanks	MO3/MO3A	Storing fresh water
11	Frame	Mechanical structure	GS	Fastening of all components
12	Switch cabinet	Additional purchase part	SS	Control of the process

As this work is concerned with deriving automation solutions in the assembly of electrolyzers, only the main assemblies are considered in the first step. The tubing and piping are omitted. Since, as can be seen in Figure 1, the pipes and hoses of the reference electrolyzer do not run in straight lines, thus the automation of their assembly can only be implemented with great effort. For this reason, FertiRob decided to develop automation solutions only for assemblies and to consider the tubing and piping in a subsequent step. However, for completeness, both hoses and pipes were included in CAD model. The complete digital image of the electrolyzer can be seen in Figure 2. All dimensions and technical components have been precisely reproduced. To give a better impression, all assemblies have also been shown once without the surrounding frame with their short designations.



(a) (b)

Figure 2: CAD model of the procured system

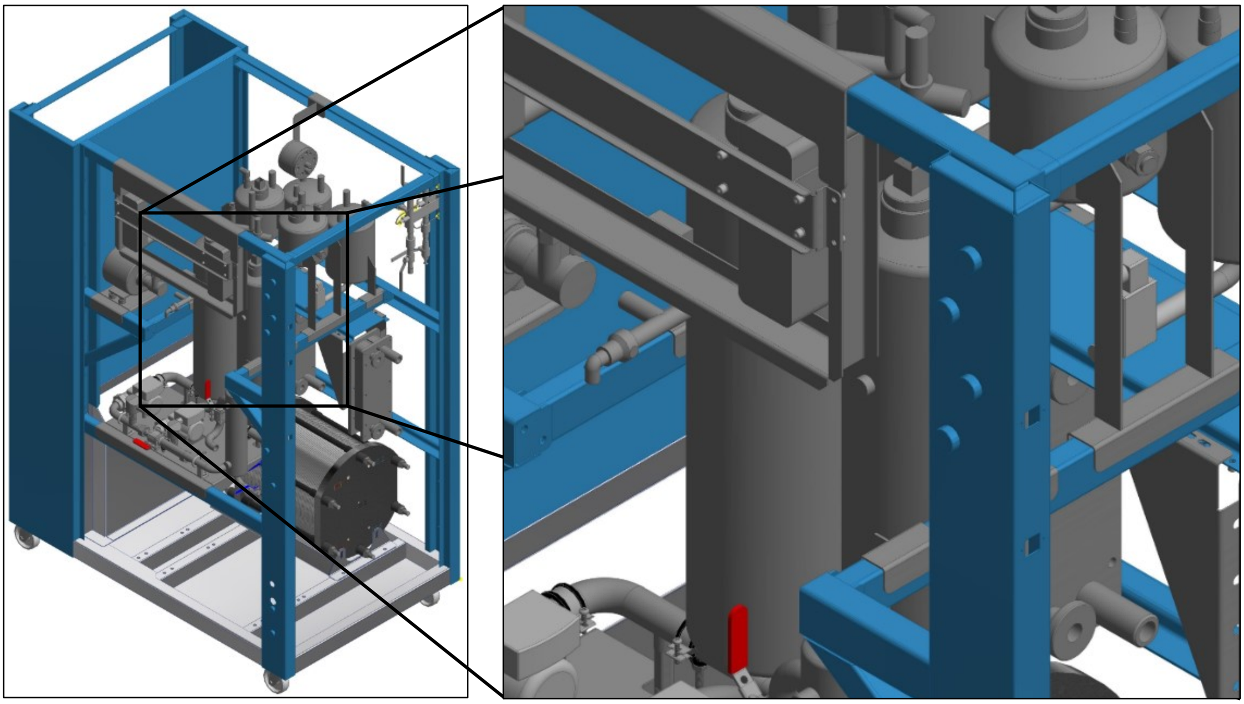
The Erredue G2 design was initially intended for manual assembly. This approach complicates the transition to automated manufacturing. Several factors hinder the direct conversion of the assembly process from manual to automated, necessitating adjustments for seamless integration. The frame's design presents challenges for effectively joining its components as there are too many interfering contours for a robot to reach in. Due to this design, assembly necessitates multiple approaches as not all parts can be accessed or joined from a single direction. Even if such access were feasible, inserting or joining them into their final positions from the same direction would be impractical regarding accessibility and assembly time. Additionally, the deficient design of the base object is evident in the absence of guiding elements to aid in the insertion process. Furthermore, the areas where components meet the base object lack chamfers or fillets to mitigate errors caused by slight deviations in assembly tools during insertion. The electrolyzer features a notable surplus of connection elements, surpassing the essential requirements for securing components. This overabundance suggests a design flaw, contravening DFA principles. Furthermore, specific peripheral components are welded together, indicating a reliance on manual assembly processes in the current design. To derive solutions for automated assembly, the electrolyzer must be subjected to a Design for Automation process.

3.2 Design for Automated Assembly of the reference electrolyzer

Numerous methodologies exist for assessing mountability, each tailored to specific considerations pertinent to the electrolyzer [11]. To ascertain the most suitable approach, it is imperative to identify criteria that accurately reflect the disparities between the original and redesigned designs, thereby effectively gauging process efficiency. In this work, the redesign is based on Eskilander's DFA2 method to be able to mount the assemblies automatically in the frame [12]. The DFA2 method is used here because it is based on all established methods and can be applied in all engineering phases. It enables the evaluation and comparison of assembly efficiency between manual and automated assembly methods, providing insights into the most effective approach for a given scenario. This method is comprehensively described in [12]. Due to the complexity of the method, the focus here is on three main aspects of design optimization. A complete redesign will be considered in a later article, and the evaluation of automation capability with the benefits of accelerated production will also be considered. The focus of optimization in this article is on component standardization, the accessibility of assemblies, and the reduction of the number of parts.

Standardizing parts is a crucial aspect of DFA2, although the unique nature of components in the Erredue G2 electrolyzer limits reshaping possibilities. However, auxiliary elements like screws and connection elements can be standardized, potentially leading to a reduction in their numbers. For instance, components such as Heat Exchanger B (WTO2B and WTH2B), despite being small and light, are secured by an excessive number of smaller screws (four), which could be standardized and reduced by DFA principles. Self-locating areas, such as chamfers or fillets, expedite assembly by providing insertion tolerances and correcting minor axial displacements. However, the electrolyzer lacks auxiliary features to facilitate insertion.

The primary challenges in the electrolyzer revolve around insertion processes, mainly due to limitations in automation capabilities. Addressing insertion issues requires significant alterations, particularly in the frame (GS) component, as it is the primary connection point for most components. Thus, enhancing the design of frame to facilitate logical and accessible connection points, along with self-locating areas, becomes paramount for streamlining assembly processes and enabling automation. In the process, various parts require stabilization during assembly. Typically, this involves one worker holding the parts while another joins them, adding time and reducing efficiency. Components such as heat exchangers A and B, magnetic filters, membranes, auxiliary pumps, and primary condensate tanks necessitate stabilization during assembly. Fastening in the electrolyzer primarily relies on bolts and nuts of varying dimensions. As discussed, the assembly process can be expedited by adapting the connection elements based on disassembly requirements. Riveting and snap-fit methods are unsuitable for the Erredue G2 alkaline electrolyzer due to the need for disassembly. For this reason, all connections to the frame are replaced by self-locating holding devices where possible. However, the original shape of the components has not been changed. This would have to be done in consultation with an electrolyzer manufacturer to ensure the chemical process is stable. By changing the connections to the frame, it is possible to have the robot place the assemblies in the frame. In addition, by adapting the frame, it is possible to insert all assemblies except for ST and WTA into the frame from one side and not previously from above and several sides. All components can now be fitted into the frame from two sides. These changes are intended to show electrolyzer manufacturers that many steps in electrolyzer assembly can be automated with minor adjustments and by eliminating interfering contours through simple modifications without changing the chemical process. In addition, each assembly can hold its position thanks to a form-fit connection with the frame without the need for a screw connection. These can then be adjusted manually. This leads to an improvement in ergonomics for employees, as robots can perform positioning tasks. It also speeds up the production process, as it frees up time for an employee to carry out processes that are difficult to automate, such as attaching hoses and cables or as named screwing. These activities can be prepared in parallel with the robot's work A uniform screw size was also used to further reduce part variance. These changes can be seen in Figure 3 compared to Figure 1 shown at the beginning.



(a) (b)

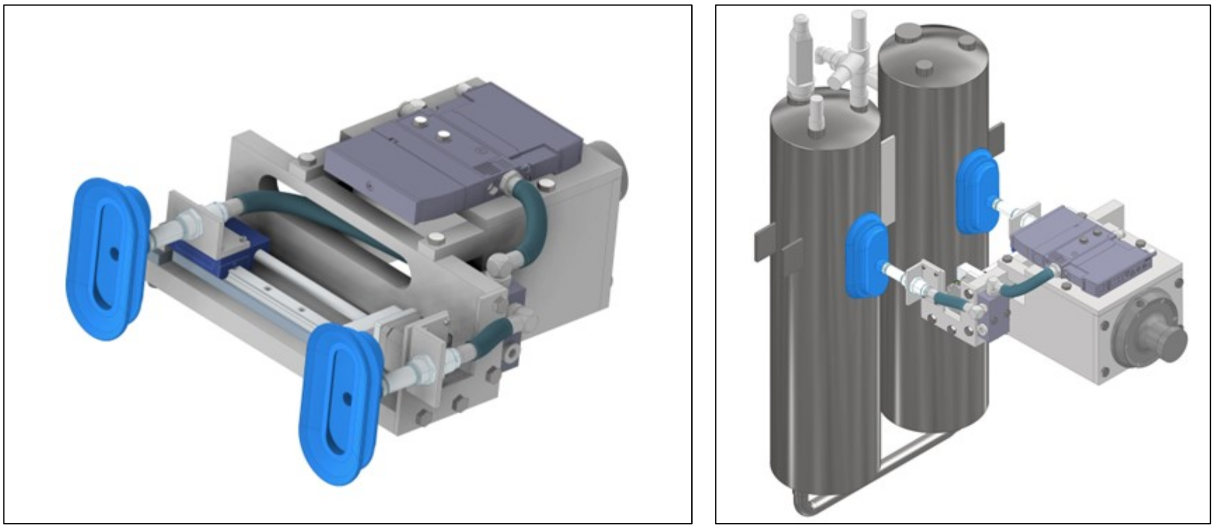
Figure 3: Elektrolyser after change in design for automated assembly

According to design for DFA principles in terms of assembly, minimizing the number of components in a system is crucial for reducing assembly time. However, in the case of the Erredue G2 alkaline electrolyzer, all components in the part list contribute directly to electrolysis. Therefore, eliminating these components to improve DFA is not feasible. Some parts of the electrolyzer are combined before assembly, reducing the overall part count. Additionally, reductions in the number of pipes, hoses, screws, or nuts can be achieved through shortening or omission. However, this would also require a redesign of the overall system. Since this paper shows how a reference electrolyzer can be used to derive automation solutions for a product design that has not yet been entirely determined, the conclusion suggests that this procedure should be generalized. It was shown how, automation solutions can be developed that are valid irrespective of the precise product shape by using a reference system. How can systems intended for manual assembly be automatically evaluated in terms of their automation-friendliness and how can changes be derived from this that can be directly transferred to production planning? A complete redesign will be considered in a subsequent paper and additional consideration will be given to the evaluation of automation capability with the benefits of an accelerated production planning process.

4. Development of a specific production modules for a test environment

The slight changes in the design of the electrolyzer led to increased automation of the assembly process as described. This shows how a reference system can be used through targeted a detailed analysis with subsequent DFA analysis to be able to develop the required automation solutions. It feeds the FertiRob configurator described with solutions that can be used as scalable applications in production planning. All the information required to integrate the application is stored in the modules to speed up planning.

Therefore, the following shows how a production module has already been developed from the existing changes and the analysis of the electrolyzer system. When looking at the components, it is noticeable that all tanks have smooth metallic surfaces. In addition, they are grouped as assemblies according to function in a double arrangement next to each other. The distances between the center axes of the tanks TK9180/81, BH2/O2 and GAO2/H2 range from 100 mm to 220 mm. The heat exchangers WTA also have two smooth surfaces with a distance between the centers in this range. By adding metallic devices to the MF and WTB components, a smooth surface can also be provided as a gripping surface for these two assemblies. A suitably designed vacuum double gripper, in which one of the two suction cups can be moved along a linear axis, is suitable for this purpose as seen in Figure 4. The design of such a gripper is scalable and can thus also be used for other sizes of electrolyzers.



(a) (b)

Figure 4: Developed suction gripper

Therefore, this gripper can be seen as a production module that is used in the configurator described above. By determining the electrolysis output, conclusions can be drawn about the required size of the electrolyzer. Based on this, the necessary design of the gripper can be selected. Of the ten assemblies to be fitted, six can be placed in the rack using this gripper and minor modifications as described. The remaining assemblies are small such as the pressure equalization diaphragm and can be handled with a simple gripper. The stack, however, also requires a specially developed gripper due to its size and weight. This allows the same principle to be followed. Depending on the electrolysis output of the system selected in the configurator, the production modules can be selected and scaled according to size. The robot required for the manual handling can also be derived from the weight and size of the components and the required grippers. The selected robot represents another predefined production module. This means that the entirety of the production modules becomes a production cell in line with the FertiRob idea, allowing production planning to be accelerated.

5. Conclusion and future work

This paper shows the difficulties described in developing of production planning processes for the automated series production of electrolyzers. This allows variable and scalable automation solutions to be developed and tested in the configurator. So that the modularized solutions can be used by companies to easily increase or decrease production capacity by adding or removing modules as needed and and replace individual modules in order to react to changes in the production process. The problem of the lack of product information from the manufacturers on the market was circumvented through market research and a reference system was procured on this basis. This was analyzed in terms of automation capability and the weaknesses of the current electrolyzer design were identified. The first steps were then taken to replace manual assembly activities with automated processes while simultaneously handling as many components as possible with the same system.

Future work will look at what a complete production cell for an electrolyzer of its size and design might look like. The further reduction of designs that hinder automation will be considered in more detail. The more efficient design of pipe and hose routing within the system will also be addressed as a particular topic, as these significantly impede the automation of assembly in the existing system.

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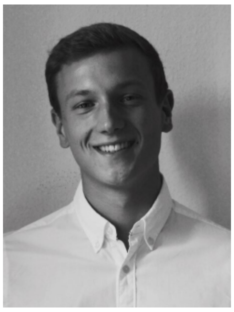
Biography



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