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Enhanced Planning Of Production Plants: A Case-Based Reasoning Driven Approach

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Abstract

Advanced industrial developments lead to increasingly customized products and shortened product life cycles. In the context of production systems, this necessitates faster engineering of suitable production resources and layouts to cope with the increasing product variety. Current engineering processes rely mainly on adapting already realized solutions and leveraging past experiences to address new project challenges. However, the knowledge about efficient planning processes is often tied to individual employees. These experiences cannot be utilized consistently, particularly in employee departure or absence due to illness. To counteract this problem, companies attempt to digitize and store knowledge in various ways. Nevertheless, the company-wide and person-independent retrieval of crucial information is still difficult or impossible. Influencing factors are, among others, non-standardized information models and forms of description. In response to these challenges, this paper introduces an approach for the standardized modeling and cross-company provision of experiences in production plant planning. Based on the paradigms of case-based reasoning and vendor-neutral data modeling using AutomationML, a system for selecting production resources and planning related layouts is demonstrated. By determining the similarity of new product structures, whose production facilities have yet to be engineered, with products whose production facilities are already realized, suitable existing solutions regarding production resources and their placement can be submitted explicitly to a planning expert. The approach is exemplified by a scenario of engineering an assembly system for electrolysis stacks. For this purpose, the similarity determination is performed using the Hamming similarity. Thus, it can be shown that case-based reasoning, which is already successfully used in other domains, has a significant potential to accelerate the subprocesses of production plant planning.

Keywords

Production plant planning; Case-based reasoning; Expert system; AutomationML; Knowledge management

1. Introduction

The manufacturing industry is influenced by significant changes related to current and future product structures and production systems. In particular, increasingly shorter product life cycles and the rising demand for individually customized products fundamentally influence engineering processes [1]. Consequently, this trend also affects the planning of suitable production plants. In the context of shorter development times, systems with increasing complexity – regarding the used resources, sensors, and software – must be newly designed or redesigned more frequently. Therefore, it is necessary to accelerate related engineering processes and support plant planners in crucial design decisions. The typical industrial approach of selecting appropriate production resources and defining their arrangement in an overall layout is primarily done in manual or semi-automated processes extending across departmental or company structures [2]. Previously developed or utilized production systems and related experiences are reused or adapted to meet new specific challenges. This can contribute to minimizing additional effort, risk, and in

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consequence costs. However, experiences and solutions from the past are often not accessible to everyone within the process chain. This is because relevant information is usually found in non-standardized directory structures and diverse data models. Further information is often not described or accessible in digital form, resulting in a massive loss of company-specific knowledge as an outcome of employee departure. As a result of the above depicted interrelationships, numerous approaches are researched to preserve knowledge or experiences throughout all company structures and make them available for specific use independently for individual stakeholders.

This paper demonstrates how the described issues in the field of production plant planning potentially be addressed by applying the paradigms of case-based reasoning (CBR) in combination with vendor-neutral standardized information modeling using AutomationML (AML). Based on this, planners can be provided with relevant experiences from past developments focusing on the processes of production resource selection and the planning of associated layout structures. This contribution is organized as follows. Section 2 gives an overview of already researched or existing approaches for efficiently planning production resources. Furthermore, the basic principles and related research concerning CBR are presented. Afterward, section 3 describes the application of a CBR cycle in the field of production plant planning. Using an example from the assembly of electrolysis stacks in combination with a developed tool for similarity determination of product structures, a possible application scenario of the shown approach is presented in section 4. Finally, section 5 draws conclusion and gives an outlook on future research.

2. State of the art

Various solutions have been developed to address the challenges in production plant planning. The following presents related research in production engineering focusing on selecting appropriate production resources and arranging them afterward. This will be extended by summarizing relevant works in the context of CBR.

2.1 Production plant planning

A variety of research work focuses on the effective selection of appropriate resources based on a matchmaking between production requirements and capabilities of production facilities. For example, in [3] and [4] requirements are extracted from product structures and the determined combination of requirements and production facilities is integrated into external planning tools or web services. In [5], a comparison between the mentioned elements is also done, but the implementation is pursued using an approach based on reinforcement learning. *Zimmermann et al.* present an advanced approach that includes not only a tool for selecting production facilities but also a concept for the optimized combination of individual resources into an overall system [6]. Furthermore, *Kathrein et al.* focus on the selection using organized resource catalogs and the description of product, process, and resource in a suitable data model [7]. In the context of additive manufacturing, [8] demonstrates a knowledge-based framework that focuses on securing expert knowledge to accelerate planning processes. Another group of research works focus on simulation-based planning of production layouts [9,10] or are using modern technologies such as augmented or virtual reality for planning tasks [11,12]. A template-based planning process for modular production facilities is shown in [13]. Furthermore, [14] depicts a methodology for automatically creating initial production layouts and [15] presents a web platform for the configuration of automated production systems based on engineering information described manufacturer-independent in AML. In the context of layout planning various approaches and algorithms are getting explored to solve arrangement challenges. In this field, heuristic methods and increasingly AI-supported systems are mainly used [16]. Nevertheless, these solutions do not have the goal of creating complex production plants with a variety of different production resources, but rather to determine an arrangement of production units in order to optimize a specific objective function, for example regarding to costs or transportation times between these units.

2.2 Case-based reasoning

CBR is an artificial intelligence paradigm based on the principle of similarity-based problem solving, where comparable problems require analogous solutions [17]. The fundamental methodological foundation of CBR can be explicitly described as “solving a problem by remembering a previous similar situation and by reusing information and knowledge of that situation” [18]. Rather than generating solutions through rule-based algorithmic manipulation, CBR retrieves relevant cases from a knowledge base and adapts them to the current problem context. The paradigm is based on the following two main principles: first, the premise that similar problems can effectively be resolved by comparable solutions, and second, the recognition that the types of problems encountered by an agent inherently tend to recur [17,19]. The primary research focuses on the efficient application of CBR in health science [20] and law [21], but also on different types of engineering activities. In the following, already investigated issues and research results concerning the application of CBR in engineering are summarized.

Various related works explore the potential applications of CBR for the detection, diagnosis, and resolution of faults or defects within the production. In [22], an approach for error diagnosis in the context of automated production systems and related logistics combining CBR with model-based reasoning, is presented. For the generation of the needed topological system model, AML, which is similar to the work of the present paper, is utilized. A comparable focus was set by *Khosravani et al.* [23], which use CBR to achieve error detection within the production of injection-molded drippers. Based on a similarity comparison between a newly appearing fault and past ones, suitable countermeasures are determined, contributing to reducing downtime in production. In [24], a system for the planning and efficient execution of maintenance work using CBR is presented. Further research work focuses on specific design challenges or planning of manufacturing processes. Thus, a system is presented that combines CBR with common product design methods, such as TRIZ, to support product developers [25]. Similarly in the context of product design, [26] depicts a CBR-based framework in the field of low-carbon product design that aims to address the conflict between product functionality and low-carbon issue. In the application area of process planning, approaches for manufacturing process selection [27] and assembly sequence planning [28] are presented, which apply an interaction of CBR with ontologies for knowledge representation.

It becomes clear that the application of CBR is getting explored in various industrial domains. However, a detailed examination of its usage in planning production resources and developing production layouts is currently missing. For this reason, the following section presents an approach to experience based production plant planning with a focus on the selection and arrangement of production resources by using CBR.

3. Case-based reasoning for plant planning

To explain the general application of CBR in the planning of production resources and necessary subsystems, a specific CBR cycle is derived from a generic cycle described by *Aamodt et al.* [18]. This provides the opportunity to initially explain and demonstrate the basic functionality of the approach before focusing on the individual process steps as well as associated tasks. Figure 1 illustrates the cycle specifically for production resource planning.

In general, the input of the depicted cycle consists of any description form of a problem. In this specific cycle, the problem description corresponds to a new product, represented in Figure 1 as an electrolysis stack for which suitable solutions, such as production resources for assembly, have to be determined and arranged in a layout. For this purpose, a set of permanently stored cases from the past is utilized. This set includes a combination of a problem and its solution. In the considered context, it consists of a product description and a set of production resources as well as layout information (see Figure 2). By applicating a suitable algorithm, the case that is most similar in terms of structure, characteristic properties and production requirements to the new given product is identified. Subsequently, this solution serves as an initial point for the engineering or decision support for the planning expert, who can implement necessary adjustments. Finally, the case base is supplemented with the newly developed combination of product and production system. The following subsections will demonstrate how the described subprocesses of the CBR cycle can be realized and continuously expand the case base.

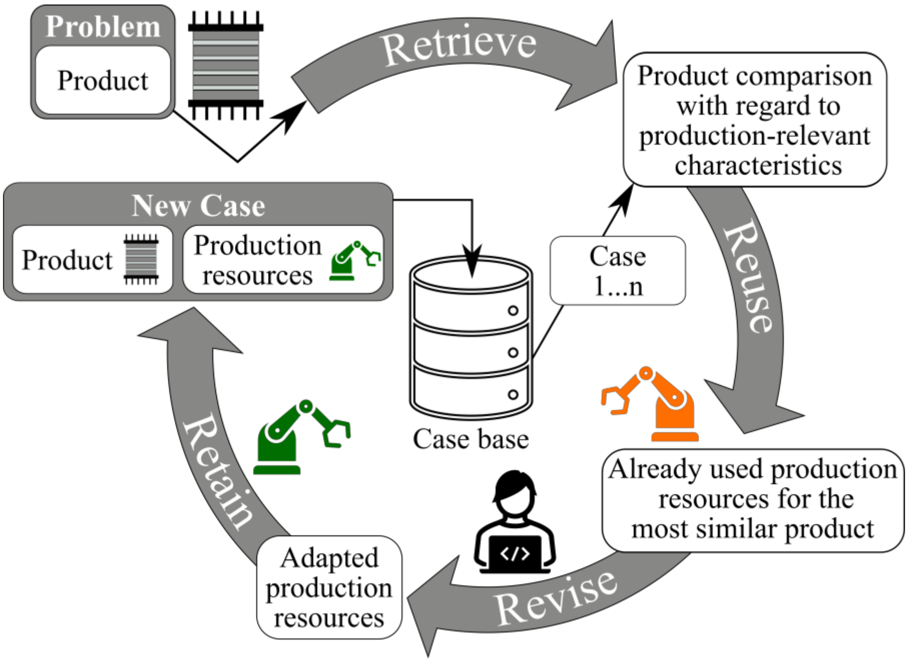


Figure 1: CBR-cycle for the planning of production resources

3.1 Case description

One crucial requirement for successfully applying the CBR approach described in the previous section is the targeted modeling and storage of information in a suitable standardized data model. This is necessary to facilitate a detailed comparison of different products. A suitable model allows to capture and provide experiences as well as expertise company-wide. Figure 2 illustrates the schematic structure of a set of information stored in the case base, consisting of product, associated production resources, and layout data.

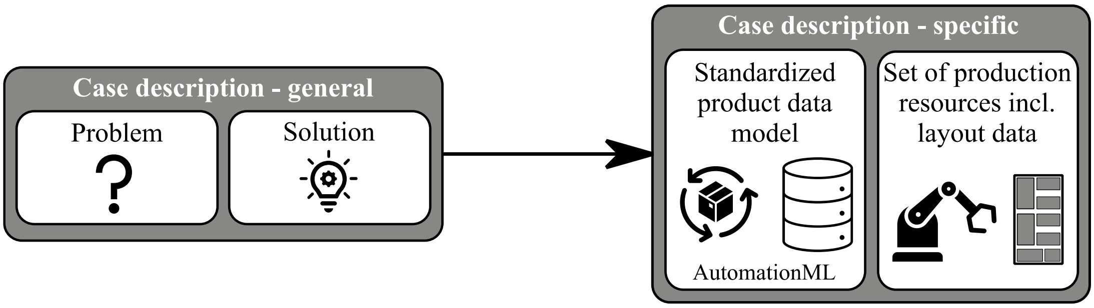


Figure 2: Case description as a combination of product and production resource information

The object-oriented modeling language AML, defined in IEC62424 [29], is used to model the product structures including related technical data. The main goal of AML is to enable a seamless data exchange across different engineering domains and tools. Thus, AML provides the opportunity to transform information into a unified machine-readable description independent of the industrial sector or data source. [30]

Figure 3 depicts how information about the product “ electrolysis stack” and how its connection to specific production resources as well as to the entire production system can be modeled. As shown, the parent product is divided into its subcomponents or individual parts. In this case into endplates, membrane electrode assemblies (MEA), bipolar plates and physical connectors or mechanical interfaces (e.g. screws or rivets). Furthermore, each product component – in a case description that already has a solution – is linked to one suitable assembly process. These resources contain assembly or manufacturing-specific sets of capabilities that meet the requirements of the processes, which also have a link to the appropriate production resources. Finally, the overarching production system, as a solution for a specific product, is composed of 1 to n production resources and a related layout description. The structures and information of the production system and resources can also be represented as AML data structures. Alternatively, based on the modeling capabilities of AML, external data in proprietary data formats can be referenced. If objects are prepared in a standardized data-technical manner according to the model described above, this offers the possibility of an efficient comparison of them. This can be done at the product level as well as the subcomponent and physical connector hierarchy levels to derive appropriate solutions for production resources based on similarities.

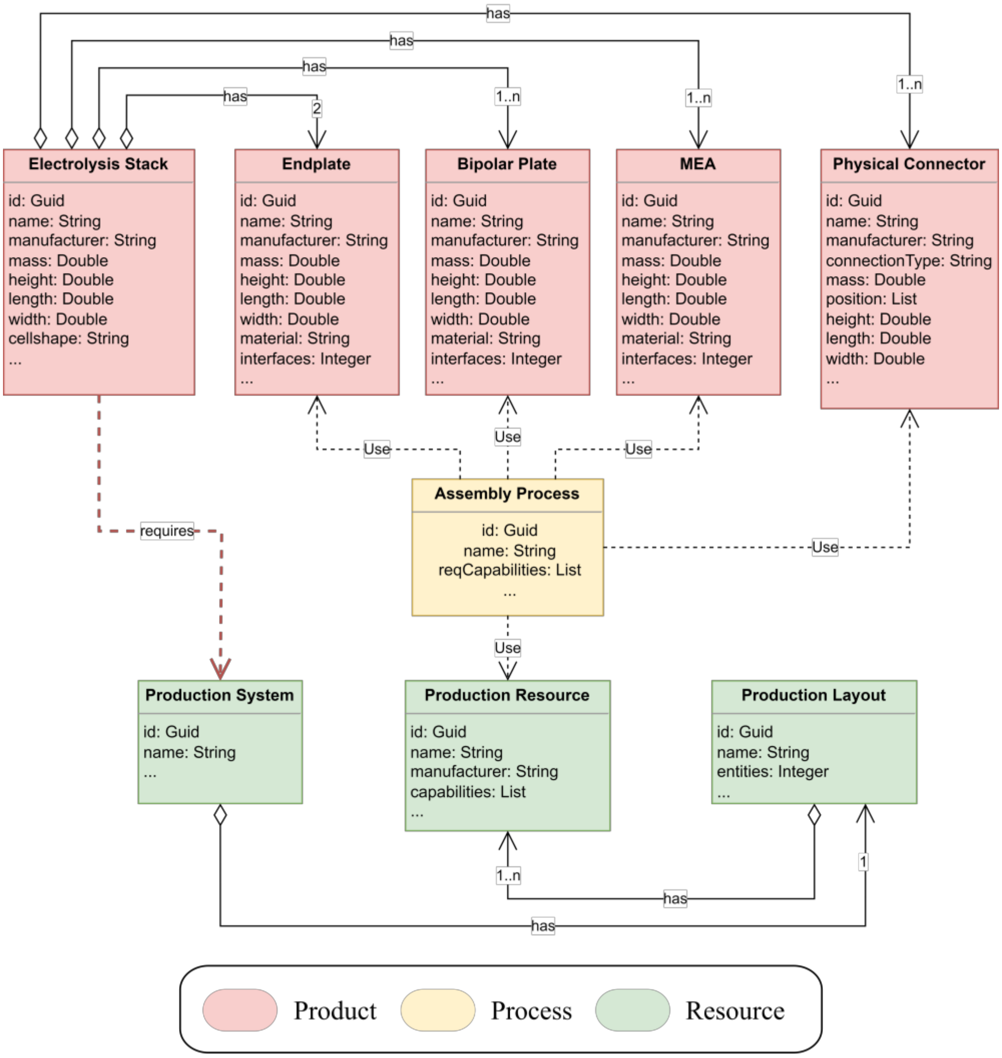


Figure 3: Data-model electrolysis stack - link between product and production resource

3.2 Determination of similarity

The aim of the similarity determination, which is necessary for the presented CBR cycle (see Figure 1), is to calculate a numerical measure that allows to assess whether multiple products are similar in terms of production-relevant factors. Two significant challenges emerge from this. These need to be addressed when implementing a suitable algorithm. First, it is necessary to define how individual technical parameters of a product, a subcomponent or a mechanical interface influence the selection of production resources and their arrangement. Second, an appropriate calculation procedure must be applied to determine a representative similarity measure.

A typical initial approach for calculating similarities in the context of CBR, intended to be applied in the following, is based on the inversion of the so-called Hamming distance (see Equation 1). Based on this, a generalized similarity measure (see Equation 2) can be established. It allows a comparison of variable values as well as the weighting of individual attributes. The weighting of the attributes and moreover the influence of single objects on the planning of the production plant can be done by the individual definition of α_i. As can be seen in the corresponding equation, the overall similarity between two objects is determined by summing the similarities of their attribute values.

$$distance_H(x, y) = \sum_{i=1}^{n} |x_i - y_i| \tag{1}$$

$$sim(x, y) = \frac{\sum_{i=1}^{n} \alpha_i \, sim_i(x_i, y_i)}{\sum_{i=1}^{n} \alpha_i} \tag{2}$$

As a result of the described relationships, the similarity of individual objects can be determined at different levels of the product hierarchy. This offers the advantage that different types of information can be presented to a planner depending on the comparison level, with varying levels of detail. For example, a comparison at the highest level of the product structure or in this case the stack level can be realized. As a result an initial overview of comparable production systems can be provided. This can supply insights into the required production resources and their quantities within the overall design. Furthermore, initial decision support regarding layout arrangement or estimation of required space can be generated. At lower levels of the product structure, which contain information about individual parts and connecting elements, solutions for different challenges can be identified. For example, by comparing the subcomponents and their attributes, a potentially suitable manipulator, such as an industrial robot with sufficient handling capacity, or an end effector for handling the respective component, can be determined. Additionally, through a similarity check of physical connectors and the corresponding interfaces of the components, a solution for selecting necessary assembly tools, for example bolting, welding, or riveting can be identified and presented. In the following, the example of an electrolysis stack is used to show the similarity determination of two products, considering the geometric dimensioning, weight and number of electrolysis cells. Table 1 lists the respective attributes and values of the products, which should be compared. In particular, it must be taken into account that the individual similarities $sim_i(x_i, y_i)$ of the single object attributes must be determined with individual calculation rules. In the presented example, the inverted distance between the attributes of two objects is normalized by the maximum distance within the complete case base concerning the specific attribute (see Table 1). This indicates that the two cases with the largest distance to the specifically considered attribute have a similarity value of 0. In the same way, two objects with identical attribute characteristics have a similarity of 1 concerning the attribute. By incorporating the similarities at the attribute level (refer to Table 1) into Equation 2, the computed similarity among the listed stacks (Stack 1, Stack 2) amounts to 0.8. The provided technical data is not specific to any particular product but serves only as an illustrative example. The similarity calculation between other objects on possibly other hierarchy levels can be realized analogously to the described procedure. However, the determination of the attribute-specific similarities must be individually adapted. This must be considered in particular in case of a comparison between not quantitative object characteristics, like the similarity determination of different connection technologies.

Table 1: Attributes for the exemplary similarity comparison of two electrolysis stacks.

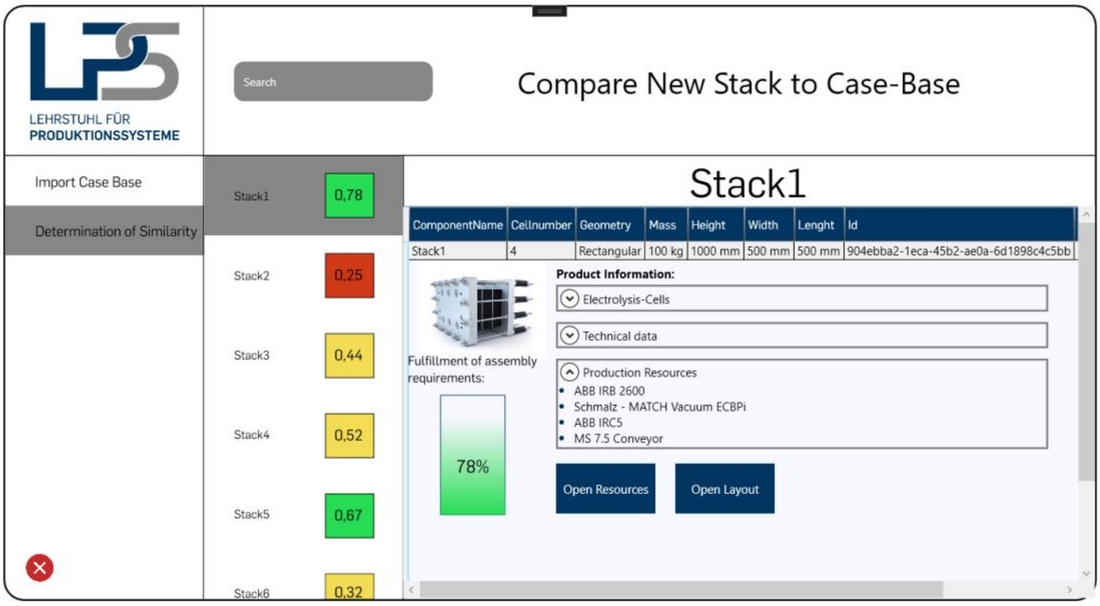
Attribute	Weighting α_i	Similarities $sim_i(x_i, y_i)$ $x_i \triangleq Stack1, y_i \triangleq Stack2$	Stack 1	Stack 2	Max. distance
Mass (kg)	1	$sim_{mass}(x_i, y_i) = 1 - \frac{\lvert x_i - y_i \rvert}{\max(distance_{mass}(x,y))}$	80	125	500
Height (mm)	0,4	$sim_{height}(x_i, y_i) = 1 - \frac{\lvert x_i - y_i \rvert}{\max(distance_{heigth}(x,y))}$	500	700	1050
Width (mm)	0,5	$sim_{width}(x_i, y_i) = 1 - \frac{\lvert x_i - y_i \rvert}{\max(distance_{width}(x,y))}$	300	350	500
Length (mm)	0,5	$sim_{length}(x_i, y_i) = 1 - \frac{\lvert x_i - y_i \rvert}{\max(distance_{length}(x,y))}$	300	400	500
Cellnum. (n)	0,5	$sim_{cellnum.}(x_i, y_i) = 1 - \frac{\lvert x_i - y_i \rvert}{\max(distance_{cellnum.}(x,y))}$	25	40	30

3.3 Solution adaptation and case base extension

After determining the similarity between a new and past product description (see Section 3.2), the obtained results, including their corresponding solutions, must be adequately provided to the planner. This can be done in various ways. One option is to output only similarity values of the compared elements and indicate references to their solution. Furthermore, based on the comparison, additional assistance can be provided to the employee, such as the specific combination of production resources and individual subcomponents. For this purpose, it is no longer sufficient to compare only the characteristics of the overall products but to take component interfaces and physical connectors into account (see Section 3.2). This can be achieved by conducting an analysis of the similarity among physical connectors across various product structures, a factor that has already been taken into consideration in the provided data model. Necessary adjustments resulting from project-specific requirements of an existing similar solution can be made by the planner. This is done using a suitable tool specific to the company for resource and layout planning. Depending on the use case, this can range from a simple list of resources to complex detailed layouts in an appropriate engineering tool. Afterward, the newly generated case (see Figure 2) is included in the case base. Section 4 shows an exemplary representation of similarities and suitable solutions using a developed graphical user interface.

4. Application example

To represent the potential application of the CBR cycle as clearly as possible, an example application was implemented that visualizes the similarity determination between a new product and an existing case base. Figure 4 depicts the graphical user interface of the application. In the context of the application, information about the products and resources are entirely described and used in the form of the shown data model (see Figure 2). Ten product variants of electrolysis stacks were compared in the context of the considered example. The results are presented to the user in the most accessible form possible and are marked with corresponding colors. Furthermore, it is shown to what extent the different production systems meet the assembly requirements of the new product subcomponents and physical connection elements. In addition, the user can access referenced files in the form of listed resources and layout descriptions in their native data models. This provides a starting point for a plant planner to develop a suitable production facility, including the necessary resources and an initial layout. Moreover, the experiences regarding the overall system directly contribute to the selection and engineering of the sub-components as well as the associated knowledge is separated from individual employees. In this way, inexperienced employees can be supported in decision-making, allowing them to build on existing solutions efficiently.



Compare New Stack to Case-Base

Stack1	0,78
Stack2	0,25
Stack3	0,44
Stack4	0,52
Stack5	0,67
Stack6	0,32

Stack1

ComponentName	Cellnumber	Geometry	Mass	Height	Width	Lenght	Id
Stack1	4	Rectangular	100 kg	1000 mm	500 mm	500 mm	904ebba2-1eca-45b2-ae0a-6d1898c4c5bb

Product Information:

Electrolysis-Cells

Technical data

Production Resources
- ABB IRB 2600
- Schmalz - MATCH Vacuum ECBPi
- ABB IRC5
- MS 7.5 Conveyor

Fulfillment of assembly requirements:

78%

Figure 4: Expert System – Visual representation of similar cases and related production systems

5. Conclusion and outlook

The engineering of production plants is subject to industrial and social changes that have a massive influence on the associated subprocesses. Therefore, these processes have to be designed more efficiently through innovative solutions. This also applies to select suitable production resources and their arrangement in a layout. Hence, this paper demonstrates the application of CBR for the support of planning experts. Initially, the entire cyclic workflow of the overall planning approach is presented, followed by a detailed view of the necessary subprocesses. Based on the outlined systematic of a CBR cycle and the standardized case description using AML, it is possible to capture specific knowledge related to concrete engineering challenges and selectively retrieve it to assist employees in their decision-making. In subsequent research work, the individual subprocesses of the presented cycle can be examined and further developed in more detail. For example, a more profound similarity algorithm can be developed, or a lean and efficient case base regarding similarity determination can be realized. The demonstrated application scenario can be expanded to generate new production layouts based on the similarities of the subcomponents, their physical interfaces and required assembly skills, which can be presented to a planner as a more targeted planning foundation. Therefore, a potential approach involves a more intricate partitioning of the comprehensive production layout into discrete sub-components, exemplified by entities conveyor systems, sensors and robotic units. Consequently, the process can then discern a solution corresponding to each constituent, based on considerations of similarity. Nonetheless, this sequential approach introduces novel complexities, prominently including the assurance of seamless integration across all elements. This necessity the formulation of a fitting rule set or a system of constraints, effectively addressing the mentioned challenge. This could contribute to accelerate the engineering process in the described domain significantly. Future research focus especially on the combination of rule- and experience-based algorithms for the efficient planning of production plants and their evaluation.

Acknowledgments

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Biography

Daniel Syniawa (*1996), M.Sc., works as a research assistant at the Chair of Production Systems (LPS) at the Ruhr-University of Bochum. His current research topics include the digitalization of engineering processes in electrolyzer production and standardized data models in the context of Industry 4.0.

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Alfred Hypki (*1963) has been chief engineer at the Chair of Production Systems (LPS) at the Ruhr-University Bochum since 2015. His main research activities are robot simulation, robot programming and human robot collaboration. Until 2009 he was a research assistant at the Institute of Robotics Research at TU Dortmund University, where he received his doctoral degree. From 2009 to 2015, he was chief engineer at the Institute for Production Systems at TU Dortmund University.

Bernd Kuhlenkötter (*1971) has been head of the Chair of Production Systems at Ruhr University in Bochum since April 2015. He received his doctoral degree in 2001 at Dortmund University. In April 2009, after working for ABB Automation GmbH as head of product management and technology, he took over the professorship for Industrial Robotics and Production Automation at TU Dortmund, where he founded the Institute for Production Systems in 2012 and acted as manager until March 2015.