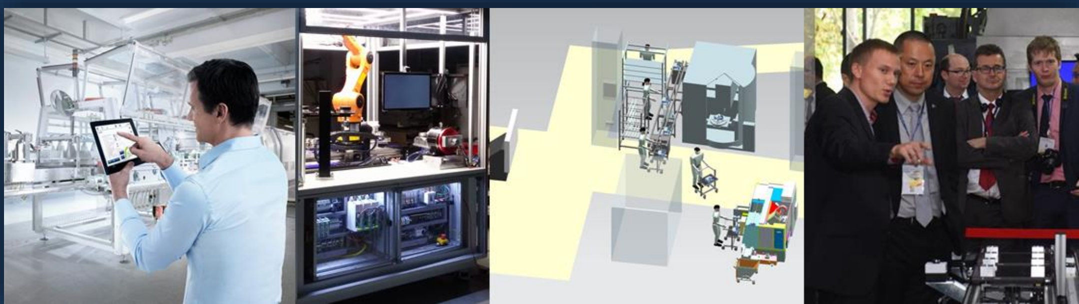
SINO-GERMAN INDUSTRY 4.0 FACTORY AUTOMATION PLATFORM

Final Report



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of the German Federal Ministry of Education and Research

Sino-German Industry 4.0 Factory Automation Platform

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Greetings

The straightforward design and commissioning of individualized production systems is a requirement to meet the advancing trend towards the customization of products and smaller batch sizes. Production system operators need turnkey production systems which are readily available and set to produce without having to undergo a lengthy commissioning process.

The software-based factory automation platform developed over the course of this project thus proved to be a suitable tool for an easy and objective-oriented deployment. An emphasis was put on the conception of a platform tailored towards German as well as Chinese industry partners in order to enable a quick access to the Chinese market and provide a competitive edge over other market actors.

I would like to thank all partners of the I4TP consortium, who made this unique research project such a success. I would also like to thank the Federal Ministry of Education and Research (BMBF) and the Ministry of Science and Technology of the People's Republic of China (MoST) for funding this project as well as the Projektträger Karlsruhe (PTKA) and especially Mr. Claudius Noll for their continuous support and the great cooperation.

The convergence of new developments – the increasing use of data from production processes and the interplay of engineering and information technology – have resulted in a growing demand for turnkey solutions for reconfigurable production systems in the Chinese market. Over the course of the I4TP project, Industry 4.0 technologies such as digital twins and cloud-edge collaboration have been combined into a factory automation platform that has become a powerful tool, enabling plant operators to react quickly to changing market requirements.

After more than three years of close cooperation, the I4TP project has come to a successful end. On behalf of the Chinese partners, Tongji University, SYMG, ITEI and Microcyber, I would like to express my sincere gratitude to all Chinese and German partners for their excellent research work and support. My further thanks go to China's MoST and the German BMBF for funding this project, as well as SYMG and Microcyber for their financial and manpower support.

This research project has been more than a scientific cooperation. It forged a deep connection between Chinese and German scholars and brought together partners from both countries which will help us on a shared path into the future.

Modern consumers demand customized products at reasonable prices. The configuration and commissioning of production systems must become transparent as well as manageable in order to cope with these requirements.

PROF. DR.-ING. JÜRGEN FLEISCHER
wbk Institute of Production Science at KIT, Director

The ability to rapidly react to market demands is a prerequisite for success in the constantly evolving Chinese market. Turnkey solutions for production systems act as enablers to meet these challenges.

PROF. DR.-ING. ZHANG WEIMIN
Institute of Modern Manufacturing Technology
at Tongji University, Director

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1 Introduction

1.1 Motivation and Demand

A number of factors and ongoing trends pose major challenges for the manufacturing industry. For one thing, the individualization of products continues to increase, and for another, product life cycles are also becoming consistently shorter. This means that, in addition to the product life cycle, the product development process is also being accelerated. Combined, these factors lead to steadily decreasing batch sizes down to the quantity of 1, which, however, must be available ever faster. Markets such as China's are additionally characterized by enormously high consumer demand and rapid growth, while the cost sensitivity of consumers requires cost-efficient high variant production. With regard to existing process models for product development, it is noticeable that the time-to-market with sequential process steps is too long. To shorten it, it is essential to be able to parallelize and integrate the processes of product development and production system development, set-up and commissioning. Web-based approaches additionally offer great potential for collaborative processes.

Global production requires simple and fast design as well as smooth commissioning of turnkey production systems. Due to the high number of complex individual machines and components from a wide range of globally active manufacturers, this leads to major challenges, from the selection of suitable machines to the configuration of entire systems through different component interfaces. Both unclear specifications of machines and components as well as mechanical and software interfaces, which are often not sufficiently defined and tested, lead to delays and high expenses. In addition, cross-manufacturer global collaboration requires procedures, methods and processes to be able to respond and deliver quickly to demand. For this, the time-consuming sequential development process of product and production system must be replaced by a more dynamic and faster configuration process. On the user side, there is also often a lack of knowledge about which functions (for identification, for example) need to be integrated into the component to be manufactured in order to be able to exploit potential in the area of Industrie 4.0.

1.2 Project Objectives

To solve the challenges described above, the German-Chinese Industry 4.0 Factory Automation Platform (I4TP) research project was conceived. As a collaboration of the binational consortium of SYMG, Microcyber, ITEI and Tongji University on the Chinese side and Bosch Rexroth, Schaeffler, Schunk and the Karlsruhe Institute of Technology on the German side, I4TP had the objective of developing a software-supported, model-based, German-Chinese factory automation platform for the rapid as well as user-friendly configuration and commissioning of turnkey production systems with integrated product consulting and customized business models.

The platform was created on the basis of which turnkey production systems can be generated, taking the specific needs of the Chinese market into account. Also, a compliance program with a test environment has been developed, with which components and associated models for the construction of turnkey production systems can be assessed. The platform thus forms the basis for an industry standard for turnkey production systems supported by the consortium and further associated partners. Key scientific issues were addressed in the area of networking as well as cross-national cooperation in an open platform with defined roles and responsibilities.

1.3 I4TP Consortium

rexroth
A Bosch Company

As a pioneer of networked automation, Bosch Rexroth enables machine manufacturers and manufacturing companies to harness the benefits of Industry 4.0 and tap into the potential of networked production. Thanks to its experience with the group's own production network, Bosch Rexroth, as a leading supplier of automation solutions, has a tried-and-tested, high-performance modular system of hardware and software components that can be seamlessly integrated, enabling customers to realize their ideal vision of a smart factory simply and in line with their needs in the form of turnkey solutions.

SCHAEFFLER

As a leading global supplier to the automotive and industrial sectors, the Schaeffler Group has been driving forward groundbreaking inventions and developments in the fields of motion and mobility for over 75 years. With innovative technologies, products, and services in the fields of CO_2-efficient drives, electric mobility, Industry 4.0, digitalization, and renewable energies, the company is a reliability partner for making motion and mobility more efficient, intelligent, and sustainable. The technology company produces precision components and systems for drive train and chassis applications as well as rolling and plain bearing solutions for a multitude of industrial applications. The Schaeffler Group generated sales of approximately EUR 12.6 billion in 2020. With around 83,900 employees, the Schaeffler Group is one of the world's largest family companies. With more than 1,900 patent applications in 2020, Schaeffler is Germany’s second most innovative company according to the German Patent and Trademark Office.

SCHUNK

Schunk, the competence leader for clamping technology and gripping systems, shows that the visions of the Smart Factory can already be realized today. During assembly, testing, packaging and transport, pick & place units and 3-axis gantries cooperate autonomously and enable smart production. The most striking feature: status and process monitoring as well as communication take place directly at component level. Smart, intelligent Schunk grippers, pick & place units and linear direct axes enable decentralized control at component level and thus a dynamic and flexible process.

KIT
Karlsruher Institut für Technologie

As one of the biggest science institutions in Europe, the only German University of Excellence with national large-scale research facilities combines a long university tradition with program-oriented top-level research. The university, whose roots date back to 1825, stands for a broad range of disciplines and knowledge. We seek to contribute to the success of big projects of our society by providing excellent academic education, conducting top-level research, and producing innovation. These big projects cover future energy supply, sustainable mobility, and smart and secure technology for the information era.

SYMG

After continuous technological transformation and technological innovation, SYMG has become China's largest comprehensive machine tool manufacturer and national CNC machine tool development and manufacturing base, and dedicated to product development and technical reserves for motion control technology and cloud manufacturing technology for the machine tool industry. A series of products, including i5 series intelligent NC system, HSHA series servo driver and WIS workshop information system, has been developed independently, the complete set of intelligent solutions are serving more manufacturing enterprises and providing infinite possibilities for intelligent manufacturing.

中科博微 MICROCYBER

Microcyber is a high-tech enterprise that undertakes several national scientific and technological research, high-tech industrialization demonstration and application projects, and is one of the framers of China's factory automation protocol standards and industrial wireless communication standards, has a leading position in fieldbus technology. As a provider of full range of industrial automation products, Microcyber has launched a new generation of networked control systems and related products for large-scale, high-reliability industrial control applications, providing key technologies and key components for a large number of domestic and foreign companies in the industry.

ITEI

ITEI is a science and technology intermediary agency based on standard science and technology and soft scientific research, guided by advanced technologies such as intelligent manufacturing and industrial Internet, and mainly engaged in research work in the fields of smart factories, network collaborative manufacturing, industrial Internet, scientific instruments, high-end medical equipment, etc., provide public welfare services to the society and provide support for the government's industrial policy and plan formulation, and industry management implementation. ITEI adheres to the development path of science and technology intermediary, conducts research on instrumentation comprehensive technology, industrial process control and automation technology, leads the development of the industry, and promotes technological innovation.

From 1907 to present, Tongji has developed into a comprehensive, research-oriented and international university with distinctive characteristics and great influence at home and abroad. The university takes the responsibility of cultivating social pillars and professional elites to lead the future, adhering to the spirit of advocating science, leading innovation, and pursuing excellence, and has successively undertaken a series of national major projects and major engineering scientific research, including intelligent manufacturing related technology. Tongji also actively expands international cooperation, and struggles towards the goal of becoming a world-class university with Chinese characteristics.

2 Industry 4.0 Factory Automation Platform

2.1 I4TP Approach

As part of the I4TP research project, a software-supported and model-based factory automation platform has been created. This platform includes the design, implementation, and operation of production systems. Apart from configuring a completely new production system, the platform further incorporates existing machines and tools based on their availability. The result of this configuration platform is used for further simulations and applications, e.g. the visualization of the proposed turnkey production system or creation of a digital twin to demonstrate the production system layout (Gönnheimer et al. 2019b).

In the context of the I4TP platform, approaches are made for the development of a configurator that can systematically customize production systems. By comparing the requirements of the product to be made with the properties and specifications of production machines, the configurator can automatically suggest possible production modules together with its tools. A modular and easily extendable information structure has to be defined, in which information regarding the product, production processes, production modules, and tools is stored (Gönnheimer et al. 2019b).

In addition, process-specific criteria are determined which subsequently are used to select the appropriate production modules and tools. The configurator generates an optimum production system concerning criteria such as acquisition cost or lead time minimum. But such an approach could lead to conflict between solution quality and computing time. Therefore, the task is to find an optimal configuration solution from a finite set of objects as quick as possible. Different algorithms are used to find a compromise between those criteria. The configurator is used for the composition of the production modules as well as for the generation of an optimal overall production process.

To design and implement a turnkey production system, several steps of a methodical approach have to be performed (see Figure 1). A multi-stage process is used to transform the initial product into the configuration of a turnkey production system. According to Figure 1, the first step is to extract features of the product. A product feature set can best be summarized as a written document that lists the specifications of a product. It contains the list of features that together make up a product. A feature listed here can represent different manufacturing information, such as diameter, position, trajectory, tolerances, surface quality, etc. To create the feature extraction list, features of the product must be identified, and modeled from a production perspective. A complete CAD model of the product is needed, which must be broken down into individual components. The model also provides information on how these components are connected to each other. The result of the feature extraction is then put into a common systematic machine-readable data structure for further processing (Mandel et al. 8242020).

The second step is to introduce manufacturing processes that can be matched against the feature list. Similarly, a library of reusable processes (drilling, milling, turning, etc.) with parameterizable attributes (turning speed, feed rate, etc.) is simultaneously deposited in the model. Features and processes are stored with attributes so that during modeling it can be decided unambiguously whether a particular process is suitable for the production of a particular feature. If there are multiple ways to machine a single feature, all possible machining possibilities are examined and evaluated. As a result, the detailed process list is used to define the tooling and

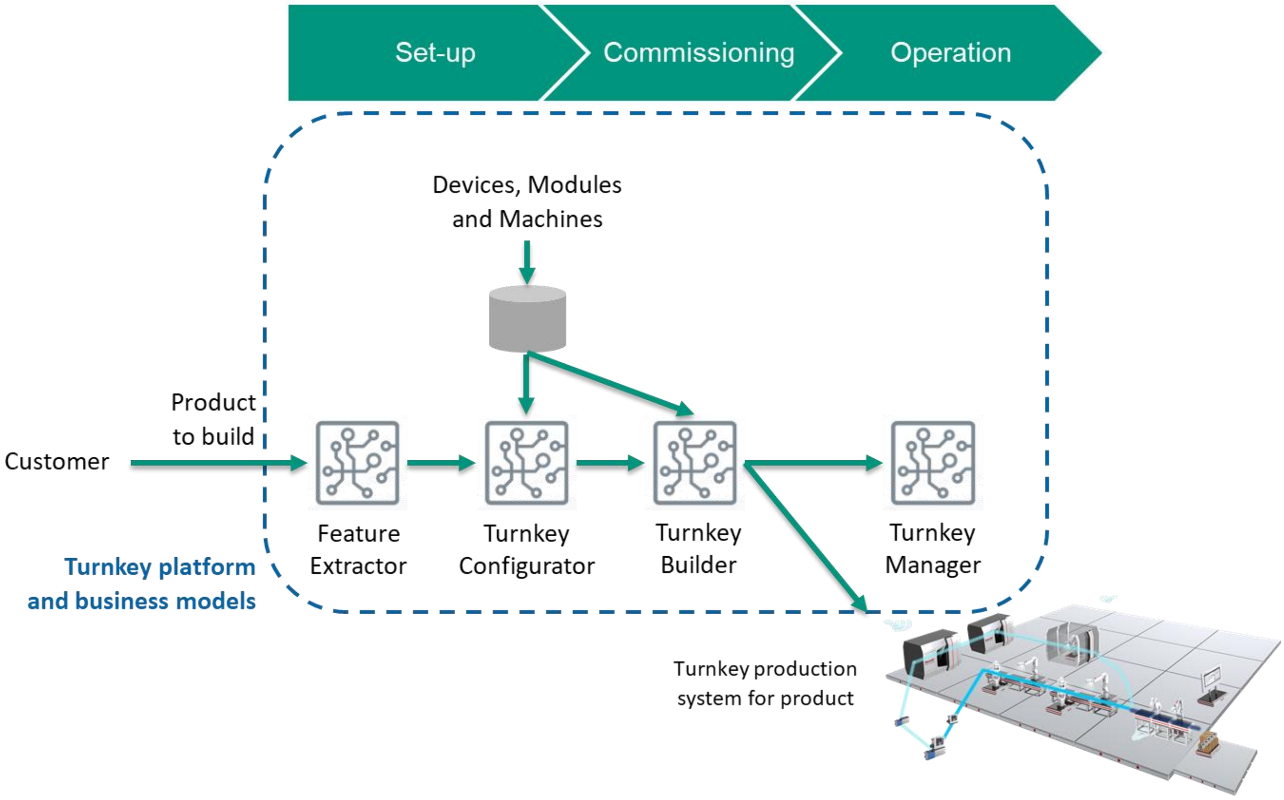

Figure 1 Overview of the turnkey configuration process (Gönnheimer et al. 2019b)

machinery requirements needed for the machining operation (Albers et al. 2019).

In a third step, an algorithm selects the machines and its tools from a database that can be used to manufacture the product. The extracted features of the product serve as requirements for the production system to be configured. The user requirements, which include the targeted production quantity, the planned total budget of the production system and the required availability, are compared with the properties of the production modules. As a result, the possible solution space can be reduced (Gönnheimer et al. 2019a).

As soon as the comparison process is completed, a list of possible machine combinations is presented in regard to all production processes. To reduce the list to a manageable number of options, an optimization algorithm suggests machine combinations with respect to criteria such as lowest operating costs, best performance, and most efficient operation. After the user selects a proposed system combination, a list of all selected production modules with machines and tools as well as the interlinking sequence and workflow is generated (Gönnheimer et al. 2019b).

The I4TP platform includes a website, a NoSQL database server, and a set of loosely connected IoT platform solutions. The website serves as a platform where users can upload their product in the form of a STEP file. The STEP file is then analyzed according to the configuration concept mentioned above. In addition, a 3D view of the user's product can be seen on the website, along with individual highlighted features generated by the feature extractor. At the same time, the suggested production processes are displayed on the website. The user can then request the configuration of their production system. This initiates the configuration process described above. The extracted product features and their matching production processes are matched with the available machines and tools. Suitable configurations are then evaluated according to the user's optimization criteria.

After the configuration solutions are generated, the proposed system configurations are visualized on the website. By visualizing the production system layout, the user can, on the one hand, evaluate and readjust the system at an early stage. On the other hand, the visualization presents the proposed production processes as well as the transport processes in detail. The machine modules are arranged in the layout according to their processes in a logical sequence. Moreover, this visualization can act as a digital twin of the production plant. The combination of cloud-based control architecture and collected real-time data of the physical machines enables the visualization of real-time machine states in the digital twin model on the website. As shown in Figure 2, the platform user has access to several services offered by the industrial project partners and integrated into the platform architecture. The platform architecture and integration of services is detailed in Chapter 5.

The configuration process was exemplified in the project using two exemplary components from the consortium, a hydraulic valve from Bosch Rexroth and a gripper from Schunk.

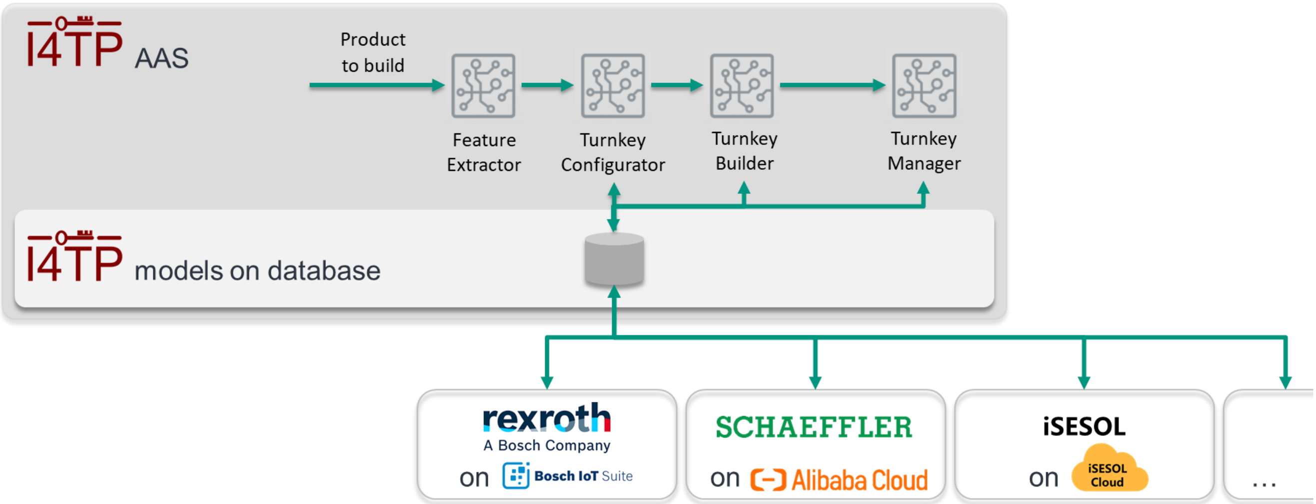

Figure 2 Architecture of the I4TP platform

2.2 I4TP Modelling

Modeling of information plays an important role to enable compatibility of the different building blocks (Feature Extractor, Turnkey Configurator etc.) of the I4TP platform and create a consistent basis for the development of methods and services. For I4TP, modeling is performed in the understanding of MBSE – Model-Based Systems Engineering (International Council on Systems Engineering (INCOSE) - Technical Operations 2007). In the understanding of MBSE, three aspects have to be considered integratively (cf. Delligatti 2014):

- The modeling method, specifying processes and tasks used to model.
- The modeling language, encompassing the elements and their (possible) relations used for modeling.
- The (software-) tool and its capabilities, in which the modeling is performed.

The modeling approach in I4TP is developed in a multi-step and iterative, i.e. not strictly sequential, approach. First, existing approaches for modeling in the understanding of MBSE and in the context of industry 4.0 are analyzed. A prominent approach to be considered is CONSENS. CONSENS is specification technique consisting of language- and methodical-elements to support a cross-domain description of product and production system (cf. Gausemeier 2012). Another reference has been developed in the BMBF-funded project MecPro[2], consisting of a modeling framework (implemented in the modeling language SysML) and a process framework for the integrated modeling of product and production system (cf. Eigner et al. 2017; Steimer et al. 2016). Other approaches can e.g. be found from (Berardinelli et al. 2016) and (Kiesel et al. 2017).

Taking those existing approaches as a background, a method is developed, that supports the modeling of interdependencies between product function, product embodiment, production processes and production modules in the context of the I4TP platform (Albers et al. 2019). The newly developed method combines and adapts aspects from existing approaches and adds new aspects to specifically support the workflow and services from the I4TP platform. On the one hand, this encompasses the methodical background for the implementation of the services from the different building blocks of the I4TP platform and their relations. On the other hand, the method helps to build an interface between different building blocks on the platform and supporting services like a product-oriented consulting by establishing a clear and shared framework. The method is continuously applied, validated and iteratively adapted based on insights from the existing production system, production processes and products, Bosch Rexroth hydraulic valve and Schunk gripper, at the I4TP demo validation center at amtc. To realize the modeling for the method, a set of matrix templates is developed in I4TP (Albers et al. 2019).

The application of the method on the example of the amtc yields valuable insights on types of information that need to be modeled and thus helps to identify and clarify requirements on the modeling language to be developed. To expand those insights even further, reference architecture models in the context of industry 4.0 are analyzed. In contrast to the already analyzed modeling approaches, those reference architecture models tend to be more abstract and describe more high-level constructs for information modeling in the context of industry 4.0. In addition, the analyzed reference architecture models have a strong focus on production system aspects and regard the product only partially. A central reference architecture model that has been considered is RAMI 4.0 (Plattform Industrie 4.0 2018). RAMI 4.0 has a mutual alignment report with IMSA - the China Intelligent Manufacturing System Architecture (Sino-German Industrie 4.0/Intelligent Manufacturing Standardisation Sub-Working Group 2018). In addition, RAMI

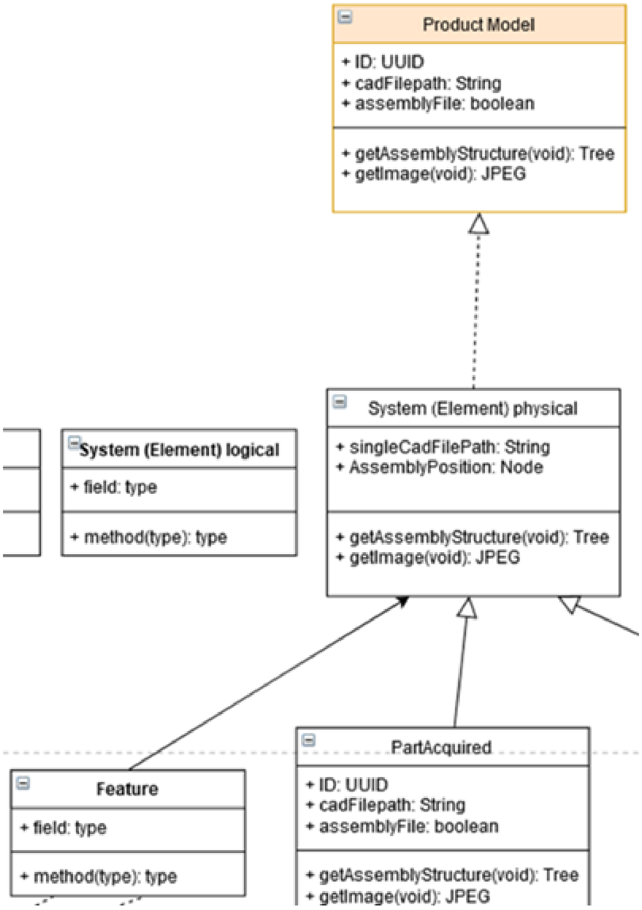

Figure 3 UML-style description of the elements, their attributes and relations for the I4TP modeling language (excerpt)

4.0 serves as a basis for more concrete descriptions like the administration shell (Plattform Industrie 4.0 2016) or implementations like in the SmartFactory KL system architecture (Kolberg et al. 2018) that have also been regarded and analyzed.

Combining the references from existing modeling approaches, the application of the developed modeling method and reference system architecture models like RAMI 4.0, information that has to be regarded for the modeling in I4TP has been consolidated. To formalize and detail the analyzed information, UML-style descriptions of the individual elements of the I4TP modeling language as well as their parameters and relations are created (see Figure 3).

The descriptions of the modeling language are the foundation for several implementations for modeling in the context of I4TP. First of all, the descriptions of the language are used to create a so called *profile*, a language extension for the formalized modeling language SysML (cf. Mandel et al. 2020). Using this SysML profile, the developed method can be supported by a formalized modeling environment i.e. a specialized software-tool. This offers potential, e.g. for semi-automating the creation of dependency overviews to show the traceability between product functions, system-element and their (production-relevant) features, as well as production processes and production modules (cf. (Mandel et al. 2020) and see Figure 4). In addition, the descriptions of the modeling language are the basis to structure file formats for the different building blocks of the I4TP platform and their realization. This enables amongst other things, to define a data structure of the description of digital module models for the platform. In addition, interfaces between different building blocks of the I4TP platform can be clarified. Like this, it can be ensured, that output files from one building block (e.g. the Feature Extractor) can be understood and interpreted by other building blocks (e.g. the Turnkey Configurator).

As shown in this paragraph, modeling plays an important role in the context of the I4TP platform. With the developed modeling language (descriptions), modeling methods and (tool-) implementations, a foundation is created to enable data and information compatibility on the I4TP platform. In addition, formalized means are created to enable modeling and analyzing the dependencies between product and production system, which contributes to product-production system co-design and can be used as a foundation for further use cases e.g. impact and risk analysis in the integrated development of product and production system (see Chapter 2.3).

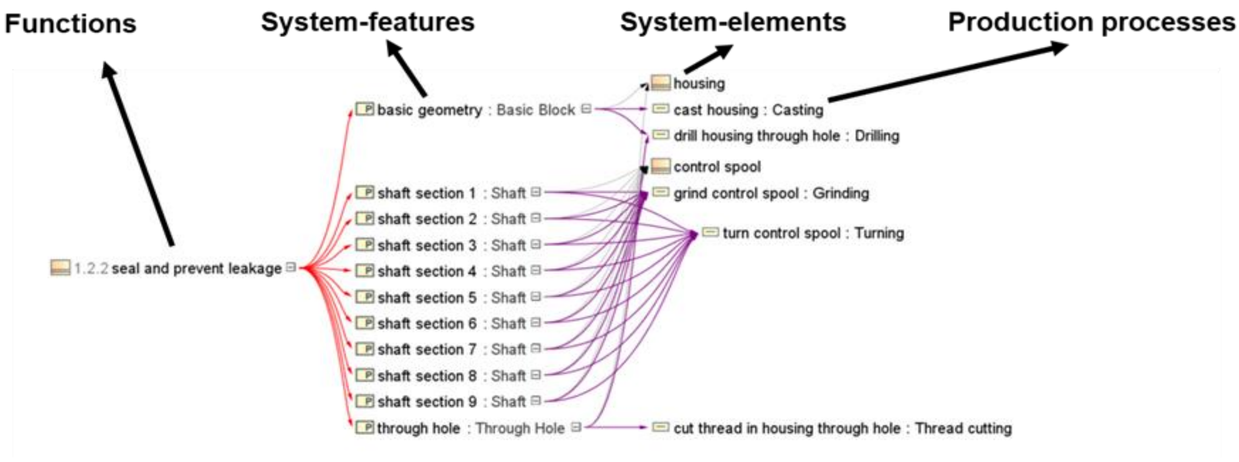

Figure 4 Traceability between different elements in a SysML model

2.3 Sino-German Collaboration and Business Models

The joint Sino-German project I4TP put a high emphasis on finding ways to collaborate across borders and work together on a common factory automation platform for German as well as Chinese partners alike. One of its main goals was the to establish of a common IoT-Communication platform enabling a trustful cooperation between German and Chinese partners in, using role-based access controls based on previously defined trust-levels.

IoT-Communication Platform

One of the first steps for a border overarching collaboration was to find and test suitable collaboration platforms in a joint German-Chinese effort. On the one hand, communication and data exchange between the partners had to be ensured and on the other hand IoT communication and cloud connectivity of the machines and systems to be used had to be provided. After converting the jointly defined requirements into corresponding systems and program components, a comprehensive market analysis was carried out, in which both IoT platforms on the Chinese market and on the Western or German market were examined. The result of this analysis was, that a wide range of IoT platforms would theoretically be suitable. However, the newly introduced Chinese Cyber Security Law requires the usage of a platform situated in China. The selected IoT-Platform enables connections to other platforms via provided interfaces.

As for the collaboration of the project partners, a thorough review of existing collaboration platforms was also investigated. For this purpose, both "open source" and commercial software were examined, evaluated according to the requirements and the best-performing platforms were then tested by the project partners. The selected platform with the highest net benefit to cost ratio was the open source platform “Nextcloud”, which can be extended in its functionality in such a way that the requirements for the collaboration of the project partners are largely met.

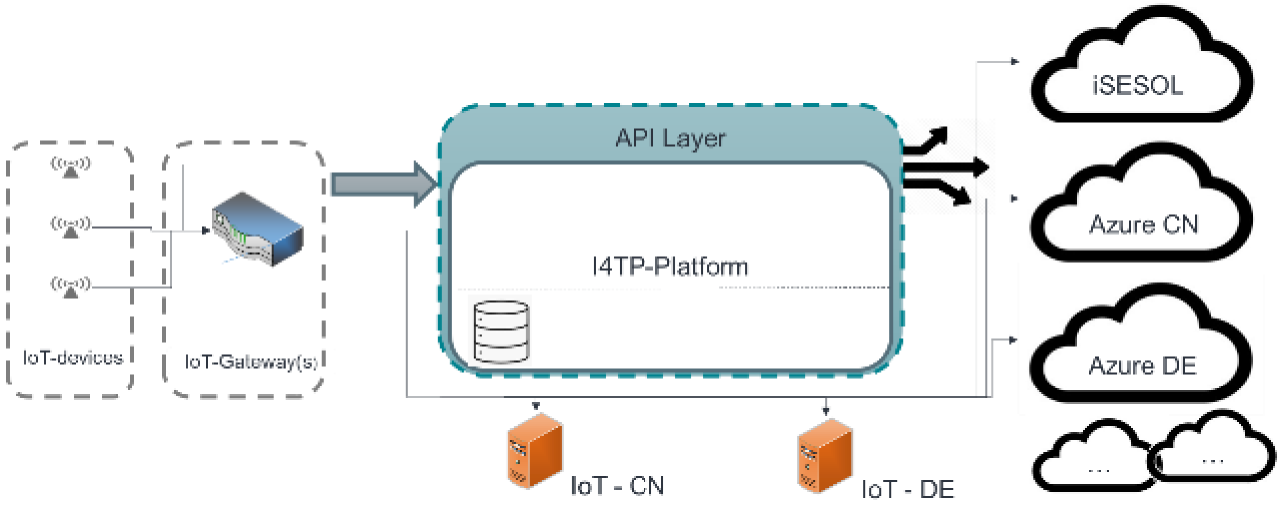

Figure 5 I4TP – Collaboration Platform

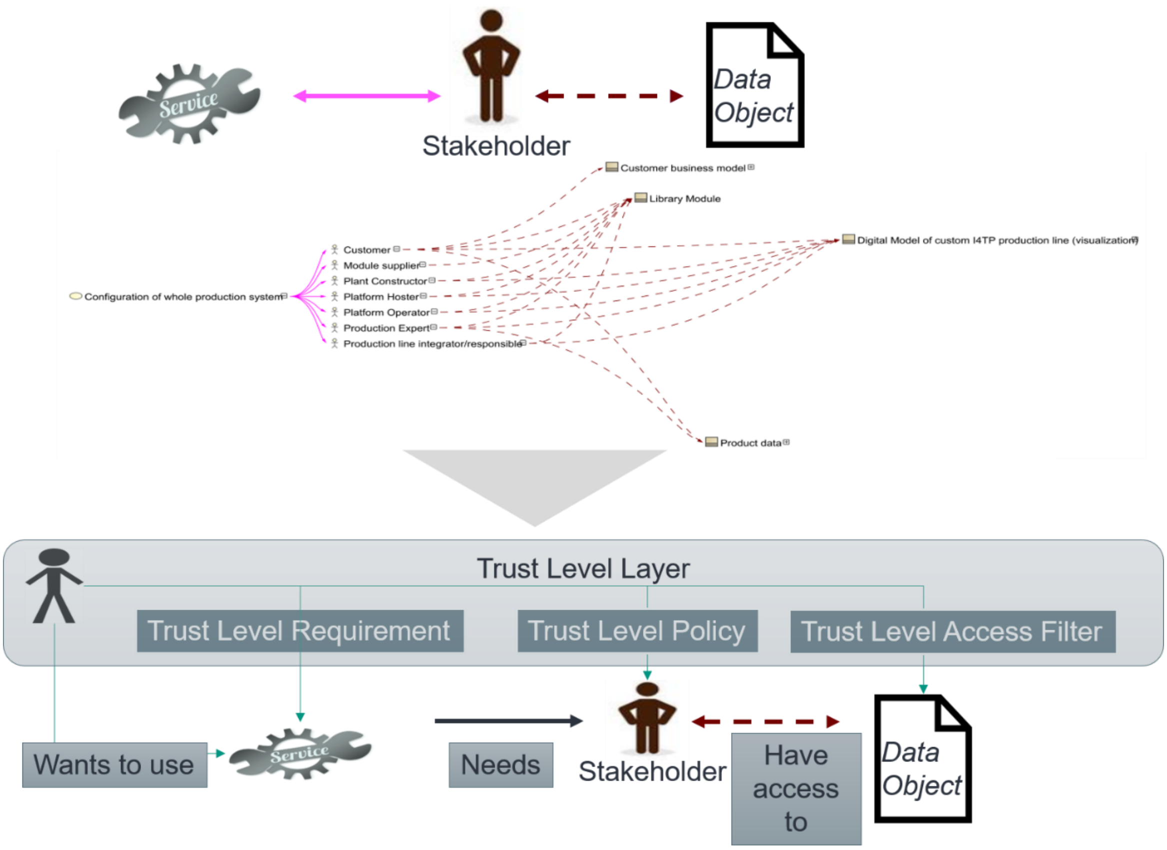

Figure 6 Business collaboration influenced by trust between businesses

Furthermore, a base PHP-web server was set up, which serves as the foundation for the integration of all project results on one publicly available platform setup. For this, partners would be provided with the basic platform components and interfaces to connect their services to. For joint coding of the framework and implementations a joint GitLab-server was used.

Horizontal and vertical models of integration

On the platforms exemplary roles were assigned to the project partners and stakeholders. The role definitions were supplemented for the Board of Associated Partners, also in order to incorporate the feedback from the industry during the project. Processes and workflows between the various roles on the platform were schematically conceptualized and supplemented.

Methods of German-Chinese Collaboration across Country and Company Borders

To ensure a trustful exchange of ideas and data between the two countries, a concept of trust levels was introduced. To enable Know-how protection data protection concepts were integrated to safely manage the storage and transfer of data.

Therefore, the different stakeholders on the platform and data on the platform were defined. Then the interaction between stakeholders and data by using exemplary services provided by the platform were being showcased and connected using a model-based approach. Furthermore, a model for Governance – Risk and Compliance was developed.

3 Feature Extraction

The Feature Extractor is the first part in the I4TP workflow. It is the interface between a product to be produced and the I4TP platform. The goal of the Feature Extractor is therefore to analyze data from a product and extract and prepare information relevant for the I4TP workflow and further processes.

A major task of the Feature Extractor is to (automatically) analyze the design of a product in a CAD – Computer-Aided Design - file format and identify manufacturing relevant features. However, in addition, the methods describing how further product information, e.g. requirements, functions etc., can be analyzed and modeled in a suited environment are also part of the Feature Extractor.

Therefore, the development of the described modeling approach (see Chapter 2.2) as well as for the methods for impact and risk analysis (see Chapter 2.3) are strongly interlinked with the development of the Feature Extractor. In addition, the Contact and channel approach - C&C²-A, see (Grauberger et al. 2020) - has been applied, to analyze and model dependencies with product embodiment and function.

For the automatic recognition and extraction of manufacturing relevant features from CAD-data, three different approaches have been developed:

- Parametrization and feature identification from a CAD software tool (e.g. PTC Creo[1] or Solidworks[2]).
- Feature extraction based on NC-code and CAM – Computer-Aided Manufacturing – software tools (e.g. Autodesk FeatureCAM[3]).
- Custom algorithm for feature identification from a Step-file (ISO 10303 (10303-242)).

The goal of all of those approaches is to generate a list of the product features in the developed I4TP modeling format (see Chapter 2.2).

The first approach was considered, as many CAD-tools nowadays have the ability to construct features that are closely related to descriptions from ISO 10303 (10303-242). Furthermore, many tools also allow an automatic recognition of such features from a file in a neutral data format like STEP (.stp). The analyzed features and their parameters can then be exported e.g. in a .txt format. Such an exemplary output file from PTC Creo is displayed in Figure 7. In order to prepare the output file for use on a platform, scripts have been developed that take the file as an input and "translate" them into the .json file format based on the I4TP modeling approach (see Chapter 2.2).

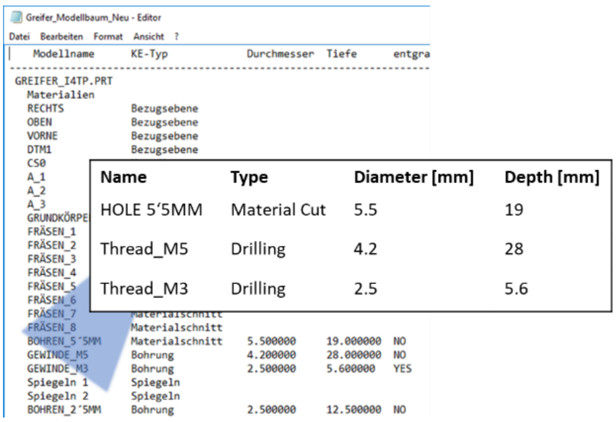

Figure 7 Exemplary output file from feature recognition from PTC Creo (excerpt)

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[1] https://www.ptc.com/de/products/creo

[2] https://www.solidworks.com/de

[3] https://www.autodesk.de/products/featurecam/overview

However, the approach based on existing CAD tools holds several drawbacks for use in the context of the I4TP platform:

- A specialized CAD tool is necessary. This would pose restrictions on the usability of the platform or require the platform to interface to a multitude of CAD tools.
- The content of the output files is dependent on the specific feature recognition algorithm of the CAD tool. Output file formats may thus vary greatly and a lot of effort would be necessary, to prepare the files for the I4TP platform.
- The CAD model has to be parametrized in order to output all the data necessary for the I4TP platform. This requires additional effort for preparing the product data and might not have been performed for every model, that should be processed on the I4TP platform.

Because of those drawbacks, alternative approaches for feature extraction have been regarded. A particular challenge for feature recognition is, when non-standard- or intersecting features shall be recognized. The second developed approach thus targets the extraction of such features (Yang 2020). It is a bottom up approach, taking a CAM tool (in this case Autodesk FeatureCAM) and generating G-Code for a given product. The generated G-code is then analyzed with a Matlab script. The Matlab script processes the G-code for boundary points of non-standard features and outputs them in the .json file format for the I4TP platform (see Chapter 2.2).

However, the analysis of non-standard and intersecting features is a special use case for the Feature Extractor. The second approach can thus be seen as an optional secondary and supporting approach for feature extraction.

The main approach for the Feature Extractor that has also been implemented on the I4TP platform is based on a custom algorithm to extract the features directly from a ISO 10303 STEP (.stp) file of a given product (Chen 2019). The STEP file format is a neutral data exchange format for product data representation. Therefore, no specialized CAD tool is required for the feature extraction. Figure 8 shows a simplified overview of the developed algorithm. It is based on two main sections: a section for the extraction of information from the .stp file and the feature recognition process. The information extraction process takes the .stp file as an input and analyzes geometric information (coordinates, direction etc. from points, curves and faces) and topology information (association between the geometry elements). In addition, for STEP AP 242 files,

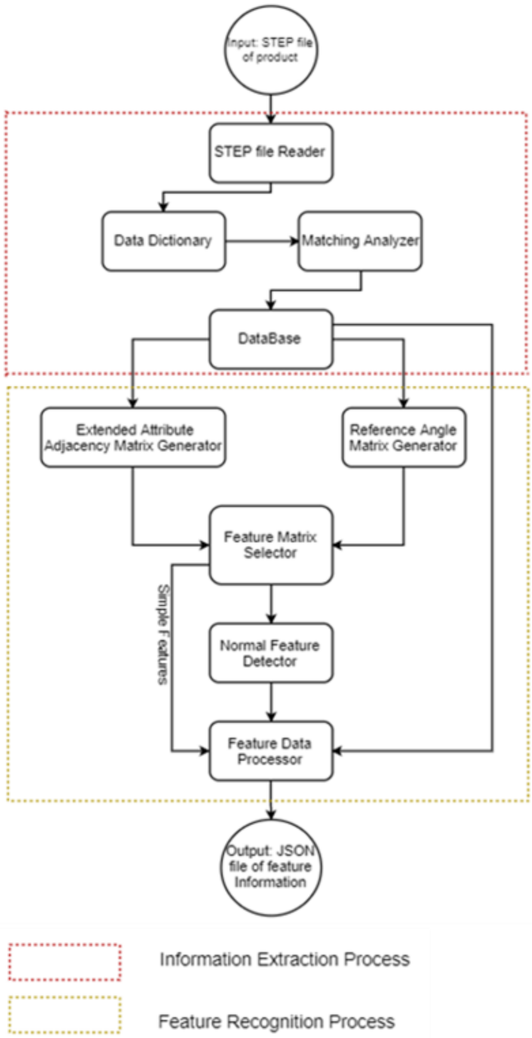


Figure 8 Custom algorithm for the Feature Extractor

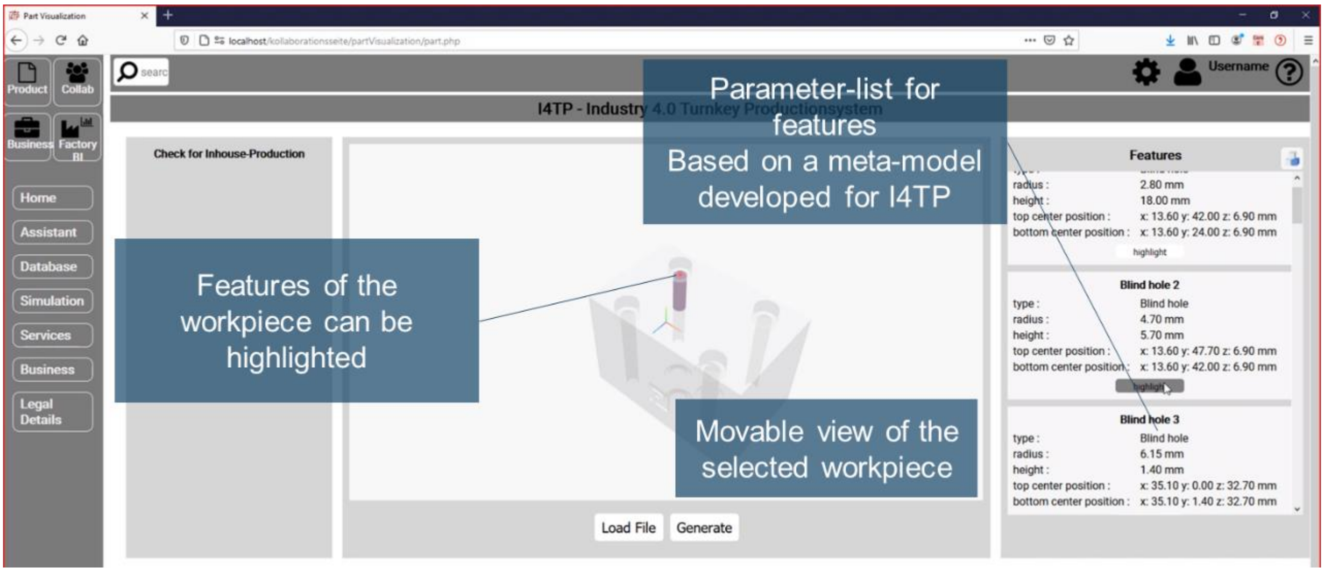


Figure 9 Feature Extractor application on the I4TP platform

Product Manufacturing Information (PMI) like e.g. tolerances can be read from the .stp file.The analyzed data is then matched to a C++ data structure for the input file. (Chen 2019)

The process for feature recognition, based on the C++ data structure, combines graph-based feature recognition methods (see e.g. Joshi und Chang 1988) and geometric reasoning for feature recognition (see e.g. Nasr et al. 2014). For each feature, that should be identified from a .stp file, a reference matrix is defined and saved in a library. This feature library can be continuously expanded in the future. The output of the algorithm is a .json file in the file structure developed for the I4TP modeling that can be used for the further components of the I4TP platform. The custom algorithm has been implemented on the I4TP platform. An overview of the Feature Extractor application is shown in Figure 8.

After uploading a .stp of a workpiece, the workpiece can be displayed on the platform. The list of features with respective parameters is displayed on the right of Figure 9. Individual features of the workpiece can be highlighted and analyzed in detailed (in the middle of Figure 9).

Based on the extracted features, general information for the production of the workpiece e.g. general Rz, workpiece material, or dimensions of the stock part, from which the workpiece should be produced, can be specified on the I4TP platform.

Based on this information, a developed rule-based algorithm proposes suitable production processes for the extracted features. The rules are based on the analysis of restrictions like potentially achievable accuracies of production processes, that can be found in literature (see e.g. (Wittel et al. 2013)). As a consequence, a color-coded scheme for possible production processes is displayed on the platform (see right side in Figure 10).

The information of the extracted features and suitable production processes is saved in separate .json formats based on the I4TP modeling approach (see Chapter 2.2). The files are then used and further processed from the other components of the I4TP platform, especially the Turnkey Configurator and Turnkey Builder.

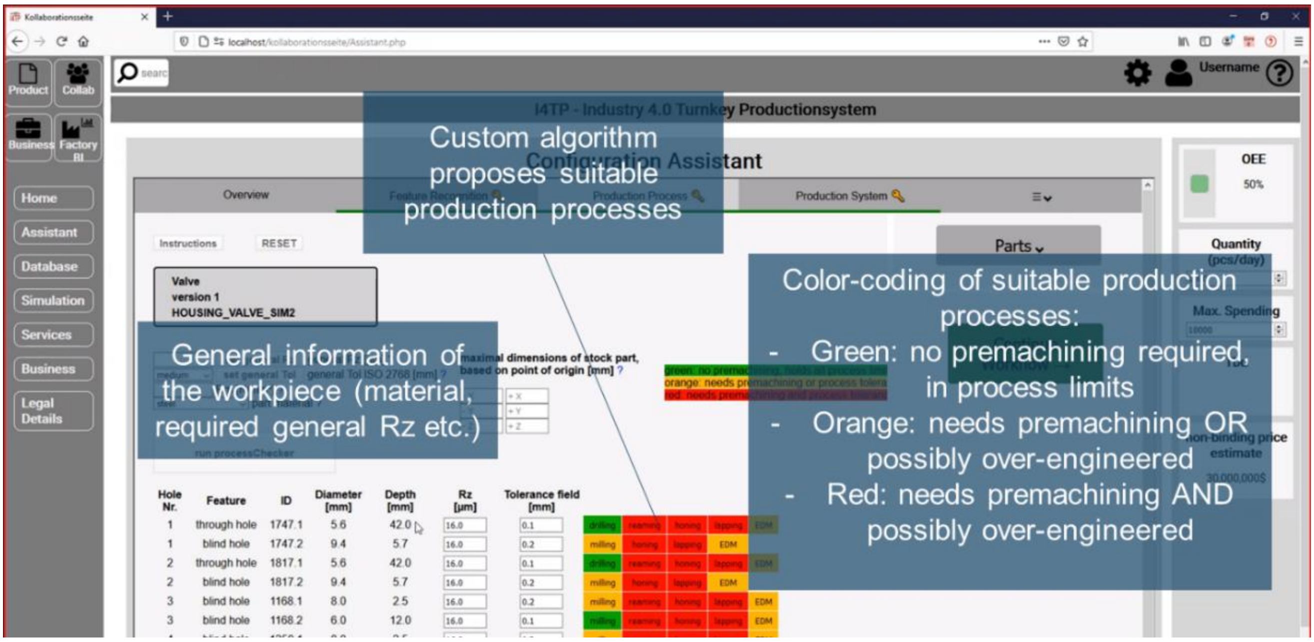


Figure 10 Proposition of suitable production processes based on the identified features

4 Production Systems Configurator

The Turnkey Configurator is the second component in the I4TP workflow. It consists of the configuration process of a turnkey production system based on defined product features and user requirements. The goal of the Turnkey Configurator is therefore to analyze data from previous I4TP workflow and use the initial product information for the configuration of a turnkey production system.

For the automatic configuration of a turnkey production system, a multi-step process has been introduced, which is shown in Figure 11:

- Extract production process list from Feature Extractor
- Extract relevant tool and machine information from Module Library
- Select machines and its tool components which can be used for the production of the product
- Generate optimal production system configuration solutions

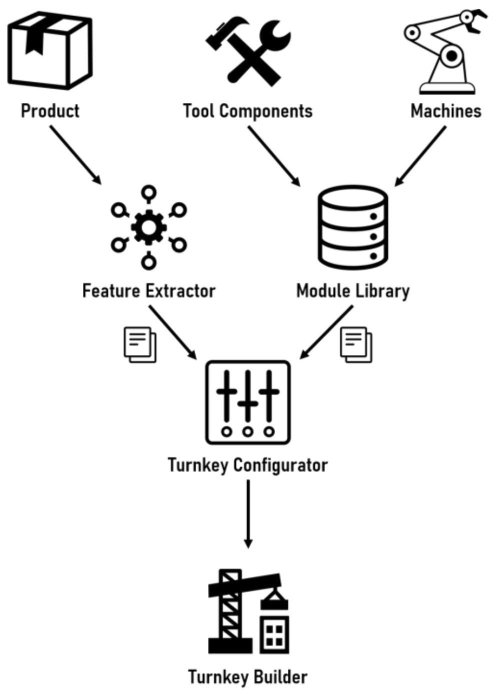


Figure 11 Turnkey configurator input information data flow

First, the configuration process is performed based on the feature extraction file and the module library in the form of JSON input data. The feature extraction file enables the definition of product features from a manufacturing point of view. The module library consists of various machines and tool components that can be selected to produce a particular product. The information in this data must first be extracted and prepared to conform to a predefined structure. The result of the extraction is a standardized, machine-readable data structure containing the extracted process specifications. The available machine and tool properties are also provided in the same machine-readable data structure. These files can then be taken over and used by the turnkey configurator.

The next step is to use an algorithm to select suitable tool components from the database that can be used to manufacture the product with its specifications and properties. To find the correct tools, several qualification keys are defined (e.g. type, diameter, length etc.). The correspondent tool properties are compared with these qualifications. Only if all the qualifications can be matched, then the specific tool is the correct choice. For each machining type, there could be multiple suitable tools to be found and would be added to the list. First of all, the tools must be able to perform the correct type of machining. To do this, the configurator matches the appropriate tool type with the machining type of the production process. If the tool type matches the machining type, the algorithm moves on to the next qualification keys. Otherwise, the next tool in the database is used for comparison. If all qualification keys match, the tool is added to the list of suggested possible machining processes. Production processes for which no tools can be found are displayed as well.

Once the selection of suitable tools in correspondence with the production processes is completed, the turnkey configurator will now need to assign available machine modules that can be fitted with the suitable tools. For this purpose, the configurator matches predefined qualification keys (e.g. material, working area, machine-tool-interface) with the machine features. The selected machines would be added to the newly created list corresponding to the given tool if all qualification keys are successfully matched.

After selecting suitable machines and tools, the next step is to list them in individual combination possibilities. This means that each tool is combined individually with all its associated machines. This allows a correspondingly large number of machine-tool combinations to be generated. The selected machines and tool components are then combined into combinations under the intended machining types of each respective production process. As a result, various process-machine-tool configurations are generated for further processing. At the same time, technical specifications of the machines and tool components are passed on for further configuration procedures.

The listed process-machine-tool configurations are then used to find the best possible configuration solution with respect to predefined optimization criteria.

The best possible configuration solution is determined based on three optimization criteria that make the turnkey production system perform accordingly. They all relate to the cost and performance factor of the machine tools.

The goal is to find the smallest possible value that can be achieved by adding the appropriate machine-tool configurations of each production process. The first criterion is the acquisition cost. Acquisition costs are all expenses incurred in the acquisition of an asset. In this case, the acquisition costs of machines and tool components are considered. The second criterion is the manufacturing cost. Manufacturing costs are costs incurred in the production of a product. These costs include fixed costs, such as depreciation of factory equipment (machinery), and variable costs, such as energy costs. The third criterion is productivity. Machine productivity is the measure of a machine's ability to convert raw materials into a useful product. Productivity is generally described as the ratio between the volume of production and the volume of inputs. The user selects each optimization criterion manually and chooses its degree of priority. An overview of the Feature Extractor assistant website is shown in Figure 12.

Configuration optimization

To find the best configuration solution from all listed configuration possibilities with respect to the three optimization criteria, a

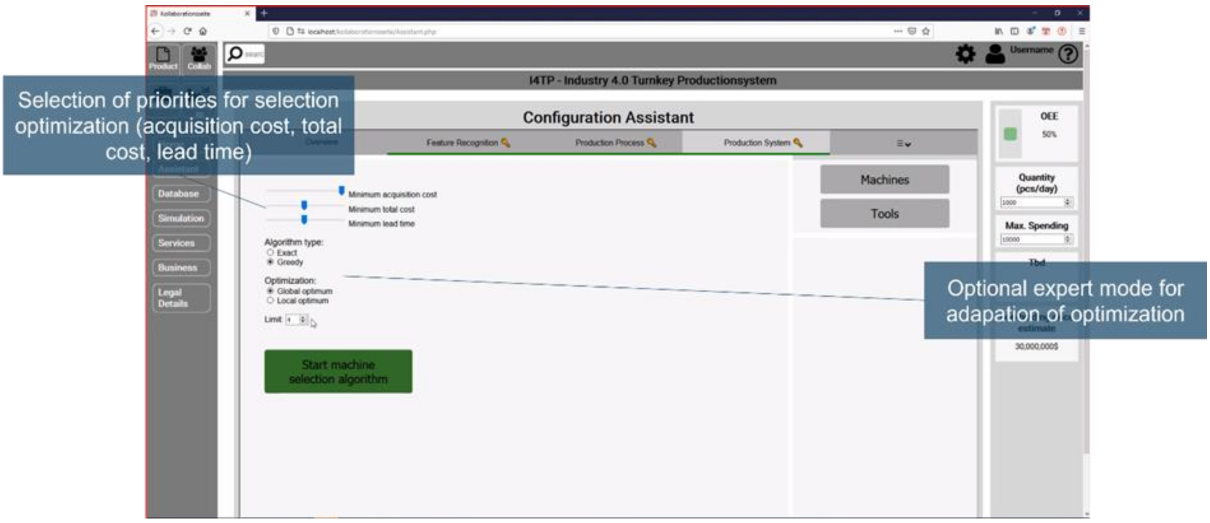


Figure 12 Configuration assistant for selecting optimization priorities and methods

combinatorial optimization problem arises. Since finding an optimal solution involves a

huge search space with a large number of possible configurations, this combinatorial optimization problem becomes NP-hard.

NP-hardness means that this problem is unlikely to be verified in polynomial time.

Two methods have been presented to find a solution to the combinatorial optimization problem. Both exact algorithms and greedy algorithms are selected for this task of generating optimized solutions. Exact algorithms are guaranteed to find the optimal solution to the problem. But the larger the problem, the more complex the solution space. This, in turn, can cause the exact algorithms to slow down. For this reason, heuristic methods such as the greedy algorithm are used to trade optimality for efficiency. They allow the problem to be solved by providing good solutions in polynomial time. Both methods have individual advantages and disadvantages that may be favorable in certain cases (Dumitrescu und Stützle 2003). Some of them are illustrated below in the table. After analyzing the characteristics of both methods, some evaluation criteria like efficiency and correctness can be generated that assess both algorithms accordingly.

	Greedy	**Exact**
Advantages	• Easy for implementation and solution finding • Fast, easier run time analysis, efficient	• Proven optimal solutions with successful algorithm • Access of the valuable information on bounds (upper/lower)
Disadvantages	• Does not always provide the globally optimized solutions	• Early program abortion due to the excessive memory consumption • Extension difficulty • Large development time needed
Evaluation Criteria	• Efficiency with regard to runtime • Proof of Correctness	

Exact algorithm solution

Several general solution methods are used for the exact solution of such difficult problems. Backtracking and Branch-and-Bound methods are the most important methods for the exact solution of mixed-integer optimization models. For this reason, an algorithm is developed for the first optimization concept involving both solution methods. Thus, the advantages of both methods combined could be utilized to calculate the exact solution in a time-saving manner. Bounding in the context of Backtracking is a very important technique because by deriving bounds for optimal solutions one can exclude many areas of the search tree from the beginning. For large models, this can avoid a critically large amount of potential search work (Mellouli und Suhl 2009).

Greedy algorithm solution

For the second concept, a heuristic approach is defined to find an optimal solution using the greedy algorithm. Greedy algorithms always decide in each step for the alternative that seems most promising at the current time. It has the advantage that it usually finds a solution very quickly in polynomial time, but a global optimum cannot be guaranteed. Therefore, an additional validation procedure is applied to compare the results of the greedy methods in order to identify their correctness for this approach. For the application of the greedy algorithm, the production processes are first divided into a predefined number of sections which can narrow down the search space accordingly. This allows a quick enumeration of the search space to find the optimal solution within a section. Then, the optimal solutions of each section are joined together for the final search which produces the result of the configuration optimization problem.

Visualization of configuration result

Based on the selection of optimization criteria and their degree of priority, the Turnkey Configurator will be able to automatically generate configuration solutions for the turnkey production system.

As a consequence, a list of possible production machines and corresponding tools is displayed on the platform that can be used to manufacture the given product (see Figure 13). Moreover, the user is able to find detailed property information in the machine and tool catalogues.

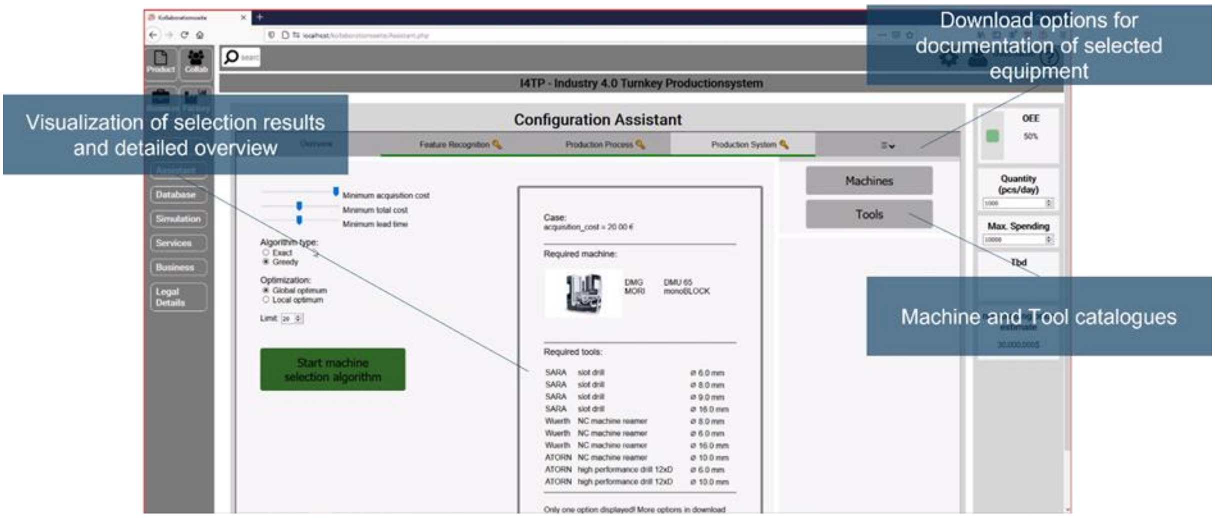


Figure 13 Visualization of the turnkey configuration results

5 Integration of Services

5.1 The I4TP platform architecture

To showcase the results of the different modules built in I4TP an extensible platform architecture was created, consisting of a prototypical web-based user interface in the form of a basic web framework, a MongoDB database server and the IoT platform connection to a MS Azure Cloud platform. The basic platform served as a common foundation for the Iterative integration of individual completed software modules within the platform architecture for demonstration and validation purposes.

Mockup View of the Factory automation platform

The platform prototype, as shown in Figure 14, serves as a dashboard providing access to all envisioned functionalities developed in the project I4TP. On the one hand it provides navigation through the main project modules of the platform process chain as well as access to generated services provided by the project partners. On the other hand, it also provides access to a basic user menu giving them access to their individual settings and roles according to their domain of expertise. Furthermore, the site provides input fields for general customer requirements and enables individualized configurations.

Once a production system configuration has been provided or automatically generated. The platform then also serves as a viewport and planning tool to view and customize the production system interactively. Once a satisfactory configuration setup is reached a customer then is able to order the individual platform components in a centrally orchestrated way. Once the hardware components

are integrated, they then can be connected through their I4TP self-descriptive modules to the platform and thus displaying the current status of the built-up factory – basically representing a bi-directionally connected digital twin of the production system.

General Process of Service Integration

To integrate all developed modules, the project partners collaborated concurrently by integrating their individual solutions for base functionalities using individual development branches or by using the APIs provided for and to external platforms. The individual development branches would then finally be merged on the main platform that is connected to the different IoT-Platforms for more advanced services like model-based simulations for robot dimensioning or advanced data processing and analytic tools (see Figure 15).

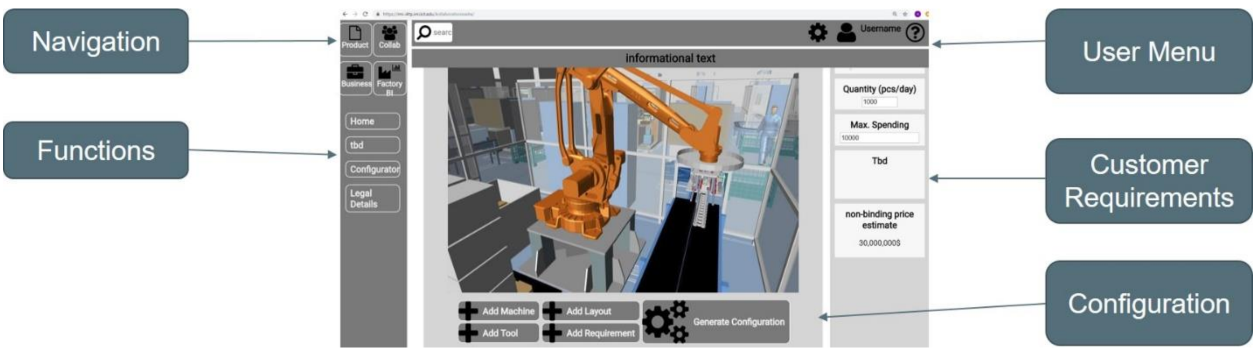


Figure 14 I4TP – Platform Prototype

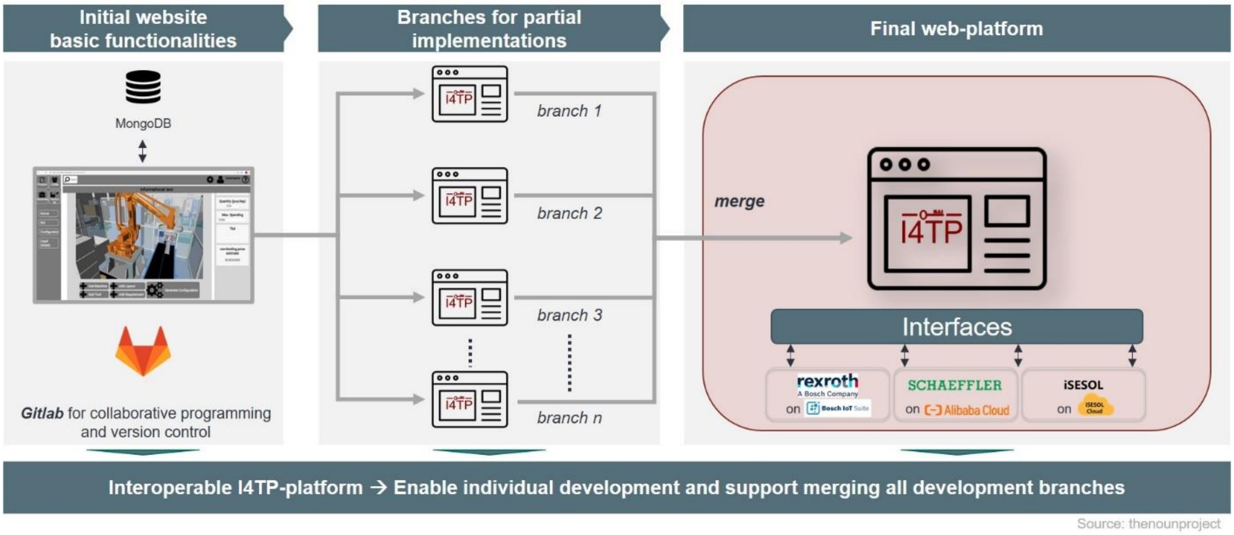


Figure 15 Factory automation platform Development Process

Integration of the Feature Extractor tool

For the feature recognition that was developed in i4.Design, an interactive process has been integrated on the platform that allows the customer to upload a CAD file in the format STEP. The file is then displayed to the customer in an interactive visualization window and allows for standard manipulation operations via the mouse, such as rotating, zooming and panning. The customer can then start the feature recognition process. On the right side of the viewport, recognized geometry features are then displayed to the customer. These can be selected and highlighted in the visualization window as shown in Figure 9, thus visualizing all obtained features by the feature recognition algorithm.

Integration of the Configuration Assistant

After the features of the product to build were successfully extracted, the next steps would be the analysis of the features and the mapping of each to a corresponding production process. To enable a user-friendly approach this was reached through an integrated tool – the configuration assistant, shown in Figure 16. The configuration assistant would guide a user through predefined steps along the I4TP process.

By enabling the user to set individualized product manufacturing information for each feature, as well as giving the user the option to select their preferred optimization criteria after the processes have been selected, the customer of the production system can interactively engage in the configuration process.

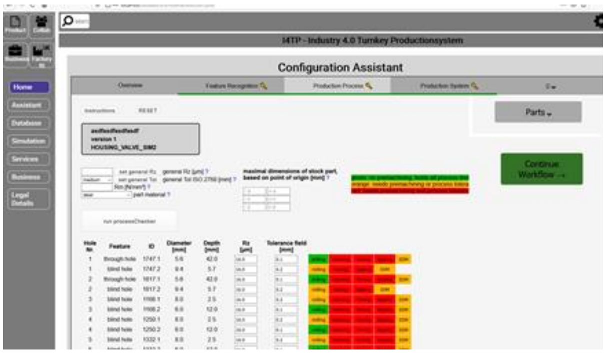


Figure 16 Configuration Assistant integration

Integration of the Platform Simulation

Once the optimal production system configuration is calculated the customer is then enabled to automatically generate a layout for his or her production system and view the production process for each generated configuration in a basic visual simulation as shown in Figure 17.

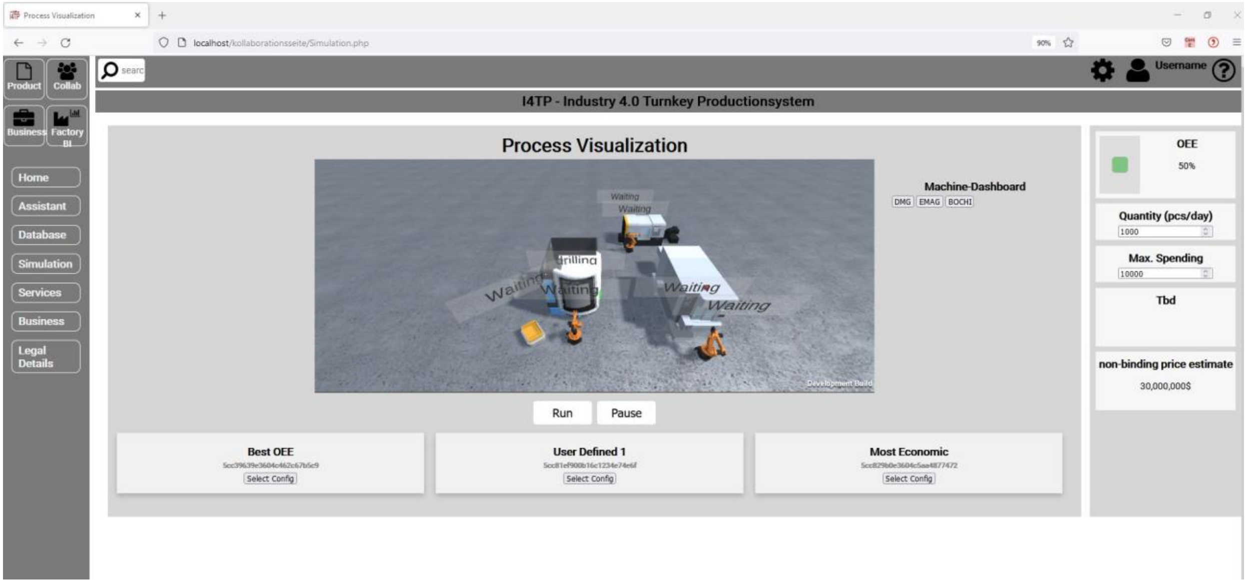


Figure 17 Simulation of the configuration

Integration of other Services using APIs

Further integrations included the bi-directional communication with the simulation tool Tecnomatix in regards to the Chinese located AMTC for layout optimization, scheduling and bottleneck analysis using machine learning methods. Another exemplary Integrations is the usage of an API to connect to a commercial IoT-Platform. The exemplary Interface would enable the user to initiate a simulation process with parameters provided by the I4TP-user. The simulation though runs on a separate Cloud Platform from Bosch Rexroth which in turn would provide the I4TP-user with the calculated simulation results, which would then be visually presented to the user as shown in Figure 18.

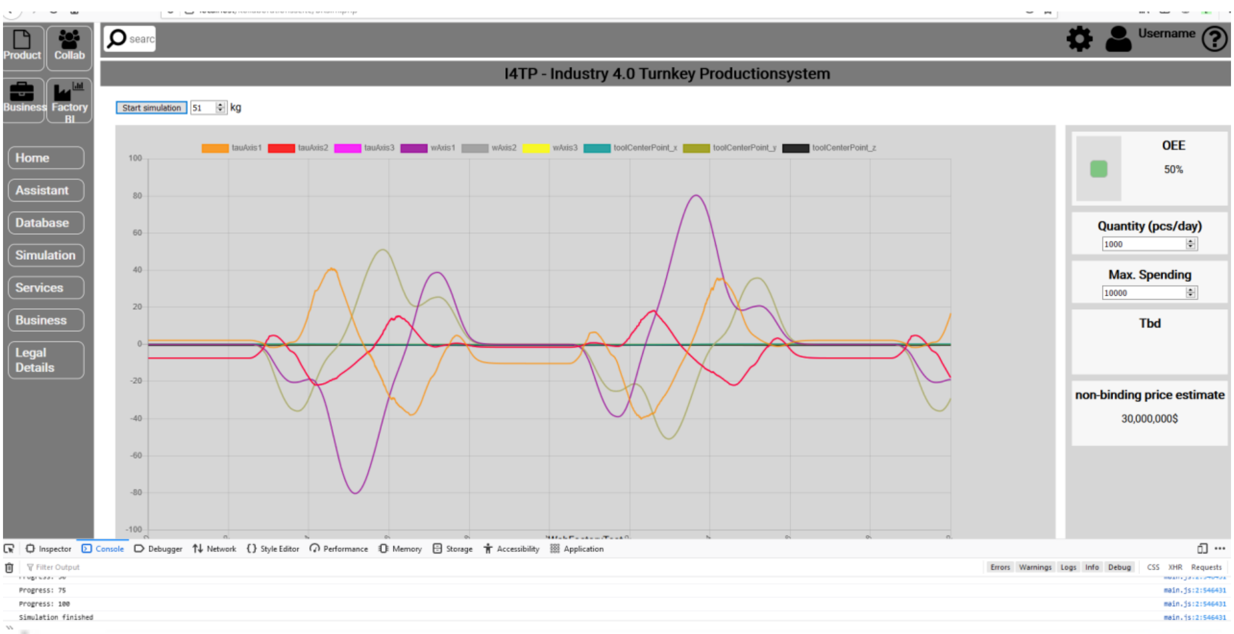


Figure 18 Exemplary Service provided by Azure Cloud of Bosch Rexroth via API

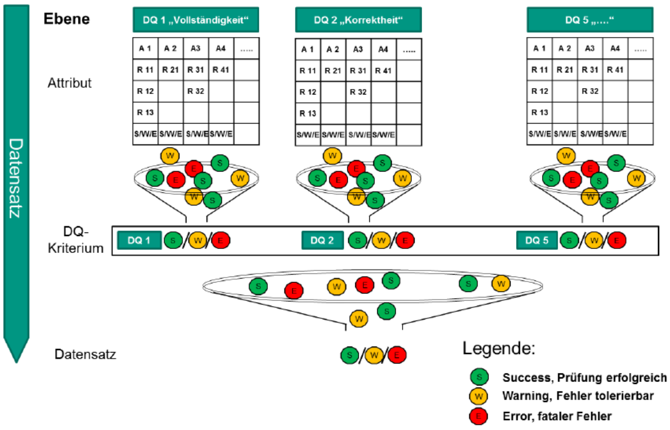


Figure 19 Data Quality Checking tool – Application structure

Integration of Databases

The database mongoDB was used to save all files with the I4TP standard format. Our research also shows that mongoDB provides scalable fast querying and excellent performance for advanced and quick searches on a large number of datapoints. Other tabular information were also integrated in separate MySQL databases. A machine- or tool-provider would then be able to upload their machines or tools in an interactive way using the GUI of the platform or be able to provide their data using a batch-file. In the correct file format.

Integration of Data Quality / Data Integrity Checking tool

Since there are interfaces to upload data and to integrate data from the user perspective, the platform needs to provide data quality check tool. For this purpose, a simplified theoretical data model for an analysis of product and machine data is established (see Figure 19). Rules and steps for checking data quality are then defined for this model, which serve as the basis for the rough structure of the application.

For each attribute of a data set or table to be checked, a three-dimensional array containing the checking rules for that attribute is created in the central class DQCheckSettings. Figure 20 shows the structural design of the array. The assignment is done in the program via a map with the corresponding attribute name as key value and the array as assigned value.

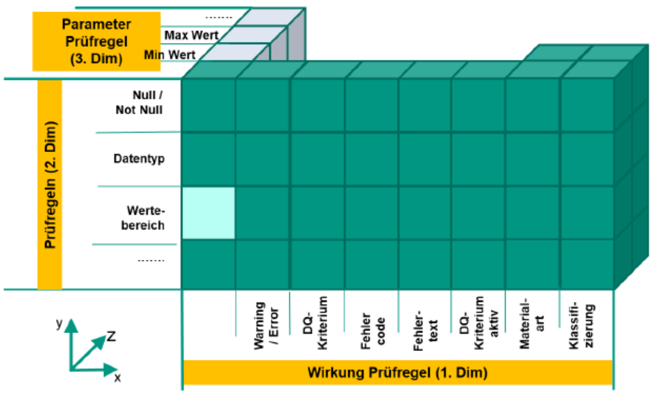


Figure 20 Data Quality Checking tool – Three-dimensional array with the test rules for an attribute

5.2 Platform services and methods

Impact and risk analysis

The created modeling language, methods and tool-implementations, enable further use cases based on information on the I4TP platform. In this understanding, a method to support an impact and risk analyses of engineering changes in the integrated development of product and production system is developed. The goal of the method is to support engineers in evaluating the impact and risk of design decisions or changes in product development by integratively regarding aspects of product and production system. The descriptions in this section will take the hydraulic valve as an example (see Figure 21).

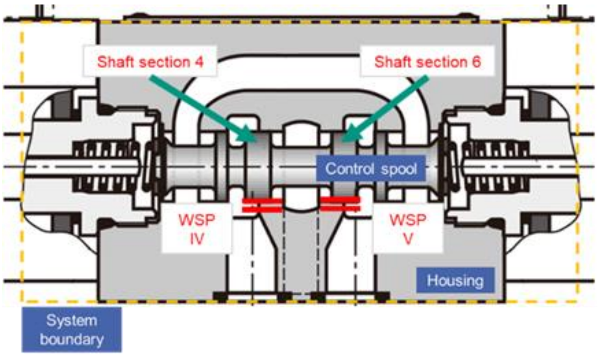


Figure 21 Section through the hydraulic valve, exemplarily displaying the parts “control spool” and “housing” as well as the features “shaft section 4/6” of the control spool

The method for impact and risk analysis is an extension of the method for modeling the interdependencies of product and production systems described in Chapter 2.2. In addition, the method is developed in the understanding of the model of PGE – Product Generation Engineering. The model of PGE describes the fundamental observation, that each new generation of a product is based on reference products. Furthermore, the development of the new product generation can be described by a combination of three types of variations, namely Carryover Variations (CV), Embodiment Variations (EV) and Principle Variations (PV) from the collection of references (Albers et al. 2015).

The assessment of risk in the method is based on two factors (cf. Stürmlinger et al. 2020; Albers et al. 2021):

- A calculated value for the impact of a variation of an existing element of the product or production system (e.g. function, production process etc.). This factor is referred to as the degree of change propagation D_C.
- A calculated value of the new development share of the varied element (share of CV and EV). The new development share is denoted as ∂_N.

The regarded elements for the methods are based on the developed modeling descriptions (see Chapter 2.2) and include system functions, system embodiment, production processes and production modules/machines (see also Figure 4). The (weighted) dependencies between those elements can either be modeled using matrix templates or the implementation in the SysML modeling environment (see Chapter 2.2)

In addition to direct dependencies, implied dependencies can be considered if e.g. a system function has dependencies to various system elements and their features, which in turn have dependencies to production processes etc. The degree of change propagation D_C can then be calculated as the (weighted) quotient of the number of all direct and indirect dependencies of an element and the number of all possible dependencies (cf. (Albers et al. 2021)).

Taking the example from Figure 4, there might for example be problems in the system concerning the function “seal and prevent leaks”. Thus, the function and its dependencies shall be investigated further. In Figure 4, we can see all direct and indirect dependencies of the function that have been modeled. Product features that, according to the modeled dependencies, have dependencies to the function are the shaft section 4 and 6 (see Figure 21).

Assuming that changes of constructive parameters (e.g. change of diameter, surface roughness etc.) of shaft section 4 should be undertaken in order to solve the problems with the function "seal and prevent leaks", the impact and risk of those changes can be assessed. To assess the impact of the changes, dependency trees, similar to the one displayed in Figure 4 can be automatically generated in the SysML modeling environment (see Figure 23). Therein both, aspects of the product and production system are taken into consideration. The dependency trees can then serve as a foundation to support the calculation of D_C.

The assessment of the new development share ∂_N can also be supported by the modeling approaches described in Chapter 2.2 Starting from the impacted feature shaft section 4, the variation types of the changes (CV, EV or PV) can also be modeled in the SysML environment. Therein, the modeling can start on a parameter level (diameter, length etc.) and the total shares of CV, EV and PV for the part and the system can thus be calculated consecutively. In order to always have the same set of parameters for the same type of standard-features, a library for standard feature types (e.g. shaft sections, through holes, blind holes etc.) was implemented in the SysML model.

The descriptions and parameters of the library elements are based on the ISO 10303. A similar library is created for production processes. After calculating D_C and ∂_N, the risk R_D of the changes in construction of shaft section 4 can be calculated as (see Albers et al. 2021):

$$R_D = \sqrt{(k_1 \partial_N)^2 + (k_2\, D_C)^2}$$

With k_1 and k_2 being weight factors ranging between 0 and 1. In addition, to compare the risks of different possible design decisions, the individual values for R_D can be displayed in a color-coded diagram.

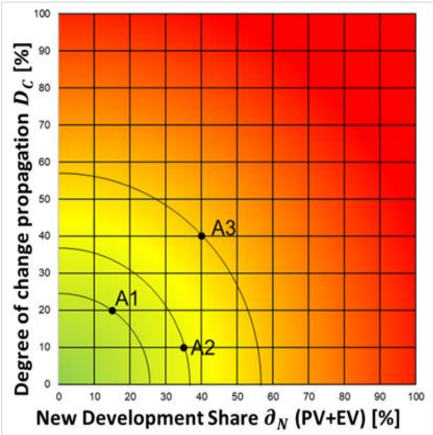


Figure 22 Diagram for the visualization and comparison of the calculated risk R_D for different design decisions/engineering changes (adapted from Albers et al. 2021)

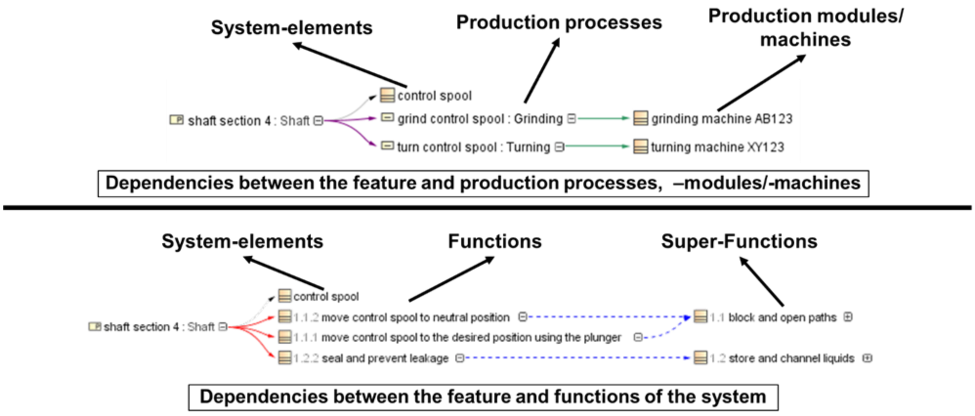


Figure 23 Analysis of the direct and implied dependencies from the feature shaft section 4

5.3 DTaaS – Digital Twin as a Service

In a traditional way, a simulation model has been used to develop or optimize new products mainly in an early stage of the engineering phase. Nowadays by using data from sensors and cloud-based computing technologies we are now able to create digital twins to use them in a wide range of applications. We can integrate this digital twin service (DTaaS) into other platforms and services to make real time analysis of current ongoing processes in the industry with the main aim to make forecast of the future behavior of the system or product.

The digital twin is gaining momentum due to increasing progress of new technologies in cloud computing infrastructures, new simulation tools and languages, better IoT interoperability and availability of machine-readable data. To strive this trend and to show the benefits of simulation based digital twins services, we developed the DTaaS solution to demonstrate how classic simulation models can be integrated into a cloud solution and how they can be incorporated into other platforms. Using the DTaaS in the organization will accelerate the usage of digital twins to help in optimizing processes as well as to make data-based decisions.

Figure 24 Delta robots

Simulation model delta robot

In order to test the maturity of the DTaaS approach on a real-life example, it was decided to build up a demonstrator. In doing so the Bosch Rexroth AG had the role of the classical machinery supplier by providing electrical drive and control components. Furthermore, Bosch Rexroth also provided the digital platform on which all services were hosted. The Chinese partner corresponds on the one side to the OEM, who builds the whole machinery and on the other site to the operator, who uses the demonstrator in his production lines. Hence, with this demonstrator, the completely engineering cycle from early design stages up to the operating phases are viewed and the DTaaS approach is tested. Together with the Chinese project partner it was decided to consider a delta robot as demonstrator. A delta robot is a 3-axis parallel kinematic. Figure 24 shows multiple delta robots within a packaging line. These robots have in comparison to classical sequential 6 axes robots the big advantage that only few masses must be moved, since the drives are fixed to the base plate. Hence, the payload ratio is advantageous compared to a sequential kinematic. Furthermore, they are mainly used in the packaging sector, which is an important key market for Bosch Rexroth. Since it is hard to conclude from the 3-dimensional movement of the tool center point (TCP) to the movement of each drive axis, the sizing of the drives is challenging and requires usually expert knowledge and a simulation of the multibody dynamics. Summing it up, the delta robot is a good showcase, since it has a distinct market relevance, the sizing is challenging, and it fits to the need of the Chinese project partner. Beneath the sizing further meaningful uses cases during the operation phases are possible, i.e. using the model for control applications or condition monitoring. So, the whole advantages of the DTaaS approach are exploited.

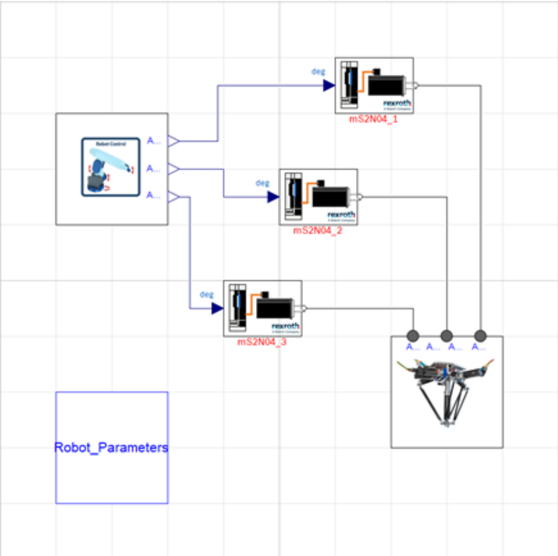


Figure 25 Simulation model of the delta robot

The used simulation model of the manipulator was built up using the Modelica modeling language within the simulation environment Dymola. Figure 25 shows the block diagram of the Modelica model. Beneath the actual modeling of the 3-dimensional kinematics of the delta robot, especially the integration of the robot control firmware and the databases of the drive parameters into the simulation model was very challenging. The robot control firmware is important, in order to have the same movement paths in simulation and reality, since the load of the drives results

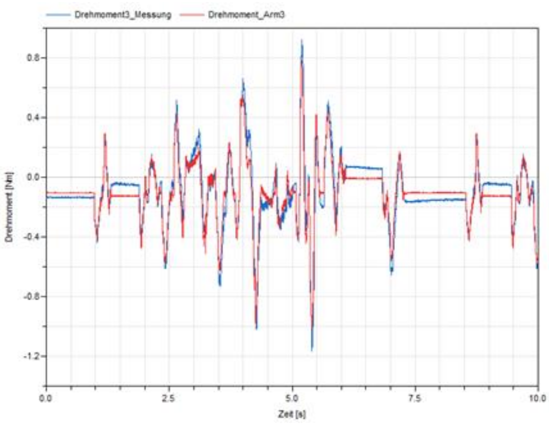


Figure 26 Measured and simulated torque

directly from the desired motion of the TCP. However, in the in the end it was even possible to export these features within an FMU. The simulation model of the delta robot was validated with an existing customer machine. The measured and computed torques of one axis are shown in Figure 26, yielding a good match. Hence, the adaption to the load data of the Chinese partner was meaningful. Subsequently the delta robot model was exported as Functional Mock-Up Unit (FMU) and uploaded to the Bosch Rexroth DTaaS suite. In collaboration with the Chinese project partner multiple simulation runs were conducted, in order to find the best possible combination of geometry, drive components and path parameters. The actual sizing was finalized by exporting the simulation results to the existing Rexroth sizing tool Indrasize. By doing so also the coupling to another software was demonstrated. Afterwards the drive components were hand over to the Chinese partner. In collaboration with the Tongji University the investigation of further use cases during the operation of the delta manipulator are planned. Overall, the functionality of the approach could be demonstrated with this example.

DTaaS Architecture and API in detail

One common challenging problem with simulation models is that they cannot run on every computing system due to missing requirements like high computing capability; licensing and further dependencies which are needed to execute simulation models.

To overcome this technical obstacle a microservice was built, so that data of Digital Twins are now accessible without worrying about the needed runtime environment. This service is a high scalable architecture, which is capable to compute many simulation models at the same time. It runs on a native cloud architecture in the Microsoft Azure Cloud environment solution.

The simulation service can be used by other microservices or end user applications without any knowledge about the underlying simulation technique or model runtime preconditions. New models with pre-defined runtime specifications can be uploaded to the service too. Afterwards the uploaded models are ready for use.

Main advantage is that a simulation model with his specific runtime pre-condition can now be used platform independent and without high computing power demand on the client side, since the heavy computing is done in the scalable framework of the developed microservice. The microservice was built as a webapi with a REST interface to create, start and stop a simulation. A signalR interface will push for updates and current simulation states.

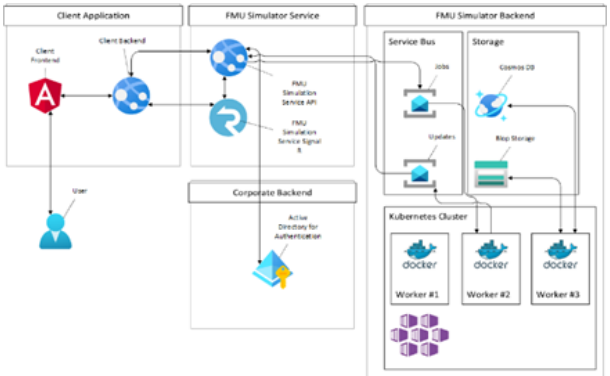


Figure 27 DTaaS architecture

The actual realized architecture is shown in Figure 27. The usage of a scalable Kubernetes cluster ensures the start of additional instances automatically for simulation computing if this will be necessary due to a high workload. Docker containers are a perfect environment to encapsulate the needed runtime environment of the simulation model. The message bus works as a load balancer, since all Docker containers with their specific runtime can consume the ticket for a requested simulation. If a specific runtime set is requested more than workers are available, than the system automatically starts new runtime instances.

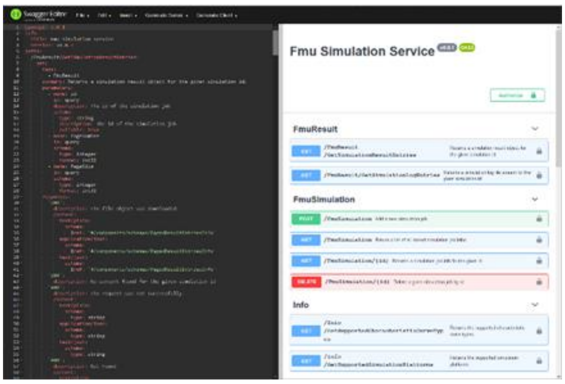


Figure 28 API documentation

For an easier use of the microservice an OpenAPI .json file is provided, so that a client can automatically be implemented to use the simulation service. Figure 28 shows a visualization of this file.

An angular web application which was implemented during this project phases, will show how the service works for features like upload new simulation models (FMU), parameterize and start a simulation. The parameters are read out of the simulation model and are auto-provided to the web application. The application can also receive the results of the simulation and plot them in an auto-generated graph. Figure 29 and Figure 30 show the application.

There is also the capability to show all simulations done on a specific simulation model - even those of other connected services. The previously mentioned model of the delta-robot is available as a simulation model in the microservice as well as available to all connected applications.

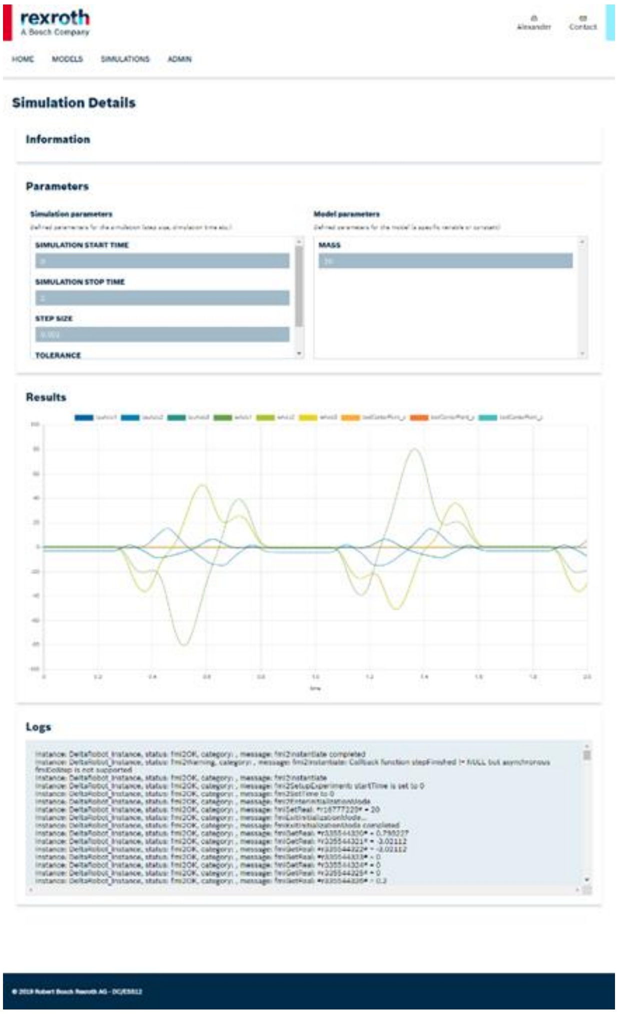


Figure 29 Web frontend using the simulation service – simulation results

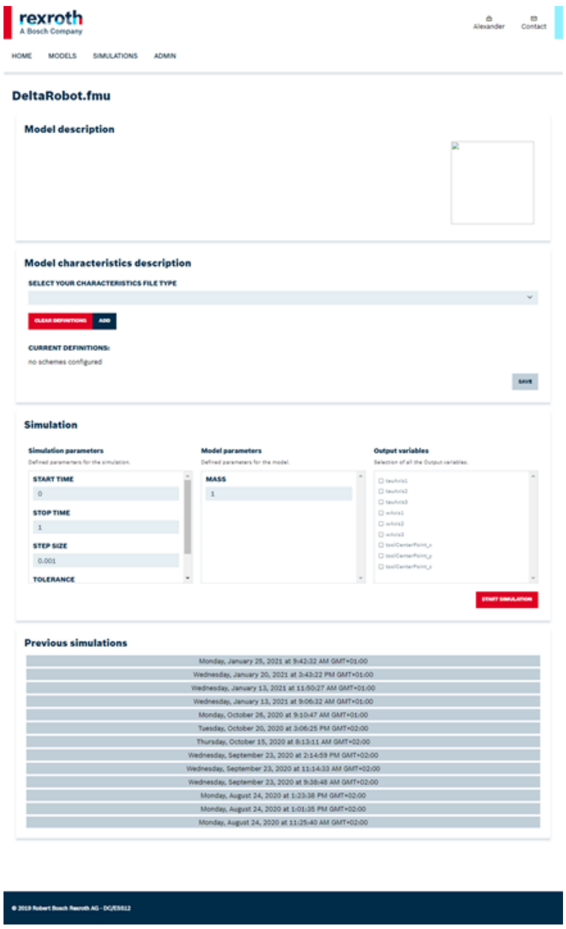


Figure 30 Web frontend using the simulation service – simulation overview

5.4 Automated Gripper Selection

The overall goal of the SCHUNK Innovation Center is to develop novel applications and solutions for our customers in the context of autonomous intelligent grasping. Our contribution to the I4TP project was focused on novel tools that automatically selects the best available gripper for a given handling problem using a simulation framework and artificial intelligence as its building blocks.

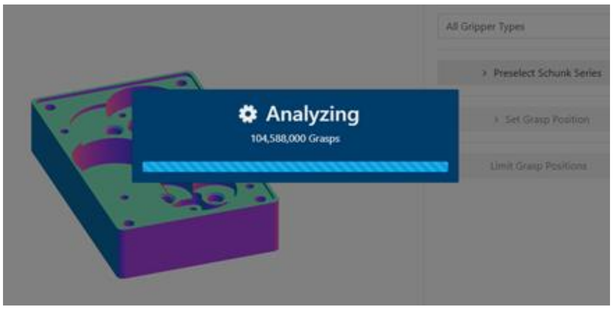


Figure 31 Screenshot of the gripper selection simulation

The path towards an optimal grasping system

There is always a time-consuming step in the planning and setup of handling cells: the selection of the best available end-of-arm tool and its integration. The idea we are following is simple.

Instead of determining the ideal gripper based on the stroke, force and finger design, we use a simulator to determine the best fit between the workpiece and the handling task. The challenge is how to provide a simulation tool that is able to quickly determine the best available gripper for a given work piece.

A gripper selection tool that provides recommendation for the best available gripping tool needs to be trained with a very large number of successful (and unsuccessful) grasps. So instead of using real objects and manipulators, we us a simulator cope with the immense training efforts that are required for well trained and experienced system. Using a simulator basically allows us to scale the training with the number of allocated CPUs in a simulation environment. Of course, we use a specifically suitable physical engine to replicate the real-world scenario in the best possible way.

There are two options to realize such a system. (i) We run simulations with every

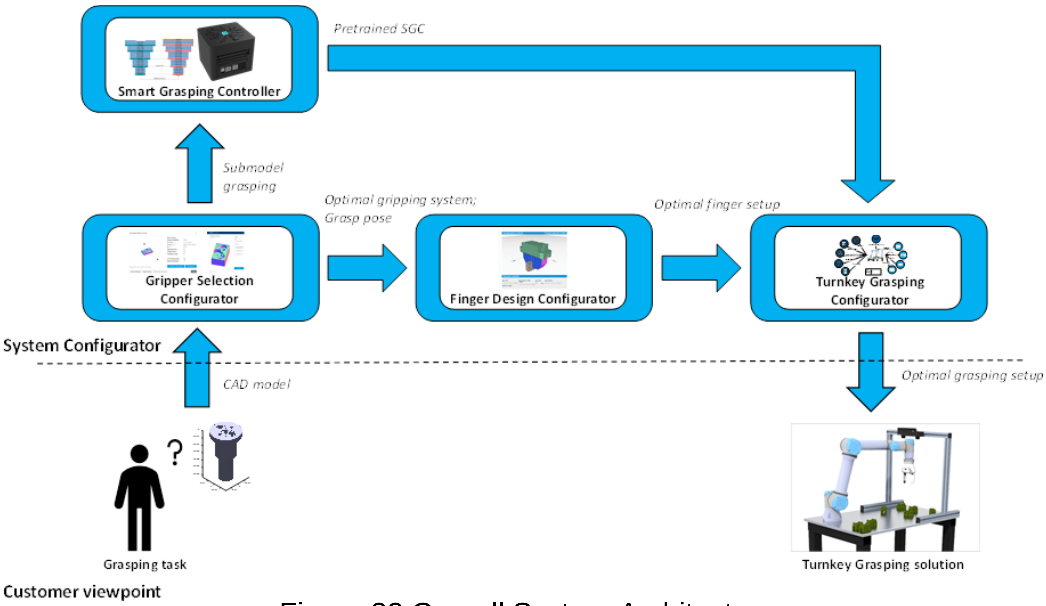


Figure 32 Overall System Architecture

customer in his exact scenario to assess which gripper works best. However, such a system does not scale in computing resources that are necessary to perform such simulation for each customer and every application. (ii) Instead, we use this simulation environment to learn the behavior of grippers, grasps and objects. In other words, we build a huge grasp database with a huge variety of objects and grippers.

In the next step, we use classic machine learning tools to model the expected grasp behavior. Specifically, we use the grasp database to train a CNN. Once the system is trained with the variety of objects and grippers, we then can apply the model with new customers.

When a new customer wants to use the gripper selection mechanism, all he/she has to do is to upload a new object to our system. The training process uses the simulation environment to test all possible combinations of grippers and object databases with the relevant grasps such that we provide a success probability for every object-gripper combination. So, the selection tool provides the list of possible grippers together with a grasp success probability.

Indeed, the gripper selection toll will not only provide a gripper recommendation, the system provides also the most successful grasp pose to the customer.

In Figure 31, we describe how the overall system architecture looks like and how the gripper selection system is integrated in the global digital service strategy. After the initial analysis of the workpiece, two work streams are started. In one work stream, the result of the gripper selection system is providing the information about the workpiece to the SCHUNK smart grasping controller. The smart grasping controller will then send the pretrained model to the Turnkey Grasping Controller for execution of the grasp in the target automation cell.

The second work stream consists in the design of the finger for the given object. The eGrip also uses the output from the gripper selection system – in that case, also the CAD model of the object – and uses this model to compute the optimal finger model. SCHUNK proposes to use additive manufacturing to produce the fingers for the specific work piece.

The combination of the two steams end in the Turnkey Grasping Configurator where the determined grasp will be executed with the manufactured gripper fingers in the target application cell.

Overall, we demonstrated in this project a possible future workflow for automation cell providers or system integrators in general. Instead of a manual planning and programming of the automation cell, the customer will be able to use a turnkey solution that will:

- Determine the best gripper for a given workpiece
- Provide the optimal gripper fingers automatically
- Gripper fingers will be produced using additive manufacturing
- Grasp poses are determined by the smart grasping controller
- Grasp execution is orchestrated by the grasp controller in the turnkey grasping configurator.

The components and solutions provided in this context illustrated well the power and opportunities given by I4.0 technologies. Alongside to the grasp planer, the gripper selection algorithm and the grasp planer offer interfaces for other component and solution provides to interface and integrate in existing control and IIoT solutions, as for example the IoT Suite from Bosch or other solutions running on cloud infrastructure like the iSESOL Cloud.

5.5 SpindleSense and Smart Controller

As an active member of the "I4TP" project funded by the BMBF, Schaeffler was able to contribute the so-called "Schaeffler SpindleSense" to the project. To prevent overloads and thus protect the spindle bearings from bearing damage, Schaeffler developed SpindleSense. This serves to monitor the spindle bearings in a main spindle. Through the combination with the "Smart Controller", a control unit also developed in the "I4TP" project, which is used to collect data and communicate with the machine control system, SpindleSense is integrated into the machine environment. In cooperation with the project partners Schaeffler enabled to transfer the product development methodology to product system development, which was essentially the core task for Schaeffler in this project.

The Smart Controller

The concept of the "Smart Controller" is a control unit that is attached to a machine in addition to the machine control. The control unit enables additional sensors to be attached to the machine and is used to evaluate the recorded data and to make it available for MES or cloud services. Furthermore, the control unit should communicate with the actual machine control to receive status data or to give control signals. On one hand, the control unit should be able to perform both time-critical monitoring functions, such as the detection of incorrect operating states with subsequent sending of a shutdown signal.

On the other hand, it should make dynamically variable, non-critical tasks, such as the execution of predictive maintenance algorithms possible.

Such a unit was developed by using the hypervisor Jailhouse on the Lemaker Banana Pi M1 single-board computer. This enables the parallel operation of Linux as a general-purpose operating system (GPOS) and FreeRTOS as a real-time operating system (RTOS).

The SpindleSense at Schaeffler

During the project, the developed Smart Controller was used to integrate a SCHAEFFLER SpindleSense sensor into an existing machine tool. It realizes the integration of the CAN bus protocol conversion, data filtering and data aggregation between the sensor and a Siemens Edge unit. Necessary software components for communication with the sensor and for data preprocessing were developed and tested during integration on machines at KIT-wbk and at Siemens. This enabled the application to be tested in industrial use cases. In addition, the achievable reaction latencies of time-critical monitoring functions were evaluated with the help of a measurement module developed in 2019.

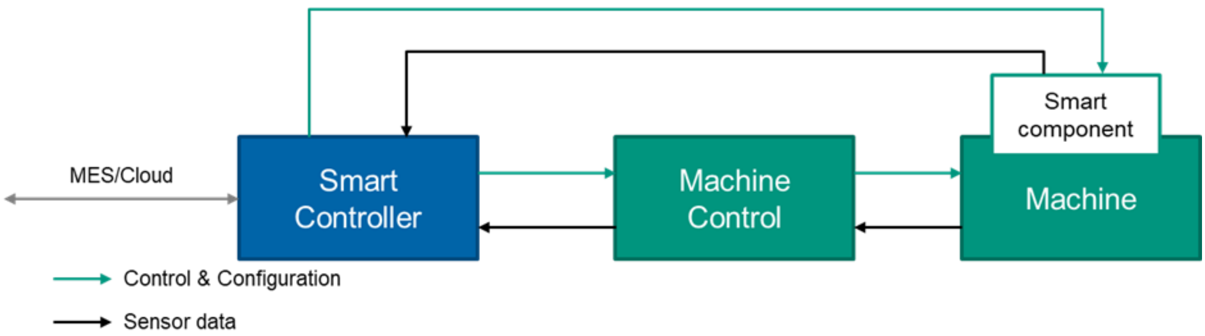


Figure 33 The „Smart Controller“ as a control unit for the acquisition of data from Smart Components and for communication with the machine control system.

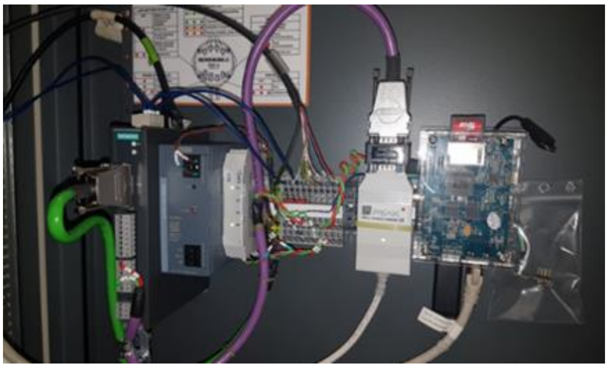


Figure 34 Use of the Smart Controller to integrate a Schaeffler SpindleSense sensor

Schaeffler has taken this approach retrospectively as of September 2020, after the installation of the SpindleSense sensor at the KIT-WBK (machine DMC60H). During this, concepts were developed for evaluating the measurement data on a Siemens Edge Device and for visualization in a cloud. Therefore, the design of the technical feasibility and the possible applications were discussed using the data provided by Schaeffler SpindleSense up to 1000Hz sample ratio. The project scope doesn't cover production ready implementation of data handling in the cloud. In this case solution based on third-party services is preferable.

Schaeffler itself has been working on ways to visualize high frequent data since September 2020. Therefore, it was very important from the beginning to have a flexible architecture because such signals are difficult to transfer into the cloud in real time. In this case data reduction near to the measured object must be performed (edge processing). At the same time, it is important to have initial raw signals for further analyses that can be done later offline. For this reason, a machine with the integrated SpindleSense sensor was set up during an internal project and the visualization was created on a Schaeffler Azure cloud.

The data from the DMC60H machine, which includes the SpindleSense technology, placed at the KIT-WBK could also be visualized in the cloud environment. The solution architecture below (Figure 37) was implemented based on the internally installed machine. There are two data streams from edge to cloud: real-time data and historic data. For the former, data is first reduced on the edge and then sent to the cloud in close to real-time, where this data is stored and visualized via web browser (on desktop or on mobile devices). The latter is stored on the edge in tdms format (NI format for measurement data) and then periodically – for example one time per hour – uploaded into the cloud. This data can be downloaded later to the local computer and it can be analyzed in detail in traditional software for signal processing, such as Diadem, Famos, and MATLAB. This architecture also enables data from outside the Schaeffler infrastructure to be connected to the Schaeffler Cloud, specifically from the machine at the KIT-wbk. The data is collected locally in Karlsruhe and then sent directly to the Schaeffler Azure Cloud where it is stored and visualized in real time. Figure 37 shows the setup of the test environment in a Schaeffler plant and shows the external data input via “IOT Hub KIT”. All visualization then runs via web services.

The focus of the project was on one hand the observation of the data during the machining process, on the other hand the offline analysis. The following Microsoft Azure Services were used:

- *Time series insights*: responsible for real time data storage and for the data visualization.
- *Storage Account*: provides storage for binary data saved in tdms Format and for real time data.
- *Azure function*: performs data processing in the clouds.
- *Eventhub*: responsible for communication between edge and cloud.
- *ServiceBus*: responsible for communication in the clouds.

Figure 35 PowerBI-Report X-, Y-, Z-axes mean values over time

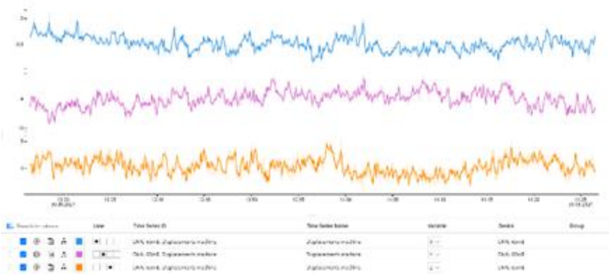
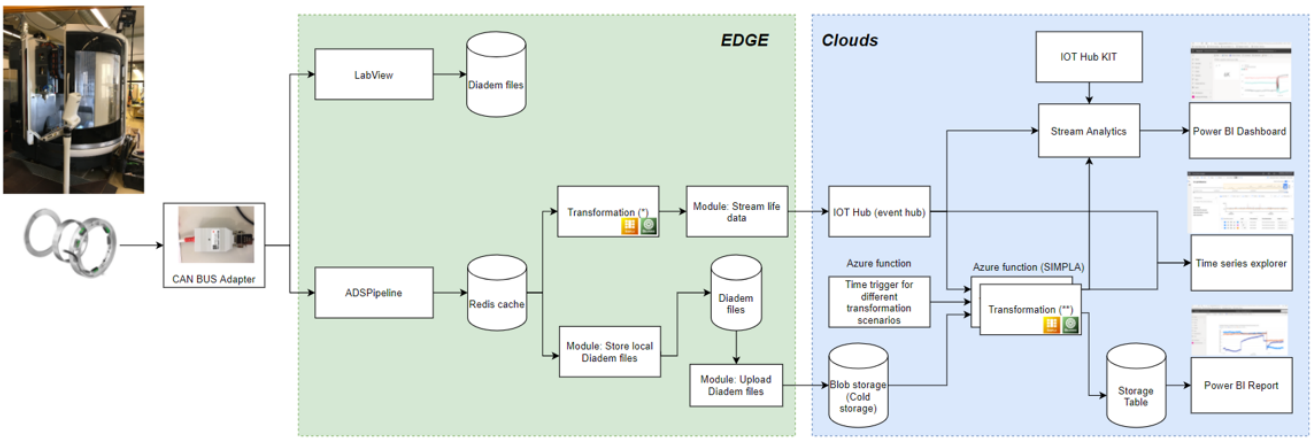


Figure 36 Azure Time Series Explorer X-Y-Z Axes in machine coordinates over time view

Three visualization options were generated. Firstly, the dashboard which displays real time data with a reduced data rate. Secondly, the offline analysis or data acquisition over longer periods of time and thirdly, offline reports on data sets with full bandwidth. The visualization itself was implemented via the Microsoft cloud services for simplicity. In addition to the live dashboard in Power BI, various reports were created in Power BI and Azure Time Series Explorer. A sample report regarding the X-, Y-, Z-axis displacement data is presented in Figure 35.

Here the displacement is shown over a short period of time. The data can be displayed directly from the cloud via a web service so access is available from any device in the company network.

Figure 36 illustrates the shift over a period of several hours, where the data was not presented at full bandwidth. That shows the difference to the application in the report and it was generated with the Azure time series application which allows to zoom into the data.



(*) Transformation block on the Edge can perform common for data processing operations like Average, RMS, Peak to peak, FFT ... + Calculations with Bearinx models + machine learning (Linear regression, gradient boosting (derivation from decision trees), neural networks)

(**) Transformation block in Clouds can do the same things as transformation block on the Edge, but in Clouds calculation power of such block can be automatically scaled, according calculation task

Figure 37 Solution Architecture – Schaeffler Azure Cloud

6 Integration of Smart Components

Increasing demands for workpiece quality and productivity lead to the need for process monitoring, predictive maintenance, and process optimization. Such methods can help enhance the efficiency of the production system by preventing downtime, early detection of defects during processing, and optimizing process parameters. While all these approaches rely on sensor data, they differ significantly in their reaction latency requirements. Predictive maintenance and process optimization are mainly characterized by long-term monitoring of sensor data and high processing complexity. In contrast, process monitoring often requires low reaction time to changes in the sensor data at lower processing complexity, e.g. to prevent damage to the workpiece or the machine.

When integrating such functionality in a production system, additional sensors often need to be integrated with the machine (forming smart components) and interfaced with the machine control and the plant network. This can be challenging, since software or hardware interfaces may not be available, especially when existing machines and machine controls shall be included in the planned turnkey production system (brownfield scenario).

Smart Controller

In I4TP, a smart controller architecture was developed to allow for the integration of sensors in turn-key production systems where interfaces need to be adapted or the processing capability is not available. The architecture is intended to support both process monitoring tasks and predictive maintenance tasks. The former requires low-latency communication to the machine control in order to influence the production process while the latter mandates a connection to edge units or cloud services for long-term data storage and profits from a rich development and runtime environment. These interfaces are depicted in Figure 38.

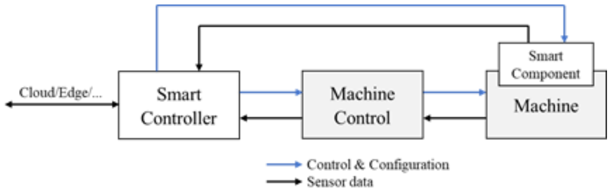


Figure 38 Smart Controller Interfaces

Hypervisor-based Architecture

To allow for both low-latency data processing and simplified development and deployment of non-latency-critical applications, a hypervisor-based architecture is used. It allows for the parallel execution of a real-time operating system (RTOS) and a full-featured Linux operating system (OS) in parallel, running in separate partitions. The hypervisor ensures isolation between the partitions, i.e. it controls access to system resources such as memory or peripherals, including communication interfaces.

In Figure 39, the hypervisor-based architecture is shown in an exemplary case where a CAN-based sensor needs to be interfaced. The real-time partition is used for sensor interaction. Process monitoring applications are realized as RTOS tasks and can directly communicate to the sensor using the communication peripherals. This enables low-latency processing, since the overhead introduced by typical general-purpose OS functionality is avoided. After processing in the RTOS partition, the sensor data is transferred to the Linux partition, where it can

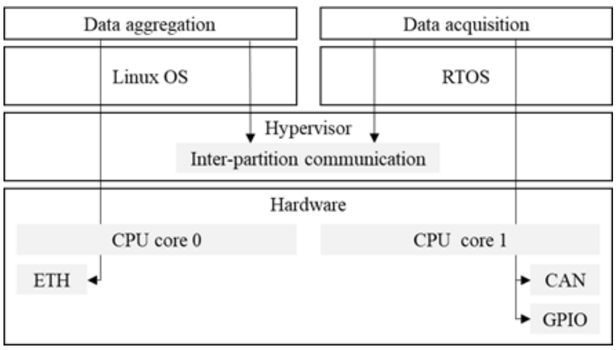


Figure 39 Smart Controller Architecture

be processed further, e.g. for data aggregation, filtering, and forwarding to cloud services.

Protocol Conversion for Spindle Monitoring

In the project, the smart controller concept was realized on the commercial off-the-shelf single-board computer LeMaker Banana Pi M1. It was then used to integrate a Schaeffler spindle monitoring sensor in a machining center for predictive maintenance and process monitoring. The sensor provides spindle position information via CAN bus, which cannot directly be connected to the Siemens edge unit used with the machine. Based on the smart controller setup, an RTOS application is used to parse the relevant sensor information from incoming CAN messages. The data is then passed on to a Linux application, which aggregates and further filters the data based on a configuration provided the edge unit. It then provides the data via Ethernet to the edge unit. In a second configuration, the sensor data is transferred to a Microsoft Azure cloud service for long-term storage and visualization.

Evaluation

To determine the achievable reaction latency of the smart controller setup in a more generic way, latency measurements were conducted using both simulated sensors CAN messages and generic digital I/O signals. An RTOS application was implemented which checks incoming sensor data for an overload condition and indicates them by setting a digital stop signal for the machine control. In this scenario, the smart controller exhibited mean reaction latencies of 130 us while the latency of a standard Linux implementation was significantly higher (12 ms). By evaluating different implementation alternatives of the RTOS and Linux applications, it could be seen that RTOS implementations allow for faster reaction times when compared to Linux user space implementations, while Linux kernel implementations may lead to comparable latencies. However, Linux kernel implementations may break isolation requirements between low-latency and other applications, which can be enforced by the hypervisor. The full evaluation was published in (Schade et al. 2021).

Reconfigurability

In the context of a reconfigurable production system, the software running on the smart controller needs to be reconfigurable as well to adapt to changes in the production system, such as different products or different tools. For Linux, software management tools are widely available since tools for regular Linux PC software management can be used. For managing the RTOS partition, an OPC-UA server application prototype was developed which allows for managing the hypervisor used in the smart controller setup. It allows for the creation and destruction of hypervisor partitions and for updating software running as hypervisor guest, such as the RTOS software. Alternatively, RTOS software updates can be achieved from the Linux partition, by running a hypervisor control software from the Linux shell.

Sensor Integration with Cloud Infrastructure

As described in Chapter 5.5, for complex data processing and long-term storage, local edge processing is not sufficient. In this case, such functionality can be realized in cloud systems. Therefore, sensor data acquired in the production systems needs to be forwarded to cloud infrastructure. Here, it is very important to have a flexible architecture. The architecture should allow for fast system reconfiguration and adaptation to the current production system status. Additionally, high-data-rate signals need to be sampled and processed. Such signals are difficult to transfer into the cloud in real-time. Therefore, data reduction near the measured object has to be performed. At the same time, it is important to have initial raw signals for further analyses that can be done offline later. To achieve all those aspects mentioned above, a solution was designed comprising the following main aspects:

Two data streams from edge to the cloud were realized: a real-time data stream and a historic data stream. The real-time data is reduced/aggregated on an edge unit and then sent to the cloud in close to real time, where it is stored and visualized in a web-browser-based dashboard. Thereby, the live machine state can be monitored in on desktop or mobile devices. Historic data is stored on the edge unit in NI-TDMS format and then periodically uploaded to the cloud service. This data can be downloaded later for detailed analysis in traditional signal processing software.

To provide simple access to sensor data visualization, the data visualization is accessible via web browser. The visualization focuses on data exploration by allowing for combined plots of different channels, zooming into the data etc.

The solution was realized for the visualization of SCHAEFFLER SpindleSense sensor data (see Figure 37). An edge unit was used to transfer real-time data to a Microsoft Azure cloud setup, where it is processed by multiple services. Data arriving from the edge is received by an Event Hub component. For real time data storage and for the data visualization “Time series insights” was used. The service “Storage Account” provides storage for binary data which was saved in tdms format and to save real time data. The data processing itself was performed in the cloud by the Azure function. In order to communicate between the edge device and the cloud the function “Eventhub” was implemented, where the “ServiceBus” was responsible for the communication in the cloud.

All those Services was organized in a dedicated resource group to simplify control over the cloud service costs.

7 Business Models

A business model plays a vital role in the success of any company, as it explains how that business will create, capture and propose value. The globalization of the manufacturing industry and the volatility of the markets require manufacturing companies to be more innovative and competitive in designing business models. The I4TP –Sino-German Industry 4.0 Automation Factory aims to offer turnkey production systems, in which „i4.Business“ in terms of the digital business model has been developed for successfully progressing individualization of products and services.

The objective of i4.Business is the development of a system and a configurator, which enable fast and precise quotation generation on the one hand and the selection of the appropriate business model on the other hand. In addition, the methods and procedures should be developed for new service aspects such as collection of load and performance data from machines and systems.

In order to achieve the objective, there are two leading questions:

• How can turnkey production systems be implemented, operated, optimized and evaluated?

• Which business model is adapted to the product and the customer?

Therefore, a systematic approach for individualized configuration of digital business model has been developed.

The developed approach consists of four parts, respectively, methodology for the targeted recording of market requirements, systematics for configuring different digital business models, systematics for evaluating different business models and creation of an IT tool for selection of business models.

Analysis of the Target Market

By market research the five phases model has been developed which contains: Goal, Plan, Do, Analysis and Result (GPDAR) (see Figure 40). The first phase is the **Goal** definition for setting up a market research. The design questionnaire of the market research is determined in the **Plan**. In the third phase, the Do, the questionnaire is distributed and collected. The data analysis for gathering useful information is completed in the **Analysis**. In conclusion, all findings are summarized in the fifth and last phase the **Result**.

As one of key processes, a GPEST+PF model has been further developed for design of questionnaire, which includes **g**eneral, **p**olitical, **e**conomic, **s**ocial and **t**echnological aspects on the one hand, on the other hand, this new model considers not only current status of the market (**p**resent), but also looks at **f**uture with development perspective. Several important insights have been discovered. For instance, large enterprises

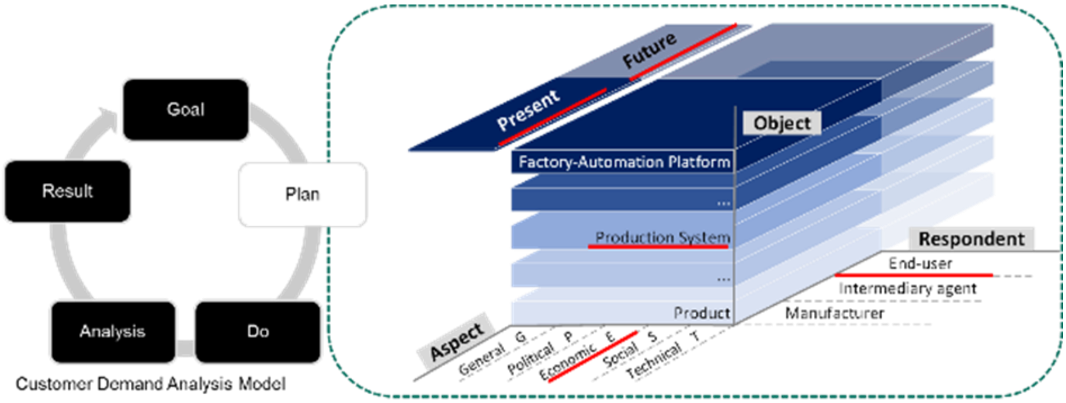


Figure 40 Goal, Plan, Do, Analysis and Result (GPDAR)

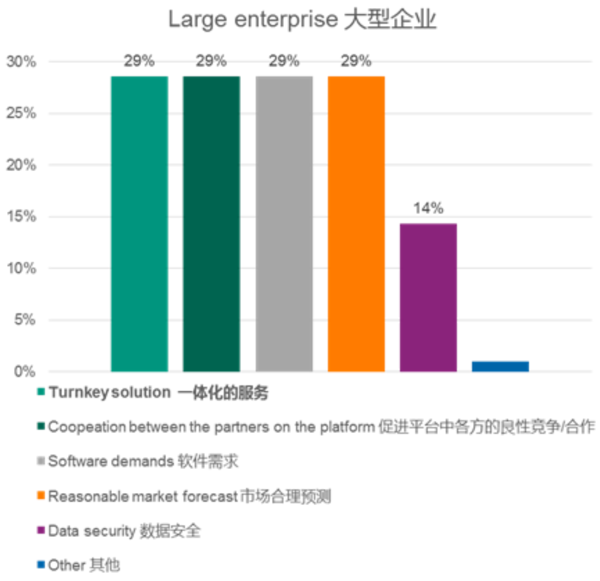


Figure 41 Demands of large enterprises within I4TP

are seeking for benign competition and partnership through the turnkey platform (see Figure 41).

Reversely, small- and medium-sized enterprises (SMEs) seek to reduce the R&D workload and improve the quality for designing production systems. (see Figure 42)

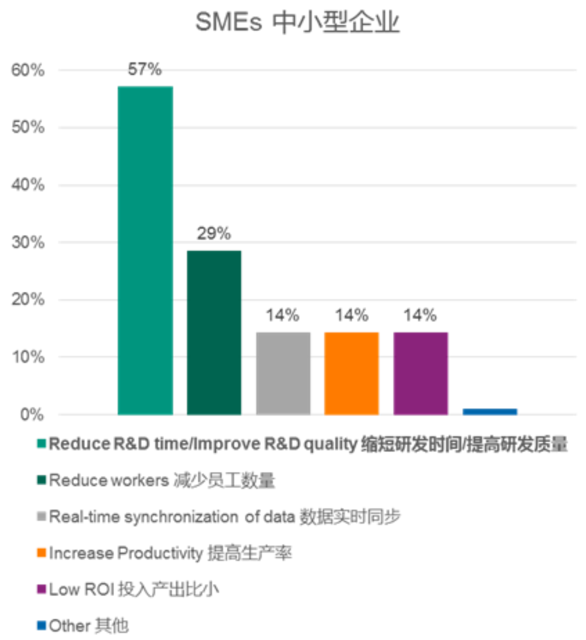


Figure 42 Demands of SMEs within I4TP

Configuration of Digital Business Model

Based on the previous analysis of the literature and the target market, a Digital Business Model (DBM) Configurator was developed with the use of a Business Model Pattern Pool. This business model configurator allows users to generate different business model ideas. According to the selected business model idea, part of the business model canvas elements can be defined, uncertain business model building blocks remain blank.

The design phase is to develop the rest unset business model elements. Firstly, customers need to provide their expectations of the business model, including budget and benefits preferences. The platform offers alternative options and recommendations of business model elements for customers, which in a way assures feasibility. The highlight of this framework is that customers have the flexibility to choose what exact options they want for their own business transactions.

Evaluation of Digital Business Models

Among the popular evaluation criteria, the consistency and profitability of Digital Business Models have been assessed. Consistency of a business model includes internal and external consistency. Internal consistency is about the harmonious design of the four dimensions: who-what-how-value. At the external consistency level, a detailed comparison between the environment analysis result and the new business model alternatives have been conducted. Meanwhile, an expert group should be formed to review all the alternatives and dig out the existing inconsistencies. The diversity of the expert group can decrease the risk of misjudgment.

To calculate the profitable business model, an utility analysis has been carried out. Each benefit will get a weight according to the importance or priority for customer. The score of every business model alternative in each aspect will be given based on the significance of the achievements. The comparison standards should be the same while evaluating different alternatives in the same aspect. For different aspects, the effects have been leveled through the weights.

For further precise assessment, the multiple criteria decesion making approaches have been analysed such as AHP, TOPSIS, VIKOR, which helps for selecting the proper DBM according to specific request.

Integration on the I4TP Platform

To realize an IT tool of creating DBM, a novel DBM innovation procedure have been developed, which has been integrated on the I4TP platform (in Fig. 4).

At first, DBM Development Roadmap is conducted to generate several suitable primary DBMs for specific scenarios. Based on these DBMs and existing DBMs from literatures, a DBM Pattern Pool is built to storage these feasible DBMs. Through a meta-model based DBM descriptive method, named Meta-digital business model (MDBM), attributes of a DBM can be extracted and be matched with inputs of customers' requirements by DBM Matching Mechanism. Afterwards, several alternatives are evaluated through a DBM Evaluation Approach in terms of 2nd inputs from customers.

Finally, a customized DBM is generated. After conducting the entire procedure, the modified DBM can still be restored into the DBM Pattern Pool, which builds a closed loop of iterations.

Summary

A business model is critical for any company. There is no exception in the Industry 4.0 era as well. Digitalization is transforming the entire product engineering process as well as customer demands. It changes the way markets are reacting, products are designed, produced and delivered as well as how services are provided. Business models have to keep in trend and be innovate to capture new value for companies and society. I4.Business provided a useful and innovative solution to develop a well-suited Digital Business Model for the Automation Factory Platform, which helps to boost Industry 4.0 and eliminates barriers for industry enterprises' way towards a digital transformation. Looking into the future, the advanced technologies such as block chain, big data and artificial intelligence provide huge possibilities, which will change how companies will operate in the future. These changes will also affect related business models.

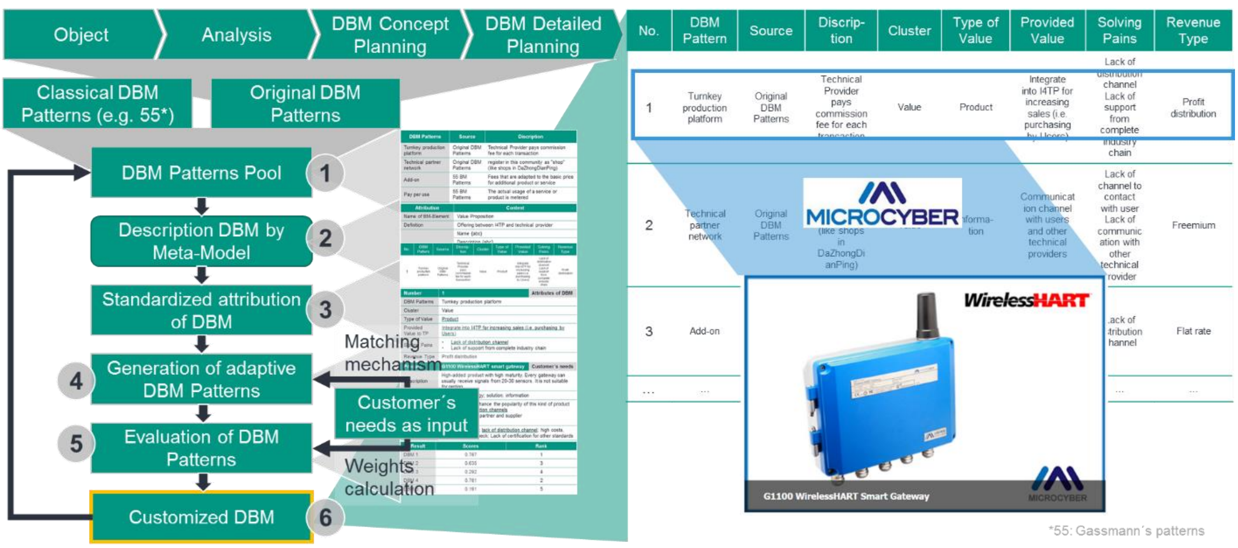


Figure 43 Steps to create the IT tool for DBM selection

8 Summary

Figure 44 3rd project milestone meeting at the Advanced Manufacturing Technology Center (amtc) at Tongji University in November 2019

The objective of the research project I4TP was to develop a software-supported, model-based, German-Chinese factory automation platform for the fast and simple design and commissioning of turnkey production systems with integrated product consulting. For this purpose, the eight binational consortium partners Tongji University, Karlsruhe Institute of Technology, SYMG, Bosch Rexroth, ITEI, Schaeffler, Microcyber and Schunk developed numerous innovative approaches, which were brought together and integrated in the created platform.

In a first step, uniform information models, interfaces and standardized specifications, e.g. for describing the technical data of individual machines and components, were defined transnationally. The resulting uniform information modeling could then be used as a basis for developing the systematic configuration process for production systems to be implemented on the platform. Test environments with defined processes were created in Karlsruhe and Shanghai for the machines and components introduced on the platform.

Furthermore, collaboration models and role models were researched with which multinational collaboration can be organized and the protection of knowledge for the respective partners can be ensured even across national borders. In addition, securely networked information and communication technologies were used. Procedures were investigated for deriving business models directly from the production system. It was also investigated how business models and services of the companies involved in the project could be integrated directly into the platform and the services available there for the user.

Another aspect was the collection of load data from the machines and systems, which can be used to increase availability or boost productivity. Integration options within the platform were also investigated for these scopes. In parallel, product development methods were developed that define Industrie 4.0 functions for the component to be manufactured, e.g. for automatic identification of a component. The objective here was to be able to fully exploit the potential of an Industrie 4.0 production system.

The result is a factory automation platform in which the necessary methods and interfaces for global, cross-vendor collaboration in the design and commissioning of turnkey production systems are defined and tested, as well as new tools and methods for the development of business models and digital services that can be operated via a platform approach. This makes it possible to quickly and easily set up production systems, communicate securely and offer equipment operators advice on product parts to be manufactured. The potential of Industrie 4.0 to open up new markets in international collaboration could thereby be exploited and placed on a broad basis through a factory automation platform.

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