Virtual Commissioning of Automated Systems

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1. Introduction

Concepts for the digitalization of products and all the production related tasks in the manufacturing and process industry have been developed for several decades. The development began with the introduction of computer-based 2D design (Figure 1).

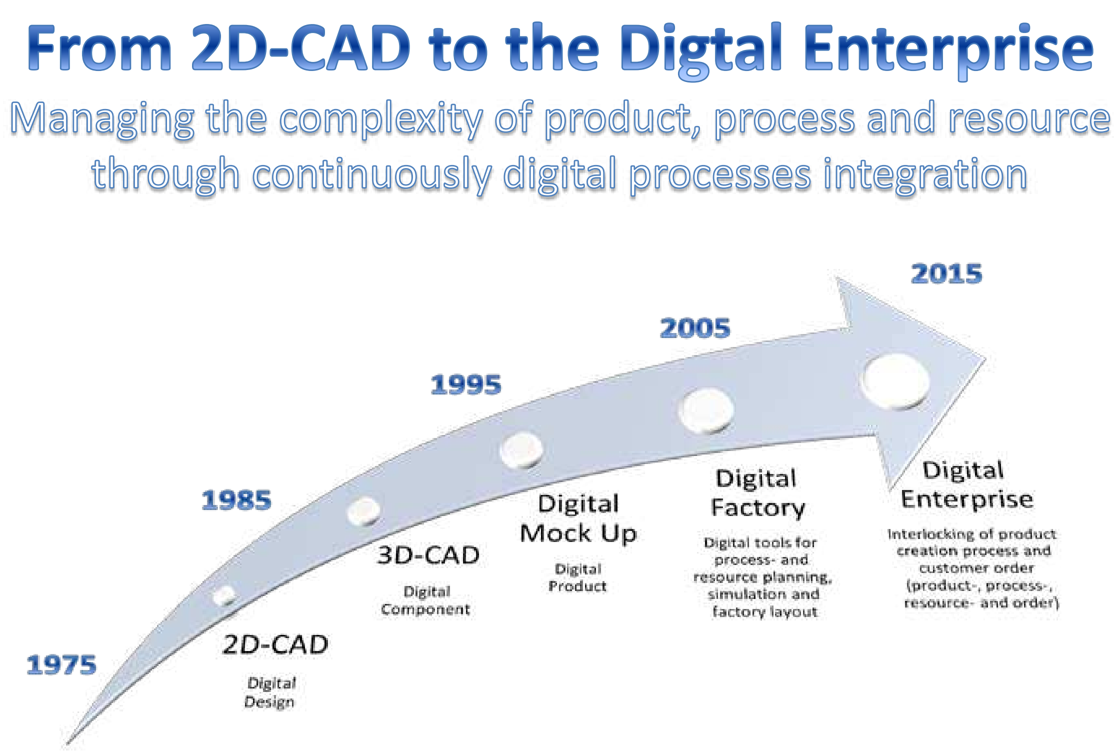

Fig. 1. Development stages for the Digital Factory (Bär, 2004)

Because of the technological developments in the information technologies field, more complex tasks in the product development process can be processed digitally (Brac, 2002). This belongs to the scope of the digital factory which includes the digitalization of models of the products and their integration into the manufacturing process chain. In (VDI 4499, 2008) the digital factory was defined as a "generic term for a comprehensive network of digital models and methods, including simulation and 3D visualization. Its purpose is the integrated planning, implementation, control and on-going improvement of all important factory processes and resources related to the product."

One of the topics in the digital factory is the Virtual Commissioning. As we know, the commissioning of the automated system is an important phase in the engineering, which makes visible whether the systems and components are planned, designed, produced and installed correctly according to the user requirements. However, this phase has been known as time-consuming and cost-consuming in practice (section 2.1) and can be improved by Virtual Commissioning.

State of the art is that the simulation of the system components is frequently used and the simulation is used without integration of automation devices and components, for example without PLCs (Programmable Logic Controller). HiL (Hardware in the loop) technologies are used only for individual components. The concept of digital factory combines both technologies.

During Virtual Commissioning the real plant is replaced by a virtual model according to the concept of digital factory. But the questions are: what digital data is necessary for the virtual plant model, how is the virtual plant implemented and configured, and how can these processes be integrated into the engineering lifecycle of manufacturing systems? This chapter gives comprehensive answers to these questions.

2. The Virtual Commissioning

The basic idea of Virtual Commissioning is to connect a digital plant model with a real plant controller (e.g. PLC- or HMI-Human Machine Interface) so that engineers from different fields such as design process and control have a common model to work with together. Thus, for instance, the PLC program can be tested virtually before the physical implementation is finished. Furthermore, the general functionalities of the plant can be validated and finally tested in an earlier phase. In this section, the general workflow of a traditional engineering process is introduced and its disadvantage discussed. Thereafter the Virtual Commissioning, as a possibility to overcome these problems, is introduced and described in detail in the subsequent subsections.

2.1 General workflow in the engineering process

The engineering of manufacturing plants begins with the construction and the rough mechanic planning. In this phase the general structure (layout) of the manufacturing system as well as the assignment of the machines in different production phases are determined, which is based on the result of product development.

The detailed planning is done in the next step. The kinematic simulation for the offline programming (OLP) of the robots is carried out, therefore the robot programs can already be created without the real robots, e.g. for the generation of a trajectory free of collision with other devices. In the phase of mechanic detail planning, a detailed CAD-based 3D cell layout (M-CAD) is created. The production workflow of a single machine is to be defined and every mechanical component in the cell can also be selected and documented in the list of materials. The results of the mechanical detail planning are used as input for the subsequent electrical detail planning. At this step the electrical energy supply as well as the control signals for the machines and their interconnection with each other is defined. This can be called E-CAD and is documented in the circuit diagram. The last phase of the detail planning is the PLC programming.

The last step in the classic engineering process is the commissioning, which can be understood as a phase of preproduction. At this phase the functionality of every single component in a function group is examined. After that it follows the interconnection check in turn from the level of function groups to the level of stations until the whole plant is complete - the bottom-up principle. The result of the commissioning is a functional plant which is ready for the production.

2.2 Today's problem in the commissioning

The above mentioned approach of the engineering process can be seen as the water fall model. A single step in this model can only be executed one after the other. There is no iteration step back to the previous steps. As a result, the debugging takes place only at the phase of commissioning. The following two main problems are identified here.

Bugs in the software

(Zäh & Wünsch, 2005) describes the time consuming for commissioning and PLC-programming in a whole project. It can be seen that the commissioning takes up 15-20% of the overall project duration, of which up to 90% is for commissioning the industrial electrics and control systems (e.g. PLC). Within the commissioning, up to 70% of the time is incurred by software errors (Figure 2).

The debugging of the PLC-Software is usually time consuming and may cause hardware damage. Since the commissioning is usually carried out under extreme time pressure, then a delay of the project must be calculated with financial penalties. Therefore it is desirable that the software debugging be carried out in an earlier phase.

Fig. 2. Contribution of control software to project delay (Wünsch, 2008)

The error is detected too late

Many errors that are detected during the commissioning arise in the earlier phases. This is a big problem since the late detection of errors and the costs of their elimination can be very high (Figure 3). When an error occurs in the early phase, an overwork of the rest phases is not avoidable. For example, if a robot is wrongly placed in the 3D cell layout and this error is not detected until the commissioning phase, then it is a great effort with extra costs to eliminate this error because all the planning data related to this robot has already been modified.

Fig. 3. Costs incurred by the correction of errors, depending on the time of error detection (Kiefer, 2007)

2.3 State of the technology

One approach to overcome the disadvantages mentioned in subsection 2.2 is the full digital planning and simulation of the production line. Concepts, concrete process sequences and the necessary resources can be defined and approved already in the early planning phase. This activity belongs to the concept of digital factory.

Fig. 4. The engineering chain in the production with Virtual Commissioning

The focus of digital factory is the digital processing of product development and production planning based on the existing CAx data with a seamless workflow in PLM (product lifecycle management). Digital simulation methods and technologies are used to secure the planning results, to optimize the process and to respond more quickly to the changes than before. In this way the product qualities are improved. Another benefit is the reduction of the planning time as well as the overall project duration. The "Time-to-Market" is thus shortened which means another advantage with respect to economy.

To test the PLC-program before the real commissioning, the Virtual Commissioning can be applied (Figure 4). It serves as a smooth transition between digital and real factory. In the case of Virtual Commissioning, the physical plant, which consists of mechatronic components, is simulated with the virtual model. This simulated system is connected to the real controller (PLC) via simple connection or real industrial communication systems. The goal is to approximate the behavior of the simulated system to that of the real physical plant by connecting the commissioned PLC to the real plant without changes (Figure 5). Therefore the development and test of automation systems can be done parallel to the electric and mechatronic development. In the case of the real commissioning, the connection can be switched to the real system again.

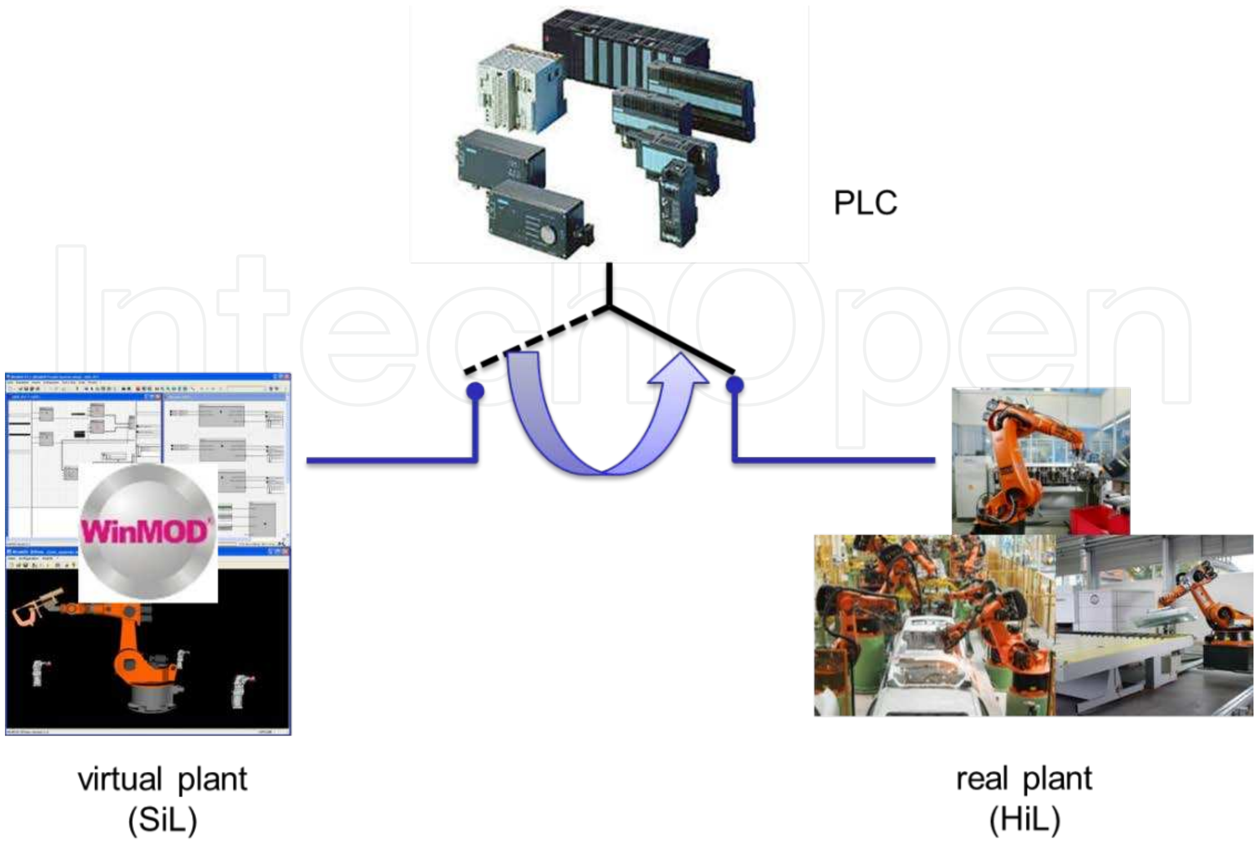

Fig. 5. From Virtual Commissioning to real commissioning

2.4 Component of the Virtual Commissioning

The virtualized plant, a mechatronic plant model, simulates the behavior of the real physical plant. It should respond correctly to the PLC control signals just as a real system. Besides, the whole process should be visualized for a better human observation. To fulfill these requests, a mechatronic model (Mühlhause et al., 2010) should be divided into a control-oriented behavior model and a kinematic 3D-model.

The behavior model simulates the uncontrolled behavior of the system. The behavioral states of the production resource are modeled and calculated by means of the logic and temporal components, which operate based on the control signals. In one PLC scan period, the behavior model should react to the control signals (output signals of PLC) according to the physical feature of the plant and give the feedback signal (input signals of PLC) back to the PLC – just as the behavior of a real system.

The kinematic 3D-model can be understood as a geometric model, which is based on the 3D-CAD model and enriched with additional information e.g. the grouping of the components which should be moved together and the definition of the DOF (degree of freedom) for every moving part. In contrast to today's mechanical CAD models, the mechatronic components do not just solely consist of the pure 3D CAD model, but also kinematic (including end positions) and electrical information like the electrical name of the respective device. For the purpose of synchronization, a signal coupling between the behavior model and kinematic 3D-model is needed.

The kinematic 3D-model is optional for the Virtual Commissioning, which helps for a better understanding by visualizing the movement behavior in 3D.

The communication between the mechatronic cell model and the real PLC can be realized via TCP/IP, field bus, Ethernet etc. There should be an interface to emulate the behavior of the communication. In the case of PROFIBUS, for example, a SIMBA-Card is needed.

2.5 Configuration of a Virtual Commissioning workstation

For the planning of a new production system, a layout plan for the necessary components (roles for the production resource to be used) and a rough workflow of the systems will be worked out based on a pattern (Figure 6). Based on this, a simulation model of the plant, including the geometric and kinematic design, will be built. This simulated layout is the starting point for the Virtual Commissioning, which is to be extended by the offline robot programming and planning process. At the step of detailed planning, the roles of resource are replaced by concrete units (function groups) under some fixed rules. For example, a certain combination of frequency inverter, the motor for a required electric moment of a torque, the type of clamp and valve cluster with the proper nominal pressure, or the robot and the weight of products to be operated, must be adhered to. These rules are to be observed by planners in the detailed planning. In a robot cell, for example, about 100 of such function groups must be matched and built. This function group can be stored in a kinematic library for the reusability. To build a simulation model, these previously created library elements can be added and connected with each other to describe the behavior of the corresponding component. Such a behavior simulation model has in average 30 inputs and outputs, which must be connected to the kinematics or to the PLC.

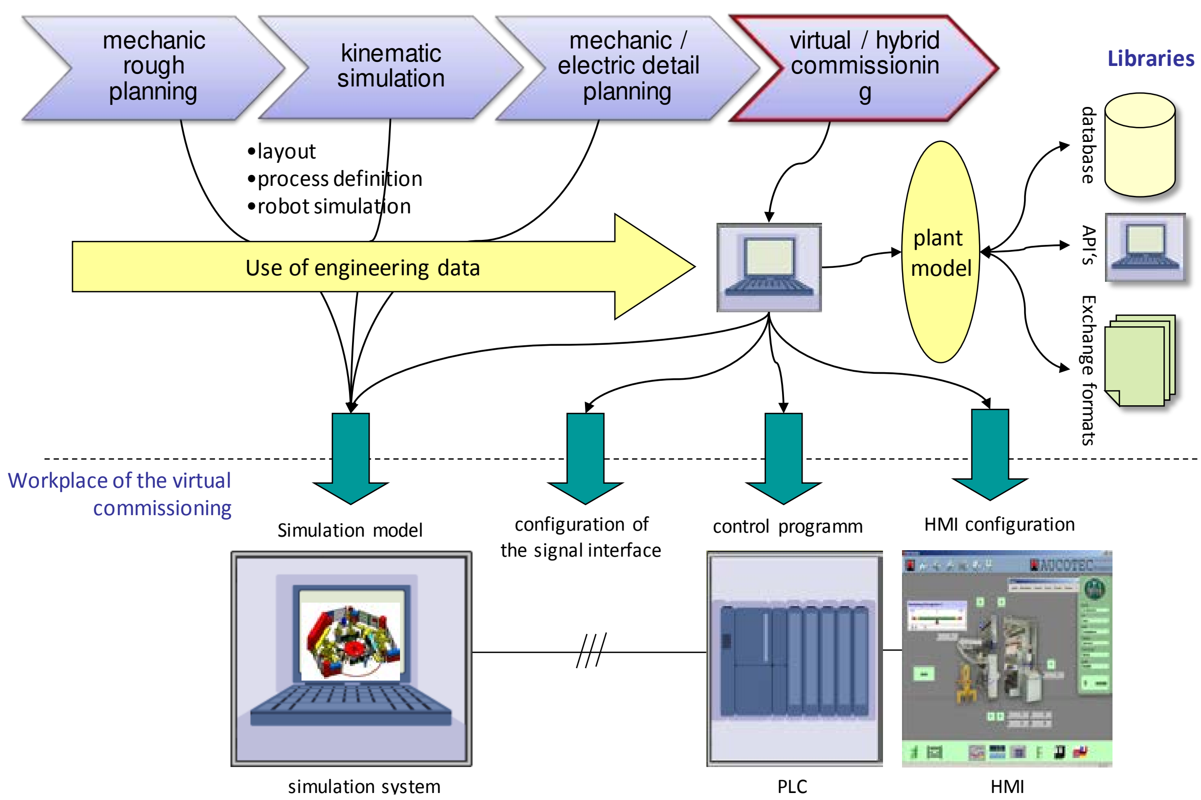

Fig. 6. Concept for integration into the Virtual Commissioning

After or in parallel to the layout planning and kinematic simulation, a suitable control program and operator visualization will also be developed, which run on a PLC or a PCS (Process Control System) system. The PLC program is developed in the following way: for each resource a corresponding control function block (Proxy FBs) is used, which is included in the control library. These Proxy FBs will be invoked in one or more SCF (Sequential Function Chart language IEC 61131-3). This control program will then be supplemented by plant-specific locks, a switch-off and parameterizations.

Afterwards, the PLC and the simulation systems are interconnected via the communication system or direct wiring. The I/O lists of the simulation system and the I/O lists of the control program must be properly connected with each other. Furthermore, each I/O has a number of features such as data type, range and unit, which need to be customized. The connection between the I/O of the Proxy FBs (or the communication configuration of the PLC) and the I/O lists of the simulation model must therefore be checked accordingly to the signal features.

A workstation for the Virtual Commissioning (Figure 6) consists of a simulation system on which the simulation model runs, a PLC which is usually connected with the simulation model via a bus system (e.g. PROFINET) and optionally a PCS.

In the phase of Virtual Commissioning, the plant which is to be tested is completely simulated in a digital model instead of a real one. This includes the automation equipment such as the clamps, robots and electric drives. When the PLC is connected to the real and digital systems at the same time, then it can be called the hybrid commissioning. For example, a robot with its controller can be integrated into a single system with other digital components, and the system should not detect any differences between the real and the digital components.

The current technology state assumes that the geometry and kinematics of the resources are provided by the manufacturer and as available libraries. In addition, the features of reused equipment may be stored in proprietary formats. These features and libraries are available in different storage systems (e.g. databases, repositories of tools and file systems).

Typical tools for Virtual Commissioning are Process Simulate/Process Simulate Commissioning and Delmia Robotics/Delmia Automation. In addition，the authors use the software WinMOD of the German company Mewes & Partner GmbH，which includes the component for 3D visualization. A circuit plan for electric planning can be edited for example with COMOS. There are also templates such as in Process Simulate, WinMOD, COMOS and Simatic S7, in which the corresponding features already exist in the library elements for converters, motors, robots etc. Today, the behavior models are not supplied by the resource producers. Instead, they are created by the users themselves for specific applications.

Besides the integration of a mechatronic plant model in the line-balancing scenario, a concept for the integration into the Virtual Commissioning was developed. The process of creating the workstation for the Virtual Commissioning has been explained above. The use of a mechatronic plant model should contribute to the construction of the workstation for Virtual Commissioning. The information which is extracted from existing data sources by using the mechatronic plant is able to represent the structure of the workstation (kinematic and behavioral simulation, PLC program, link-up between PLC and simulation model).

3. The mechatronic plant model with semantic techniques

The domain specific models in the individual life cycle phases usually have their own concepts depending on their physical phenomenon and tasks. This is essential because the models reflect only the necessary characteristics of the domains. A universal valid model is not thinkable. However, for seamless information flow it is necessary for the information consumers to have knowledge about the context of the transmitted information so that they can act in a proper way. (Rauprich et al., 2002) and (Wollschlaeger et al., 2009) point out that the historical separation of engineering disciplines, their workflows and thus the information integration is still an unsolved problem. One of the most common model structures in the manufacturing domain is the Product, Process Resource approach. It is the basis of digital planning of major tools like the Delmia tool set of Dassault Systemes (Kiefer, 2007).

Therefore, each piece of information has to be unambiguously identified and validated before it can be used in one of the engineering tasks. Additionally, its semantic including, its context information has to be specified and must be available. Mechatronic components, i.e. plant or machine parts consisting of mechanical, electrical and logical aspects, build up the modular blocks of the model, which are used in the engineering process. Thus these mechatronic components have to be represented by its semantic enriched information. Consequently, the mechatronic model must be based on semantic methods.

3.1 Mechatronic plant model

Today the information management in companies is characterized by a variety of available information, which is mostly stored distributed in a monolithic form and in different data sources. However， the size of each data source increases continuously over time, so that a connection between the information can only be realized through significant human work. As a result, much of the available information is very difficult to find by the user. Hereby a situation relevant lack of information arises within the information stream in the company. The time required for the complex information search and retrieval rises exponentially with the increasing amount of information， which results in significant costs. The mechatronic plant model is a logical layer above the design data and can be divided into the basic aspects of product, process and resource (Figure 7). Planning and other tasks in the plant life cycle can be executed by tool applications. These tools add new data to the existing data pool. These applications are modeled as so called facets (roles for the user data) in the mechatronic plant model. The resources could be further refined (see Figure 7). The basic idea of the model is to disperse all aspects (products, process and resource) in smaller features. For example, a construction group has the feature of the diameter of the pressure pipe connection or movement duration of a valve. The typical process features are process step number and number of the predecessor or successor step. If the mechatronic model is used for the acquisition of the data storage, the addressing data (e.g. data source type, URI of the data source) is also to be modeled. The mechatronic model is thus a hierarchical structure of sub-elements based on the three aspects product, process and resource. These three aspects are then to be further dissected into even smaller features, until no more division can be undertaken. In addition, these features are categorized so that semantic information about the individual elements of an aspect and its relationship with other elements of other aspects in the model can be enriched. (Figure 8)

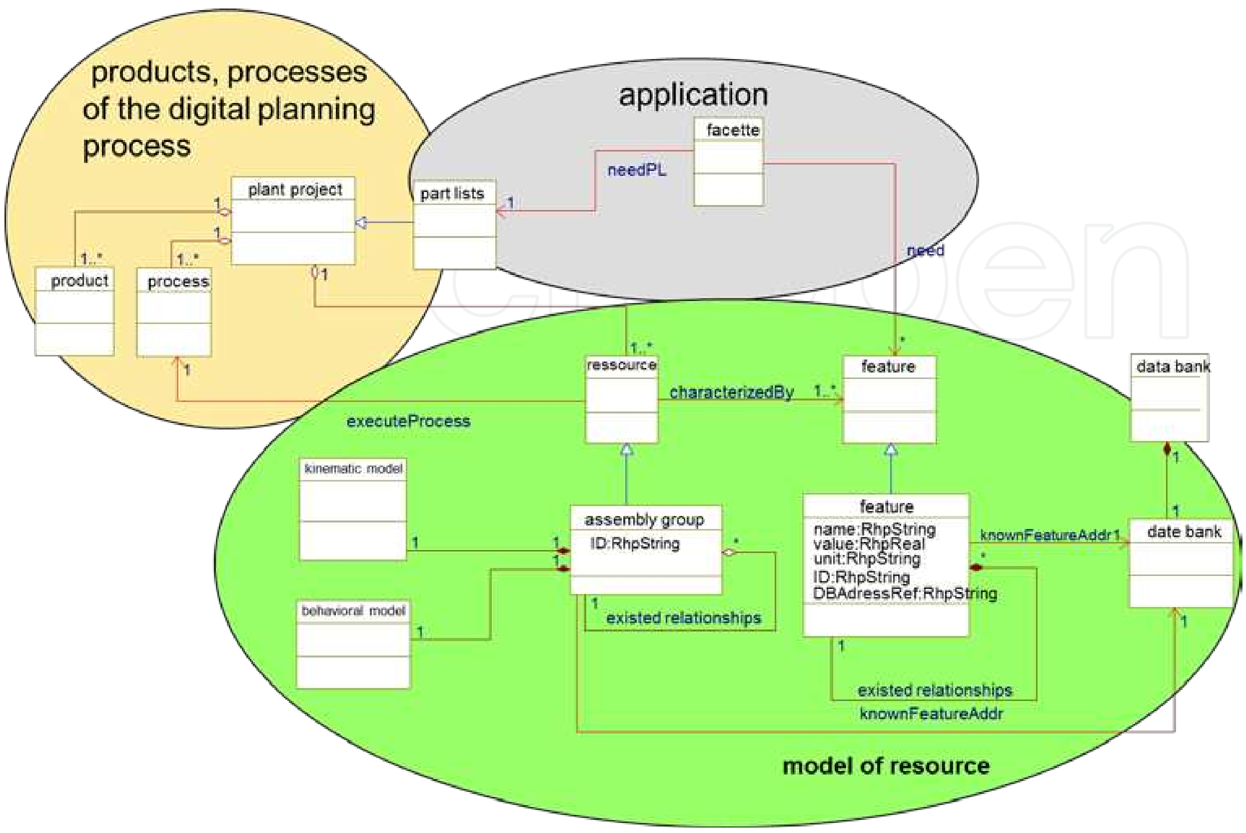

Fig. 7. Basic structure of the mechatronic plant model

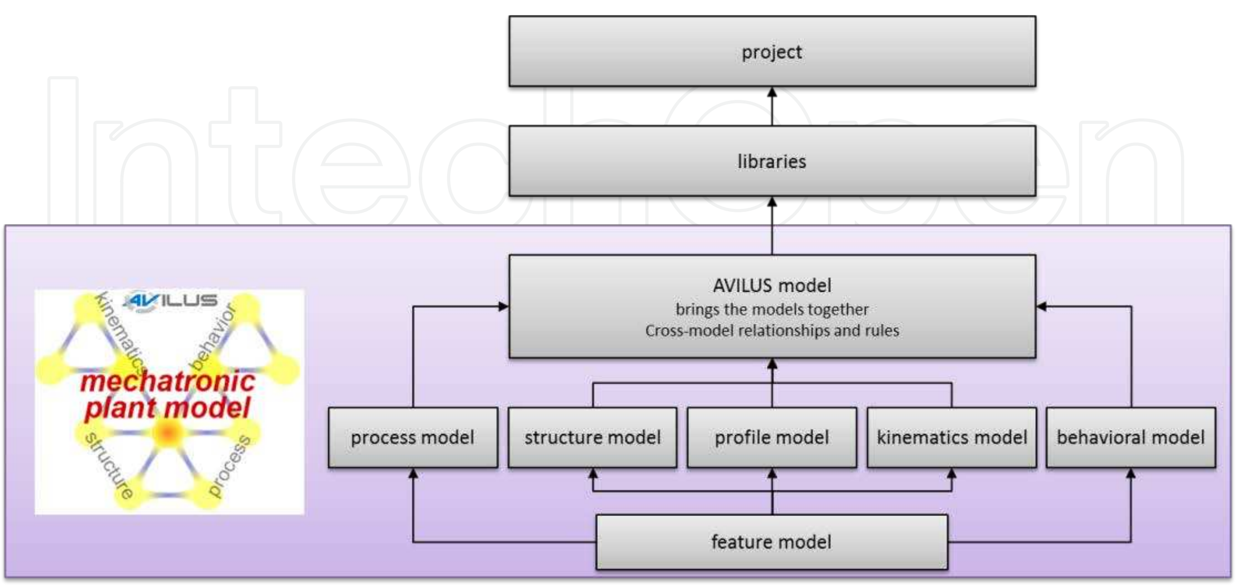

Fig. 8. The intern structure of the mechatronic plant model

3.2 Potential of the feature-based modeling approach

The basic idea of focusing on the features of engineering is to make engineering decisions and the underlying rules simpler to relationships between features. A unified set of features, for example coming from the standardization of technical product data, enables an automated execution of rules. This makes it possible to resolve the relationship with defined rules between feature carriers (e.g. valve or clamp or behavioral description and proxy FB).

This means the following assistance functions are available for the planner:

- Consistency check
- (semi-) automatic assignment
- Restrict the solution

An important element of the mechatronic plant model is the coupling between kinematics and behavior of the mechatronic components (aggregation relationship between the module as well as the kinematics and behavior model in Figure 7) and the integration of the PPR model (product, process and resource). Figure 7 shows the connection between resource and process (executeProcess). For the purpose of semantically unambiguous modeling, the description language OWL was used, which can clearly formulize the relations between the classes.

The extensive relationship between kinematics and behavior model are described in Figure 9.

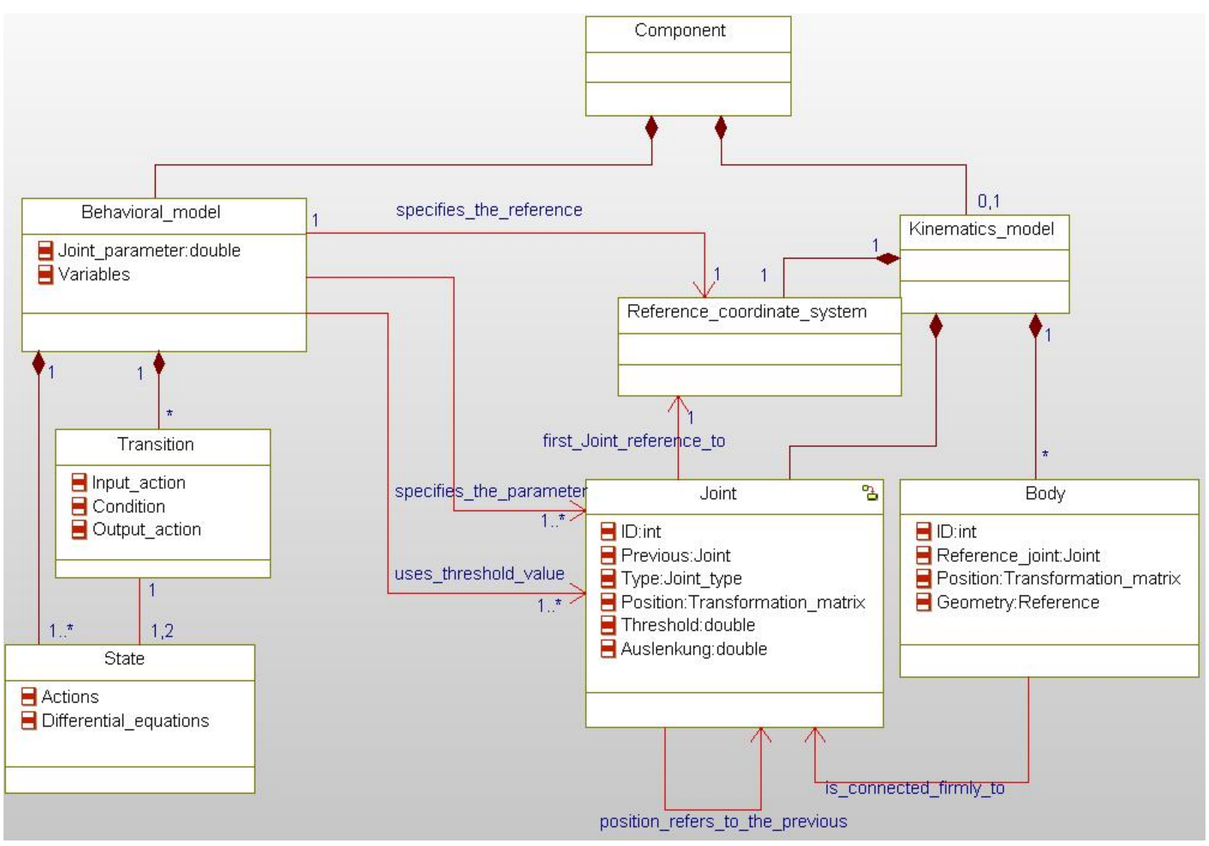

Fig. 9. Kinematic and behavioral model

In summary, the mechatronic plant model has the following essential basic elements:

- Basic structure is the grouping of product, process and resource
- Relationships are defined between the basic elements
- The PPR elements are then further specialized
- The properties of the PPR elements are described with features
- The features can be structured in a specialized hierarchy
- The features can build relationships with each other

4. Application of the model for Virtual Commissioning

4.1 Assistance by means of mechatronic cell model in the Virtual Commissioning

As described above, the starting point to establish a workplace for Virtual Commissioning is the layout and the kinematic model of the plant. In addition, it can be assumed that the information about the resources and process is located in component related files (kinematics, geometry, behavioral descriptions), in databases or tools.

The goal is to build a workplace for Virtual Commissioning. A tool should be implemented to assist the configuration of the workspace. This assistance tool is called VIB configurator or VIBCon (Figure 10).

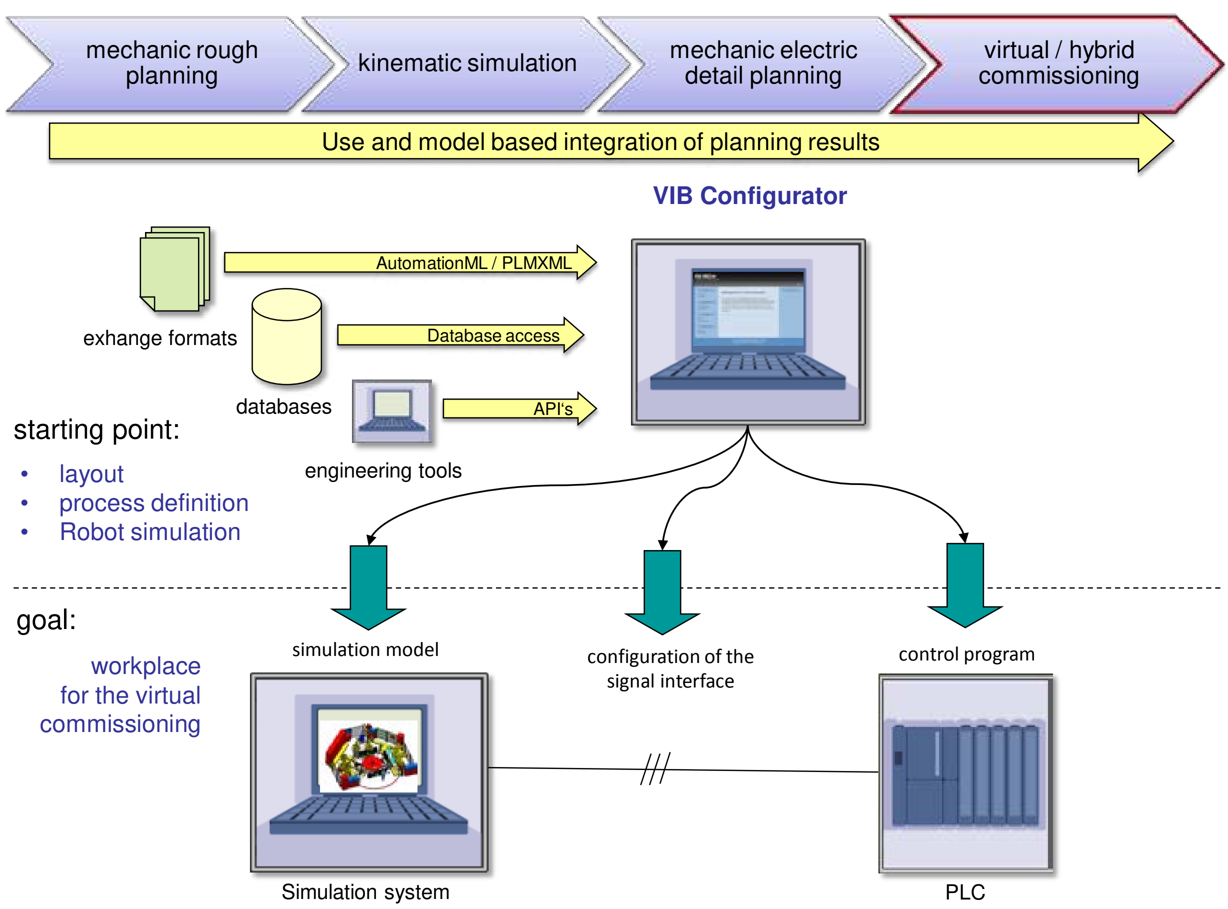

Fig. 10. The demonstrator for the Virtual Commissioning

The methodological foundations of the assistance tool allow the rule-based processing of raw data, which is related to a specific working step. The raw data can be extracted from various data sources. The result is the necessary configuration data or files for the workspace of Virtual Commissioning (Figure 11). In this way a semantic-based model is established in the mechatronic plant model. The model contains relationships such as the structure-based relationship "consistOf" or "isCharacterizedBy" (Figure 7). In addition, there are naming conventions that make, by using prefixes or suffixes, uniqueness semantic out of the mechatronic model. In this way, a check list based on the previously finished work can be generated. Based on this list, the library elements are instantiated. All these rules are defined in the VIB configurator. The following functions were implemented by the mechatronic plant model:

- Specification of the relationships between model elements and the workflow and the corresponding rules
- Generation of the needed configuration information by semantic inference or support of their derivation through a selection of possible alternatives

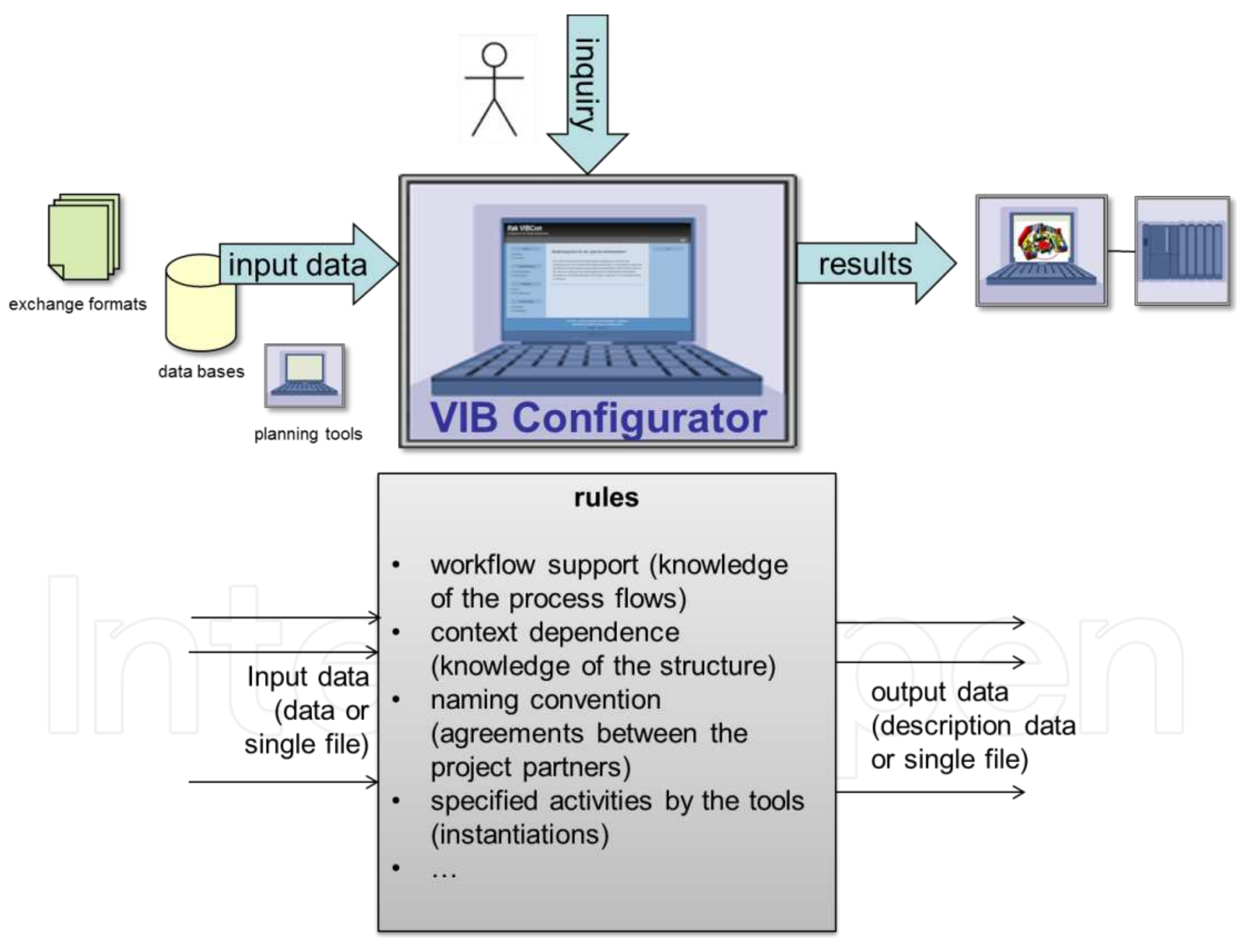

Fig. 11. Methodological approach of the rules

An example can be found at the beginning of the configuration of a Virtual Commissioning workstation (Figure 11). The needed document types (e.g. RobCAD file, VRML file, PLC program...) should be selected according to the context. These files will be earmarked and stored in the VIB configurator. When a new project is started, which uses the pattern of an old project, only the references to the types of these files and information are needed. These references are derived from the structural knowledge of the relationships between the types of resource and the types of their description.

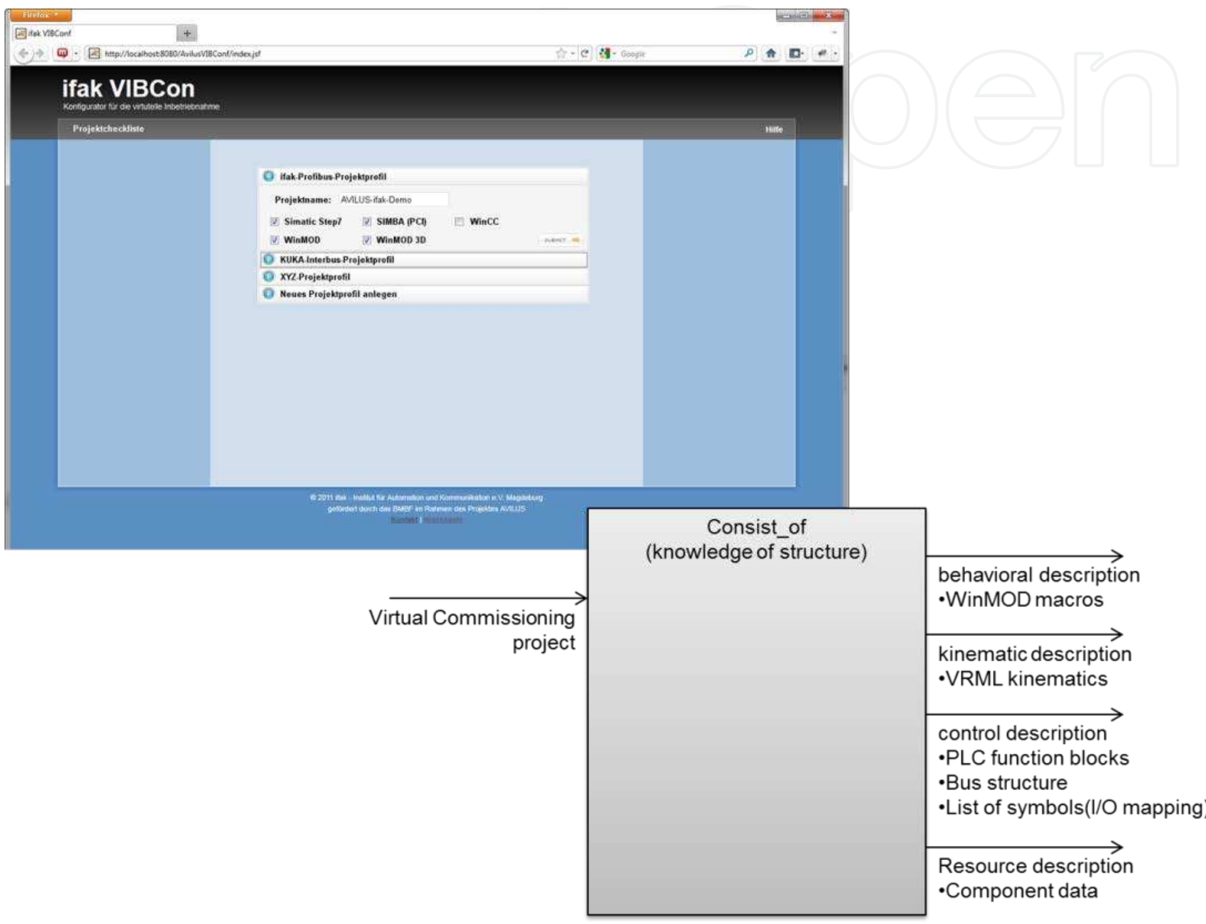

Fig. 12. Sample rule from the knowledge of structure – creating a project

A second example is the acquisition of information for all modules or components (implementation of the resources) that are included in the layout of a plant (Figure 13). The proper types of the files and information are needed for each resource in the project. The relationships between the model elements are integrated in the mechatronic plant model. Following the chain of these relationships between the elements leads to the references of the data sources. Naming conventions are applied here, such as extensions of the file name.

The mechatronic plant model serves as a knowledge model between the heterogeneous data sources and the data which is to be generated (Figure 13). The semantic model contains the know-how of the plant. The proper types of the files and information are needed for each resource in the project. The whole model is embedded in a software environment, which is described in subsection 4.2.

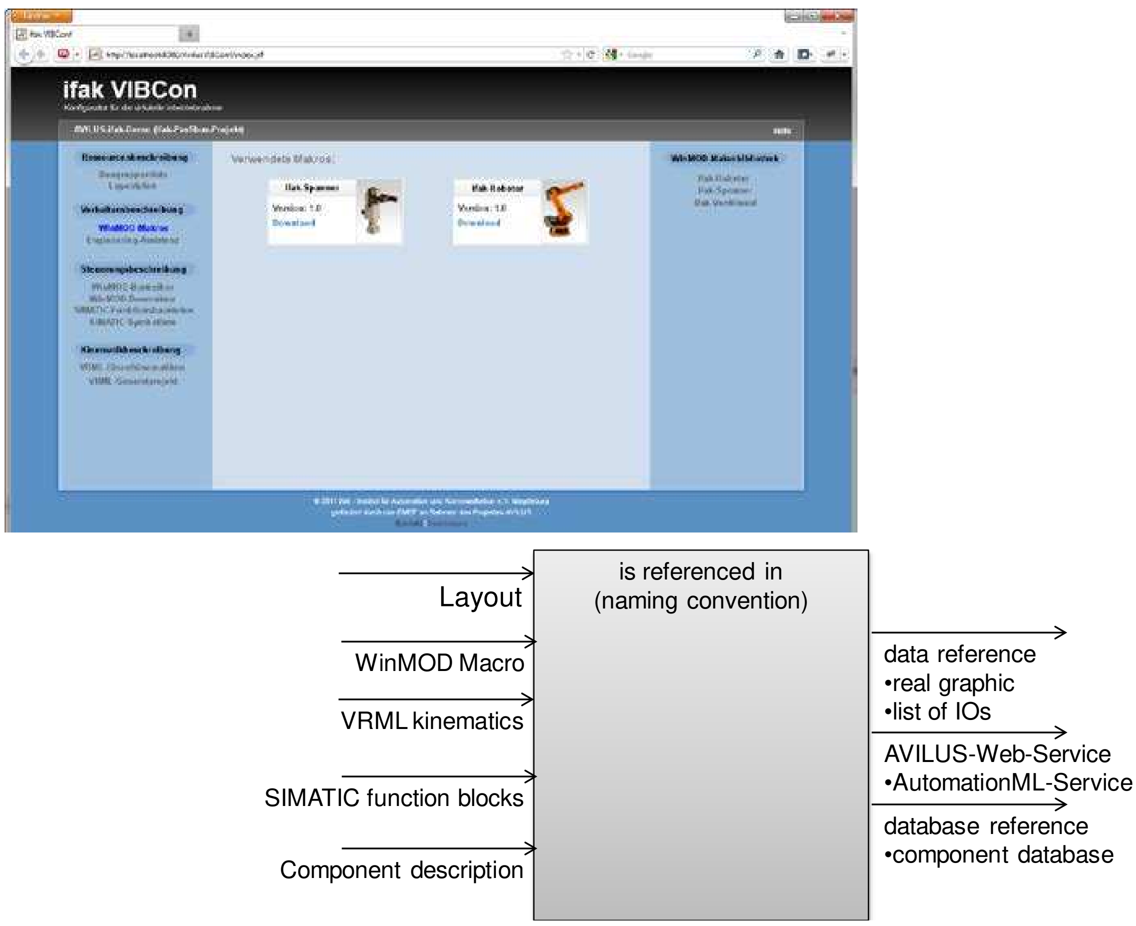

Fig. 13. Sample rule from naming convention – acquisition of information resource

4.2 Practical implementation of mechatronic cell model based on the semantic model

The main focus of the mechatronic model is the semantic modeling of the mechatronic components and the processes of the plant. This includes not only the description of the structural characteristics, e.g. the mechanical or electrical features, but also details like resource behaviors and process steps. Furthermore, a unified structure for the formal description of system properties is set (see Subsection 3.1). A framework (Figure 14) is implemented in order to access the information contained in the model like rules and relationships. Therefore, the needed information is found from different data resources (e.g. web services, exchange files of different formats). This process can be called reasoning.

The components and tasks of this framework include:

- Design and modeling (Figure 14, green)
- Standard technologies of "Semantic Web" (Figure 14, gray)
- Integration and evaluation (Figure14, orange)

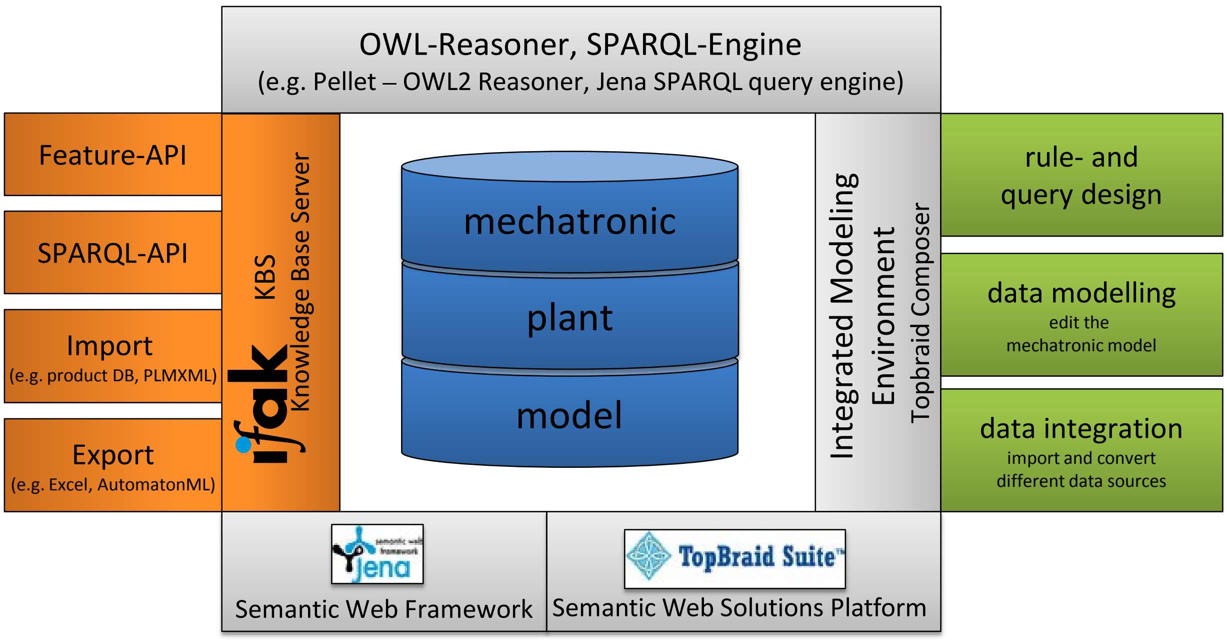

Fig. 14. Framework of the mechatronic plant model

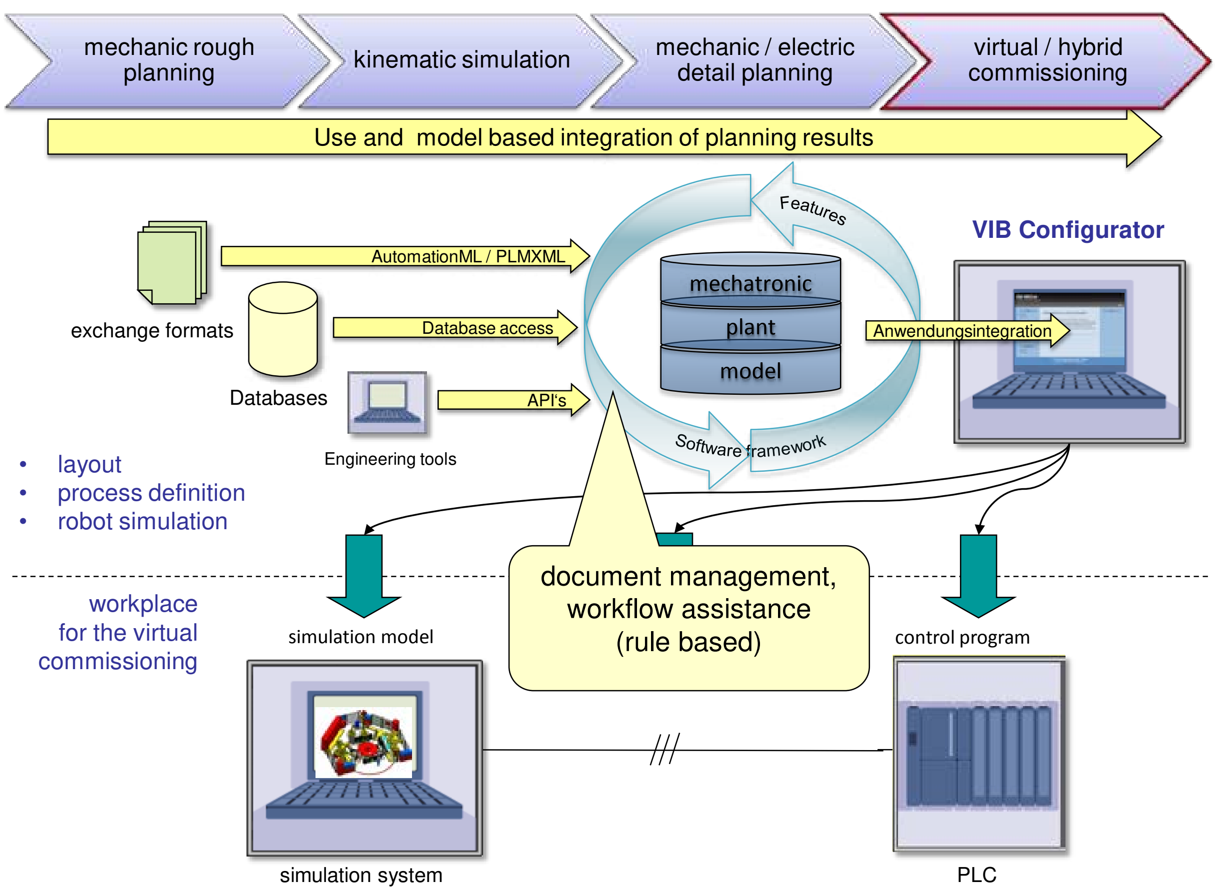

Fig. 15. Role of the mechatronic plant model in the preparation of a workstation for Virtual Commissioning

The most important technologies of the methods are data modeling and design of the rules and inquiries. For data modeling, as mentioned above, a semantic-based approach was deployed. The design of the rules and inquiries was based on this approach, which forms the basis of the knowledge processing known as automated rules-based reasoning. The instance data, which is based on the mechanisms of import and conversion, was integrated into the data model.

The integration of existing standard technologies became the focus in the development of the mechatronic plant model. The necessary technologies for knowledge processing have been implemented by applying the well-established tools and frameworks (e.g. OWL reasoned and SPARQL engines) for the Semantic Web. In this way, a semantic-based model with the functions, such as consistency check, reasoning and graph-based query, was built.

Different interfaces, which are based on a synchronous communication, are implemented as prototypes for the integration of the model into the engineering process. These interfaces enable the feature-based access (Feature API) and the query-based access (SPAQL API).

The concept, based on standardized exchange formats such as PLMXML and AutomationML (Draht et al., 2008), enables the flexible import and export of engineering data. The "Knowledge Base Server" (ifak-KBS) is a middleware which facilitates the integration of the mechatronic model using different interfaces into the engineering tools.

A conclusion of the important features of the VIB configurator is listed as follows:

- The development of a Virtual Commissioning workstation is a combination of tasks such as selection, classification and design, which are specified in a defined workflow. Assistance functions can be offered based on the knowledge of workflow and structure as well as naming conventions.
- The fundament of the assistance functions is the mechatronic plant model that was implemented in a software framework, based on semantic technologies.
- The introduced functions serve only as examples here, which can be supplemented by other detailed analysis of the process.
- Checklists and possible tests can be derived out of the available digital data.

5. Acknowledgment

This work is funded by the German Federal Ministry of Education and Research (BMBF) within the project AVILUS.

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