Demands on Virtual Representation of Physical *Industrie 4.0* Components

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Abstract - Industrie 4.0 **as one of the leading research and development initiatives for factory automation systems envisions a hierarchy of *Industrie 4.0* components that exhibit a generic structure and behavior related to its utilization within production system life cycles. The components are equipped with an administration shell containing a virtual representation of the component. But up to now it is still unclear on which layers of a production system *Industrie 4.0* components can be found with which granularity and what are the relevant information to be modeled within the administration shell. The System Engineering (SE) plays a significant role in the *Industrie 4.0* scenario. In order to align SE modeling with the new smart factory automation environment, this paper intends to meaningful *Industrie 4.0* components and identifies information relevant from the viewpoint of production system engineering and control.**

Keywords **– Industrie 4.0 components, virtual representation, production systems, automotive, engineering.**

I. Introduction

Industrie 4.0 has been introduced as a vision for an advanced production system control architecture and engineering methodology (see [1], [2], [3], and [4]). It is accompanied by similar approaches in Europe, even worldwide. There are similar activities in the US led by the "Industrial Internet Consortium", in France and the UK that coined the term "Factory of the future", and in China.

All of these initiatives have the same background: the production system stakeholder's need for highly flexible production systems that can be adapted to rapidly changing customer demands, and empower increased capabilities of information acquisition, exchange, and processing applicable in the engineering and control of production systems.

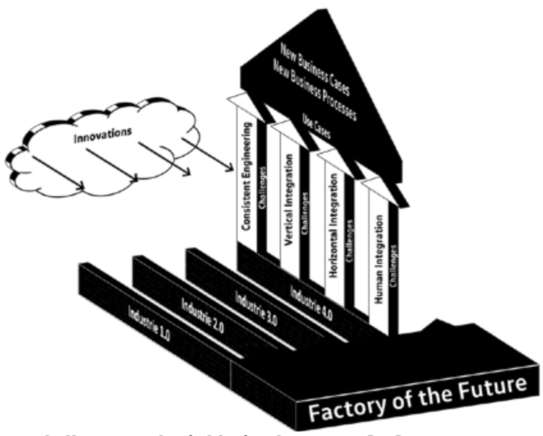

Figure 1: Challenges in the field of *Industrie 4.0* [25]

Main starting point of *Industrie 4.0* is the consideration of all life cycle phases relevant for a production system. Beyond the production system life cycle there are the life cycles of products, and product orders [5], and the identification of needs related to the optimized integration of the different life cycle phases and activities within them. Based on them a set of challenges especially regarding integration (e.g. horizontal integration) has been identified as depicted in Figure 1.

One of the most interesting results reached within the *Industrie 4.0* research area so far is the "Reference Architecture Model *Industrie 4.0*" (*RAMI 4.0*). This model combines the production system life cycle with the control hierarchy and the value streams relevant for production (see Figure 2).

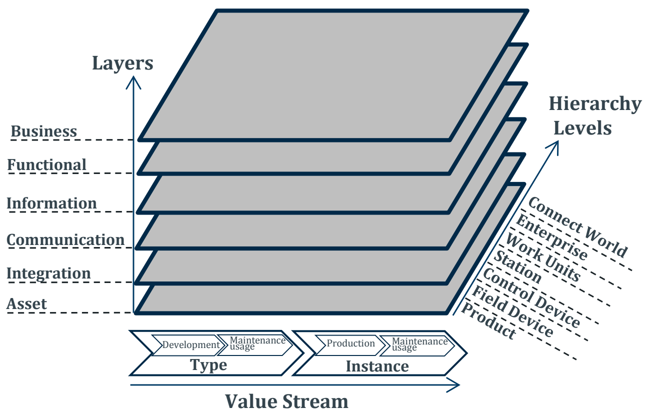

Figure 2: Reference Architectural Model *Industrie 4.0* (*RAMI 4.0*) [6]

As one key element of RAMI 4.0 the *Industrie 4.0* component has been identified. In [6] a set of structural, functional, and information-related requirements to the *Industrie 4.0* component is collected. Main characteristics of an *Industrie 4.0* component is the combination of objects of the physical world and the virtual world, targeting to provide dedicated functionalities within both worlds as a holistic approach. Therefore, it is identifiable, is able to communicate appropriately, contains an administration shell, provides *Industrie 4.0* conform services, is able to control its own state, and can be hierarchically structured (see Figure 3). For more details see [2] and [6].

The System Engineering is a multi-disciplinary approach that has the potential to describe such components of large complex systems, such as cyber physical systems and smart factories, through special tools and languages.

However, as the complexity is defined with the number of components and their connections, several challenges are now addressed to System Engineering for the development of smart production systems with highly interconnected components within the context of *Industrie 4*.0. One of the key challenges is the virtual representation of these smart and complex physical objects within a system.

The virtual representation of the *Industrie 4.0* component shall contain all relevant information related to the physical, functional, and behavioral properties of the represented physical object. One part of the virtual representation is the Manifest covering characteristic properties, dependencies between these properties, product, and process related characteristics, and a formal representation of the function, and behavior of the component. For more information on relevant data within the virtual representation see examples [7] and [8].

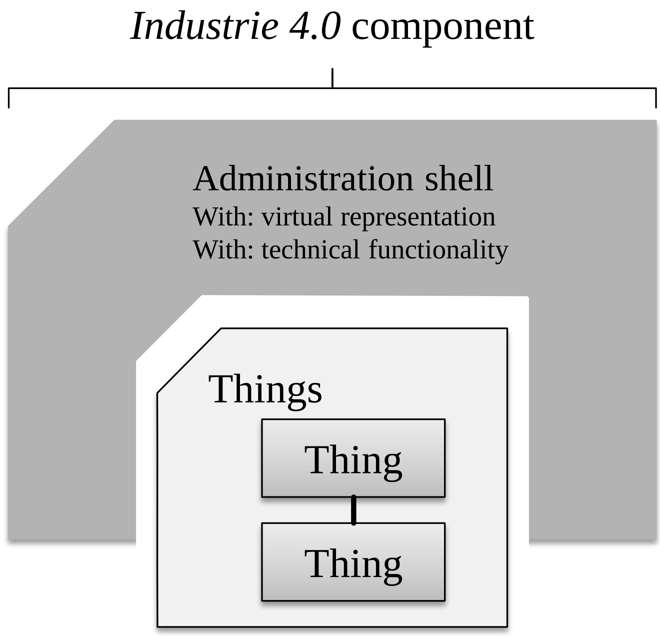

Figure 4: *Industrie 4.0* component following [6]

In order to properly design *Industrie 4.0* components the virtual representation has to be filled with information. But depending on the granularity of the component within the hierarchical system architecture as well as depending on the life cycle phase this information might be completely different.

Within the *SkillPro project* (www.skillpro-project.eu) the capabilities of *Industrie 4.0* components on manufacturing level are considered [9]. Here especially the dependencies between the product to be produced, production resources to be used for production, and its connecting production processes are modeled.

Within the *Conexing project* (www.conexing.de) a much lower level of granularity is considered [10]. Here the focus is on automation devices. They are modeled in a way enabling their provision by device suppliers and their application in CAx tools. Thus the virtual representation follows engineering needs.

Even if there are strong activities within the *Industrie 4.0* initiative to define model structures for the virtual representation, up to now it is neither clear on which layers of the production systems *Industrie 4.0* components are meaningful nor which information is relevant within their virtual representation. Within this paper an attempt is made towards the identification of relevant component layers and to assign meaningful information to them required within the life cycle of a production system. As it is very challenging to characterize a production system structure that applies to various industries, considerations, made in this paper, will be related to manufacturing systems. In addition, the paper will mainly address information relevant within the engineering phase of the production system life cycle. The information relevant within the use phase of the production system life cycle will be considered in [11]. Thus, the paper will follow two main research questions:

Research question 1: What are relevant layers of components within a production system and which are their identifying characteristics?

Research question 2: What information is relevant on and characterizing for the different layers of production system components to be virtually represented in the administration shell?

Therefore, the paper is structured as follows. In Section II the approach answering the research questions is described. Section III reflects the analysis of different production system hierarchies in literature and practice and gives the relevant layers of the production system hierarchy. Section IV identifies engineering artifacts usually applied within production system engineering and assigns them to the layers of the production system hierarchy. With a summary the paper ends.

II. APPROACH

To answer the research questions two main research activities were performed.

At first, structures of production systems were considered. Therefore, a detailed literature survey was conducted resulting in a set of existing production system structure representations. In addition, existing production systems within the automotive industry were reviewed. Based on both considerations an initial production system component hierarchy was developed. Afterwards, this hierarchy was validated by considering production systems of different manufacturing related domains.

Secondly, the early life cycle phases of production systems were investigated covering the engineering, and use phase of a production system. Different engineering areas of expertise involved in the execution of these phases were analyzed using the 4D method presented in [12]. As a result the engineering processes have been modeled as a network of engineering activities executed by humans, creating and exchanging engineering artifacts, and exploiting engineering tools.

Based on that evaluation, the assignment of engineering artifacts and the information modeled within them to the identified component layers was possible. This has led to an identification of engineering artifacts relevant for the different layers of *Industrie 4.0* components.

III. GENERIC PRODUCTION SYSTEM ARCHITECTURE

One of the main tasks in System Engineering is the definition of the system architecture. Usually, three main layers are considered: environment of the system, system of interest, and system element [13]. However, modeling complex system, it is not easy to understand what level of detail is needed to define each system element and their interrelations. Moreover, it should be taken into account that every system has much more than just one internal structure and the same elements can be connected to each other in different ways [14].

As stated in [15], the response to this challenge will be domain specific, and within the context of *Industrie 4.0*, understanding the relationships among the smart components and their combined behaviors can be very challenging.

To answer the first research question a literature survey and an analysis of existing production systems within the automotive domain was conducted. Following, a hierarchical structure model was developed and validated to support system engineering modeling.

A. Literature Survey

Production systems have been investigated by various researchers. Depending on the layers of interest the different researchers have developed different layer structures. But all of them have considered only parts of the overall set of meaningful production system layers possibly of interest to host *Industrie 4.0* components. Within this paper it was impossible to review all identified structures. Hence, only classes of structures are named here with only a few representatives of these structures.

Within literature sets of researchers have considered the production systems from a company or factory planning viewpoint. Using this viewpoint the production system is structured in hierarchy layers like Network, Company, Site, Segment, System, Cell, and Station focusing on the manufacturing resource structure of the production system. Two representatives of this viewpoint are [16] and [17].

Another set of researchers has taken a production function oriented view. They considered elements of the hierarchy providing technological manufacturing functions to the overall system required to produce a defined product and, therefore, to execute manufacturing steps. They discuss hierarchy layers like Cell, Main Function Group, Function group, and Sub-function Group. Three representatives of this viewpoint are [9], [18], and [19].

A third set of researchers has considered the individual components of a production system applied to execute the physical behavior of the production system and its integration. They address a rather device and mechatronic oriented perspective discussing layers like Function Units, Devices and Device Functions. Three representatives of this viewpoint are [20], [21], and [22].

Summarizing the identified approaches, layers, to be considered, range from the complete company down to individual automation devices and mechanical parts. But all layers are based on a function oriented consideration of the manufacturing process to be executed.

Especially for automotive industry, the layer structure needs to address the different sections of automobile production, i.e. press shop, body shop, paint shop and final assembly. Similar or equal objects in different sections have to be located on the same layer within the production system structure. Also it has to be possible to assign mechanical objects to hierarchy layers in order to virtually represent them. As the hierarchy layers in the RAMI 4.0 model are related to IEC 62264 [26] /IEC 61512 [27], the lowest layers belong to automation domain exclusively, i.e. control and field devices. Thus, mechanical objects, like safety fences or mechanical clamps, cannot be assigned to the current layers. Therefore, a new layer structure is presented in this paper which suits automotive production system's needs by considering its sections as well as its objects and equipment.

B. Hierarchy Layers

Based on the literature survey, a set of layers was preliminary identified. For the identification of the different layers of objects in a production system different criteria were exploited. The most important criterion is the technical functionality of the considered objects following the definition of the technical functionality given in *Industrie 4.0*. It refers to the functional part an object is providing to the overall function of a production system regardless of whether this function is a value adding function or a support function for value adding, or even a function required to supervise, control, diagnose or maintain the production system or parts of it. Additional criteria are the hardware modularity and hierarchy of the production system, the control architectures and control information identified, the relations to human labor, the relevance within engineering phases and engineering activities, and the relation to the product complexity. The initial set of layers identified is given in Table 1.

	Layer	Example
9	Production network	VW cooperation
8	Factory	Golf 7 production system
7	Production Line	body shop line
6	Production Line Segment	vehicle body line
5	Work Unit	vehicle body plant
4	Work Station	welding cell
3	Function Group	welding group (robot, controls, welding equipment)
2	Component	welding gun
1	Construction Element	welding cap

Table 1: Hierarchical Structure Model [25]

Here the functional criterion is sketched. In the following the different identified layers are described in more detail.

1. Construction Element (Layer 1)

A Construction Element is essential for functionality of components. It ranges from passive elements like a wire or a cast metal machine bed to active components like drives, proximity switches, or welding caps. It may have different states related to the execution of functionality like a drive might be switched on and off.

2. Component (Layer 2)

A Component fulfills a manufacturing method or a support function. The process is not alterable, but its parameters are configurable. There are two classes of Components. A Process Component has influence on product quality and creates product features. Its parameters like electric current, holding force, and holding time are configurable. In contrast, a Control Component processes and transmits data.

3. Function Group (Layer 3)

A Function Group includes all components to fulfill one function of a production system, e.g. reshaping, inclusive all necessary support functions. Several different manufacturing methods can be integrated in one process, e.g. deep-drawing and cutting. The different manufacturing methods will not be applied independently but every time in a fixed combination. Thus, the function is not reasonable separable. A Function Group executes a value-added manufacturing process or/and handling functions.

4. Work Station (Layer 4)

A Work Station includes one or more value-added functions and support functions. It provides product quality by combination of manufacturing process functions and support functions. Summarized, a Work Station can be seen as a combination of manufacturing and logistical processes.

5. Work Unit (Layer 5)

A Work Unit combines Work Stations, i.e. includes several value-added and support functions. The amount of functions united in a Work Unit can be reasonable separated from other processes or Work Units in the surrounding based on its necessity for product or product part creation. Different manufacturing processes are involved or only one manufacturing process with support processes.

6. Production Line Segment (Layer 6)

The Production Line Segment is characterized by linked manufacturing functions, support processes and buffers, i.e. combines Work Units and buffers. The elements of this layer are used in resource planning. A Production Line Segment contains all related functions needed to produce a certain amount of a whole product.

7. Production Line (Layer 7)

A Production Line is a separation between different disciplines, e.g. press shop, body shop, and assembly line. Additional criteria are the production method, e.g. defined mix or batch production, the type of functions, i.e. related functions and the kind of manufactured products, i.e. a defined variety of related products which can be produced.

8. Factory and Production Network (Layers 8 & 9)

The Factory and the Production Network are characterized by the combination of all manufacturing, logistical, support and other functions required for manufacturing a given number of products by integration of one, a few, or several input elements. Depending on the emergence of the input elements, the involved locations, and the ownership of production systems, we distinguish between Factories and Production Networks.

C. Validation

The developed hierarchy has been validated based on different student research activities by considering different practical use cases covering different industries. These use cases include press shops, body shops, paint shops, final assembly, and logistics in automotive industry, a hot-rolled stripe production system of steel industry, a stone cracker used in mining industry applications, a production system for roof trusses within wood industry, a micro cuvette production system within medical device industry, a logistics centre, a solar park and a gas turbine production system within energy generation industries. In the case of automotive industry, physical production objects and equipment were identified and assigned to the defined layers. Two compulsory requirements for validation are: 1) all assigned physical objects comply with the layers' definitions and 2) same or similar objects, concerning their functions, found in different production sections, e.g. robots in press shops and robots in body shop, have be assigned to the same layer. All assigned objects in this use case have met all requirements. In other use cases, a similar validation process was conducted.

For more details on the assignment of different industries' production equipment to the defined hierarchy see [11] and [25].

Based on these validations the authors are convenient, that the developed hierarchy can get a broad application.

IV. ENGINEERING INFORMATION FOR *INDUSTRIE 4.0* COMPONENTS

To support the conceptual modeling of a complex system the system engineer need to establish a framework that facilitates understanding of the problem and to define the relevant information needed for the process analysis [23]. In SE these "boundary objects" [24] are defined as artifacts that support the system analysis generally including requirements, system information, use cases, logical scenarios, functional models, simulation tests and trade studies [15][24].

To answer the second research question the relevant engineering artifacts have to be assigned to the different layers of the production system hierarchy.

A. Artifact Identification

To identify the necessary information relevant for the different layers of the production system hierarchy detailed process analysis of the engineering processes of the technical systems used for hierarchy validation following the analysis methods described in [12] have been executed. As a result the following engineering artifacts have been identified as relevant for the *Industrie 4.0* components within manufacturing industries (and especially within the automotive industry). As there are myriad of different detailed engineering artifacts only major artifact types will be named here.

1. Requirements

The set of requirements covers initial requirements coming from the product design like production process specifications, e.g. a welding spot list, coming from economical departments like maximal cost values, and coming from legal authorities.

Block layouts define the set of manufacturing resources and functional units within a production system and put them in a logical interrelation.

2D layouts represent the construction of the production system in more detail following a "paper work" strategy. There are concept layouts, rough layouts and other 2D layouts for more detailed information like a transport system related 2D conveyor system layout.

3D layouts provide a more detailed representation of the general concept of the production system. They remain in a conceptual state covering the identification of production system components and functional units and their geographical locations. There are for example 3D rough layouts, 3D layouts including electronics.

2. Basic Specifications

The basic specifications contain general definitions of production system components. They cover for example the component quantity structures, general interrelation structures between product defined processes and resource structures like clamping concept and specifications.

3. Behavior Models

Special types of specifications are behavior models. They describe the production system behavior ranging from very abstract models like Gantt charts to more detailed models like Impulse diagrams down to simulation based decision models.

4. CAD Construction

The CAD construction covers the detailed mechanical construction of the production system often named MCAD.

The *electrical construction* covers the detailed electrical engineering of the production system often named ECAD.

The *part list* covers the detailed definition of all parts of the production system which have to be purchased.

Simulation models are usually developed for the validation of special production system properties related to production system behavior. For example virtual commissioning or accessibility models are often developed and applied.

Control programs subsume the complete set of software developed to control the production system. Within this artifact set there are especially the HMI, PLC, and robot programs.

The *power supply concept* represents the detailed engineering of the supply of necessary energy to all elements of the production system.

The *fluidic plans* cover the engineering of the hydraulic and pneumatic systems within the production system.

The *safety concept* contains the detailed engineering of all safety related features.

All the named artifact types are not independent from each other. Figure 5 provides an overview of the dependencies between different artifact types as identified within

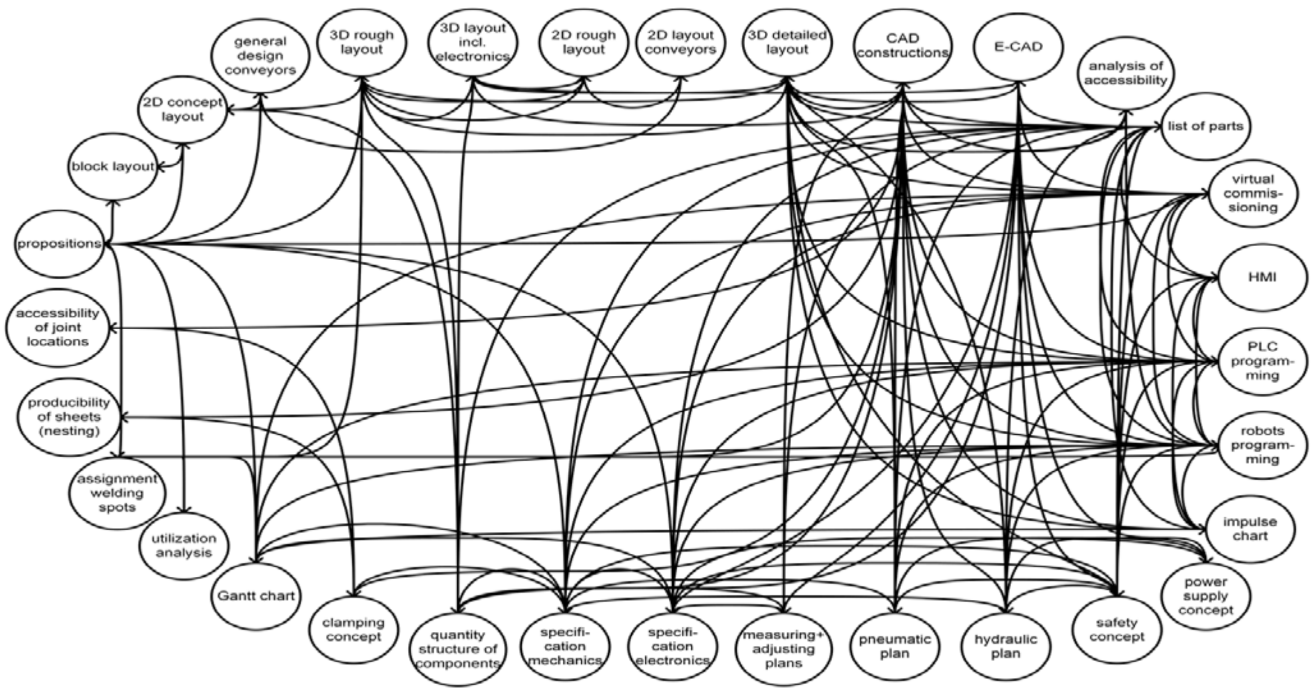

Figure 5: Dependencies between engineering artifacts

automotive industry.

B. *Artifact Assignment*

The different identified engineering artifacts can be mapped to the different layers of the production system hierarchy by considering the engineering activities within the engineering life cycles they are involved in and the hierarchy levels they address. As a result the mapping presented in Figure 6 can be concluded.

At the Construction Element layer the most detailed engineering information are relevant. They include part lists, mechanical and electrical specification, CAD construction, and electrical construction.

Similar to Construction Element layer at Component layer detailed engineering information is covered. Here basic specifications and behavior models like joint locations and clamping concepts, 3D layouts, part lists, mechanical and electrical specification, CAD construction, control programs, powers supply concepts, safety concept, electrical construction, detailed behavior models, and simulation models can be found.

At Function Group layer the engineering information are a bit more abstract, e.g. basic behavior models, 3D layouts, mechanical and electrical specifications, control programs, fluidic plans, powers supply concepts, safety concept, electrical construction, detailed behavior models, and simulation models.

At Work Station layer also rough and detailed engineering information can be found. Here basic behavior models, 3D plans, 3D layouts, mechanical and electrical specifications, control programs, fluidic plans, powers supply concepts, safety concept, electrical construction, detailed behavior models, and simulation models are relevant.

At Work Unit layer the level of detail of engineering information gets reduced. Here we can find basic behavior models, 2D layouts, mechanical and electrical specifications, 3D layouts, and safety concepts.

At Production Line Segment layer only 2D layouts are still relevant. Finally, at Production Line layer requirements and 2D layouts are considered.

For Factory and Production Network layers the analysis has not provided engineering information of interest. But following usual engineering processes only requirements and economical and technical constraints (so called propositions) might be relevant on these layers.

V. SUMMARY

In order to enhance the System Engineering approach to model the new generation of production system and their smart components, within this paper an attempt has been made towards the identification of relevant component layers and assignment of meaningful information to them required during the life cycle of a production system within the *Industrie 4.0* context.

It was possible to identify relevant layers of components within a production system as well as to answer the question which information is relevant on the different layers of manufacturing components to be virtually represented in the management shell. Within future work the authors will extend and improve the identification properties as well as the information relevant for *Industrie 4.0* component management shell for example related to component reuse and will try to model this information on a prototypical level.

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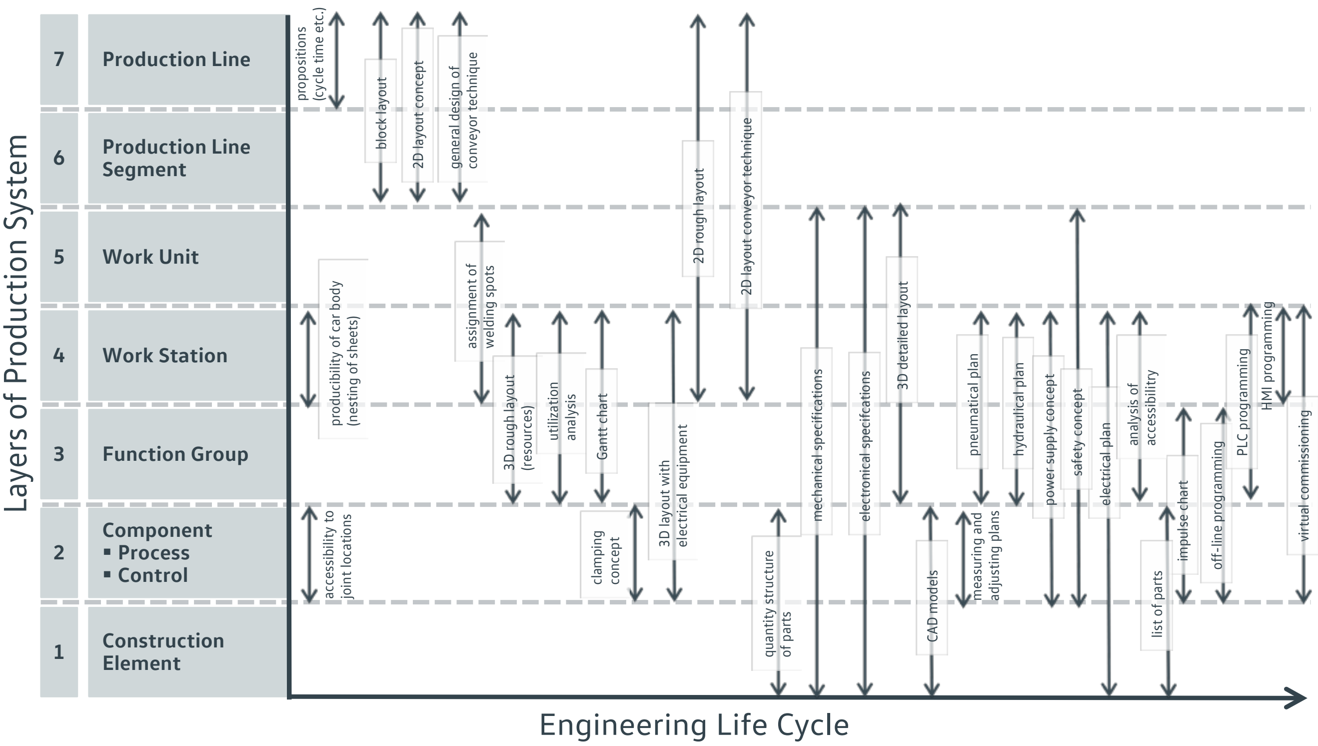

Figure 6: Layer mapping of artifacts in engineering process

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