FAKULTÄT FÜR ELEKTROTECHNIK UND INFORMATIONSTECHNIK

INSTITUT FÜR
AUTOMATISIERUNGSTECHNIK

Orchestration of cyber-physical systems based on property-based descriptions

Thomas Hadlich

Technical Report
(Draft)

IFAT-LIA 1/2015

14.07.2015

Universität Magdeburg
Fakultät für Elektrotechnik und Informationstechnik
Institut für Automatisierungstechnik
Postfach 4120, D-39016 Magdeburg
Germany

Abstract— **With introduction of cyber-physical production systems, new challenges arise. Traditional engineering approaches are not sufficient for this new type of production system and new approaches are necessary. This contribution proposes an approach to orchestrate cyber-physical systems based on properties.**

Keywords—cyber-physical system; engineering; orchestration; property-based descriptions; IEC 61360

I. Introduction

A. Classical cyber-physical systems

„Cyber-physical systems (CPS) are engineered systems that are built from, and depend upon, the seamless integration of computational algorithms and physical components."[1] – In other words: a cyber-physical system is a system consisting of physical components and software components which communicate (e.g. via the internet). As described in [2] a system may be characterized by structure, behavior and function. The behavior and functions of a CPS depend on the assigned tasks. The general expectation in regard to CPS is that the software components are some services which are executed in the cyberspace and which may be adapted quickly in order to use the physical components for some new tasks. One of the simplest examples for cyber physical systems would be a light that is monitored and controlled by a service in the internet. One of the more complex examples for cyber physical systems would be a set of production facilities, distributed all over the world, that are coordinated by services in the internet in order to produce a physical good.

Definitions of cyber-physical systems often put emphasis on the complexity of the system [3] [1]. Complexity of such systems in general describes a high level of interactions between the components [4].

Coming back to the example of the light; monitoring the light from a central service provides the benefit of less effort for maintenance of the light. – It is not necessary anymore to check the light by personal inspection, security is increased, because a failure in the light is recognized early and the costs are decreased, because a preventive exchange of the lighting material is not necessary. The interesting observation is that this monitoring service may function for any kind of lighting material, for light bulbs as well as for LEDs or fluorescent tubes. – The important part is that the function "illumination" may be monitored independently of the physical implementation.

Also – since there is a controlling function for each light, by extending the software components it is possible to extend the advantages of the complete system. For instance it would be possible to implement more cost efficient lighting schemes e.g. by lowering the lights during night hours or it would be possible to improve security by switching on all lights in an emergency situation.

Role models for extensions of existing CPS are mashup services like If This Then That (IFTTT) [5] or Zapier [6], which allow to combine existing services in a new way be defining trigger-action-statements for various types of triggers and various types of actions [7, 8].

IFTTT supports 168 sources of information (so called channels) – see [9]. For each channel, an adaptation for accessing the source of information is necessary. Such adaptation, mainly consist of defining an access mechanism for the API of the information source and a mapping of the data from the information source to a data format, which may be processed in the trigger-action-statements of IFTTT (so called recipes). The limiting factor is that the system needs to be adapted for each different source of information. Such an approach would not be acceptable for an industrial environment.

B. Industrial cyber-physical systems

Similarly to classical CPSs it is possible to develop scenarios for the integration of production facilities with software components in the cyber space. Givehchi et.al. show how for example enterprise management functions and manufacturing execution functions are executed in cyber space[10]. "Industrie 4.0" is an initiative of the German government to promote establishment of information technology (including cyber physical systems) in the German industry. The "Industrie 4.0" initiative targets flexible and dynamic production of goods executed in virtual production systems that are based on integration of production facilities even from different companies. The virtual production systems are created on demand [11][12].

C. System model

This proposal is based on a general system model introduced in [2]. A system consists of a number of system components (which in turn again may be considered as systems). The system components are connected by functional relationships. The system provides a system function. The term "system function" here describes the relation between input and output of a system without reference to implementation. For production systems this input and output is defined by information, energy, and material (e.g. starting materials and produced product). The execution of a function is described by a process. – This means a process in general describes the execution of one or multiple system functions in regard to time and space with a start state and an end state of the environment of the system.

Access to information about a system function and to execution of a system function may be offered to the environment of the system by means of a service (see Figure 1).

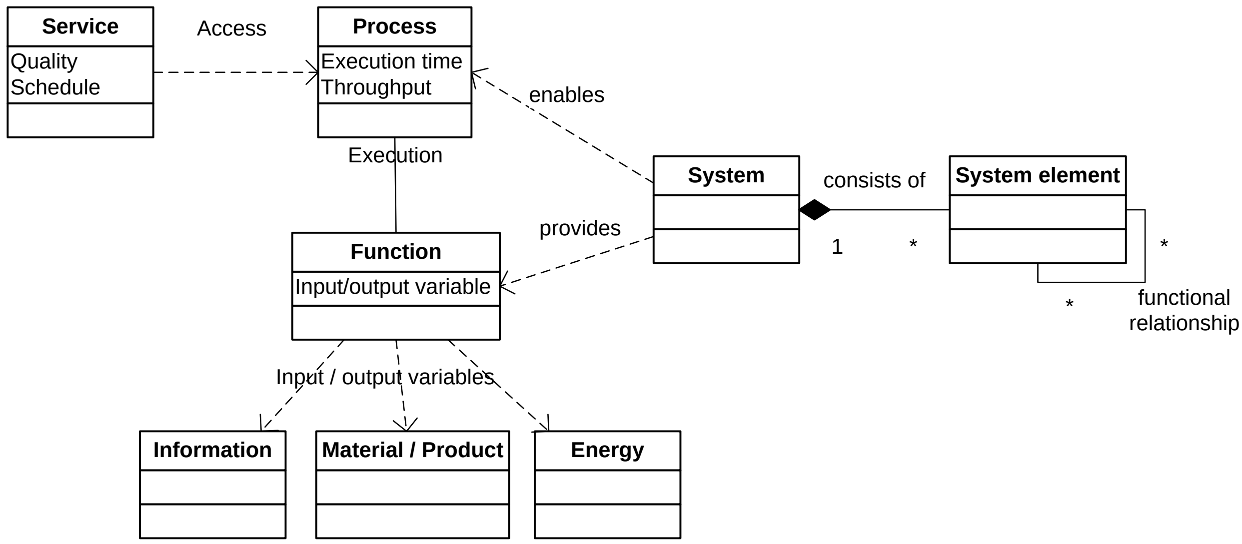

Figure 1.System model

The system function may be characterized by its type and by its inputs and outputs. The process may be characterized by the executed function and by the time required to execute the function on the respective system as well as the possible throughput (amount of input/output per time period). The service may be characterized by the executed process as well as by the agreed level of quality and the time plan for execution of the process.

D. Engineering of production systems

Creation of production systems typically starts from description of the product, for example from a Gozintograph as shown in Figure 4.

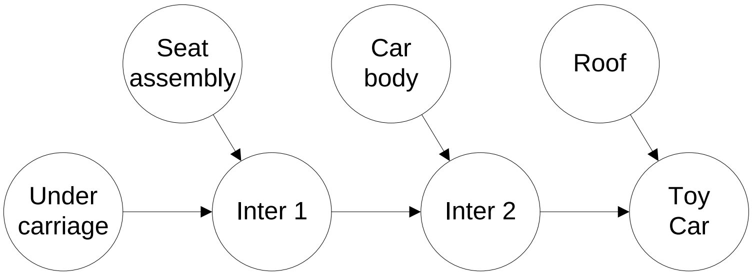

Figure 2.Gozintograph of a toy car

The product description is the base for a functional model of the production process. The functional model describes the process of creating the product. Different ways of presentation may be uses for functional models: manufacturing industry typically uses workflow diagrams, function block diagrams and Gantt-charts [13][14]. The formalized process description [15] originally was developed in order to model production processes in process industry [16], but can also be used to describe production processes in manufacturing industry [17].

Since formalized process description provides the most explicit description of a production process it is used as example in this contribution. Formalized process description shows how materials (depicted as “product”, red circle) and “energy” (light-blue rhombus) flows through “process operators” (green rectangle). A “process operator” may depict a material or energetic transformation. It is possible to show the composition of a process operator by a separate process description. For each depicted process there is a clear boundary showing the interfaces of the process in terms of material and energy. It is possible to allocate the process operators to appropriate technical resources, on which the process steps are executed [18],[15], [19], [20].

The process steps of the production describe the execution of functions of the system (see Figure 3). Traditionally this functional model is the starting point for planning the production system. The system components and the interconnection between the system components are defined. Several steps of refinement lead to detailed design of the production systems [21]. After the production system is designed, it is possible to allocate the process steps to the respective production resource (represented by the gray ovals on the right).

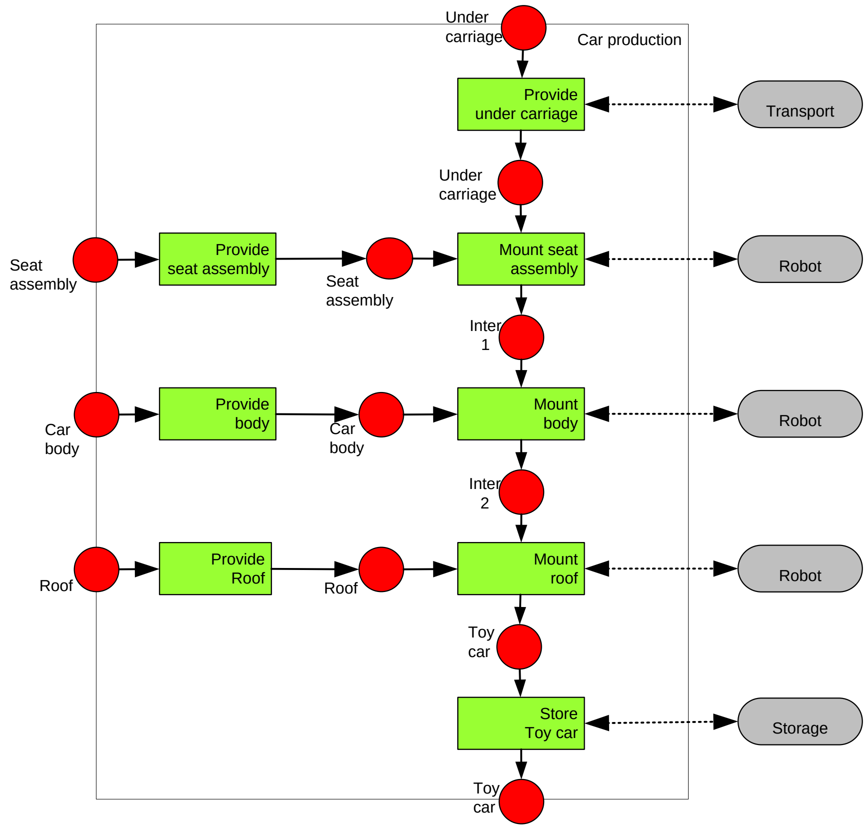

Figure 3. Description of production process according to [VV03]

Such a design of production systems is appropriate for production of high volume products. If the product is produced only in small numbers, it would be more appropriate to re-use existing production systems for execution of the production steps, even if those production systems have different locations. The currently highly favored approach for such a solution is the organization of industrial CPS, where the production is distributed across multiple production sites and is managed by services in cyber space.

E. *Orchestration of industrial CPS*

The process of integration of system components within service oriented architectures typically is described as orchestration and includes the steps of selecting the components to integrate, adaptation and management of the components [22]. Of course for a highly dynamic integration of different components, the adaptation of components for each integration must be minimized.

Starting point for such an orchestration would be the conceptual description of the production process (see Figure 4). This description would be provided by the owner of the product design (product owner), who wants to produce the respective product.

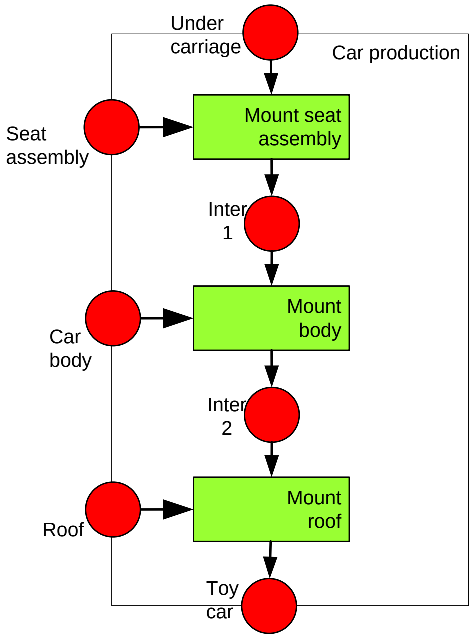

Figure 4. - Description of production process

Such a description of the production process would have to include information about the inputs (material, energy, information) as well as information on the production functions (e.g. required speed and quality).

TABLE I. Properties of product and materials

Property	Under carriage	Seat assembly	Car body	Roof	Toy car
Length(mm)	136	90	137	76	147
Width (mm)	66	51	62	56	66
Height (mm)	36	27	47	27	64
Weight (g)	54	19	34	26	133

In the next step the product owner would search for production facilities to execute the production process.

In order to facilitate such a search, the owners of production systems will advertise the production services, which can be provided with the respective production system. As explained with Figure 1, such a service description will include a description of the available system function and a description of the possible input and output (material, energy, information) of the function to execute. Such a service description does not necessarily include a description of the production system, but if the properties described in TABLE I. are considered, it becomes clear, that it is not necessary to support payloads of up to 750kg, as described in [23].

Figure 5 shows an example for a description of a production system with its production functions. The example shows that production functions are associated to system components (which itself may again be modelled as systems). It is not necessary to

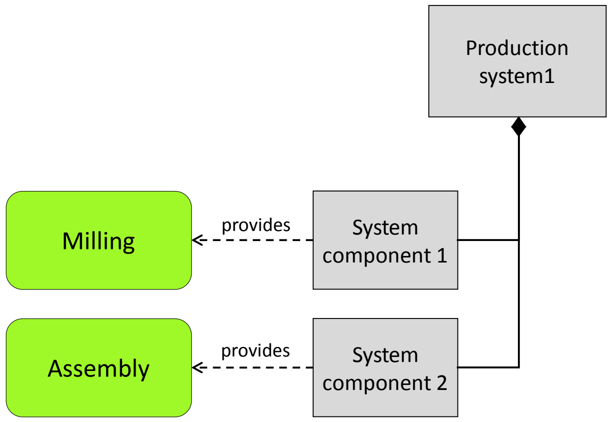

Figure 5. - Description of a production system with its system functions

Depending on the required production steps (which represent execution of system functions), one production system or a number of production systems may be needed for execution of the whole production process. The result of the orchestration of the different system components into an structure, that supports the targeted production process may be considered as virtual production system (see Figure 6).

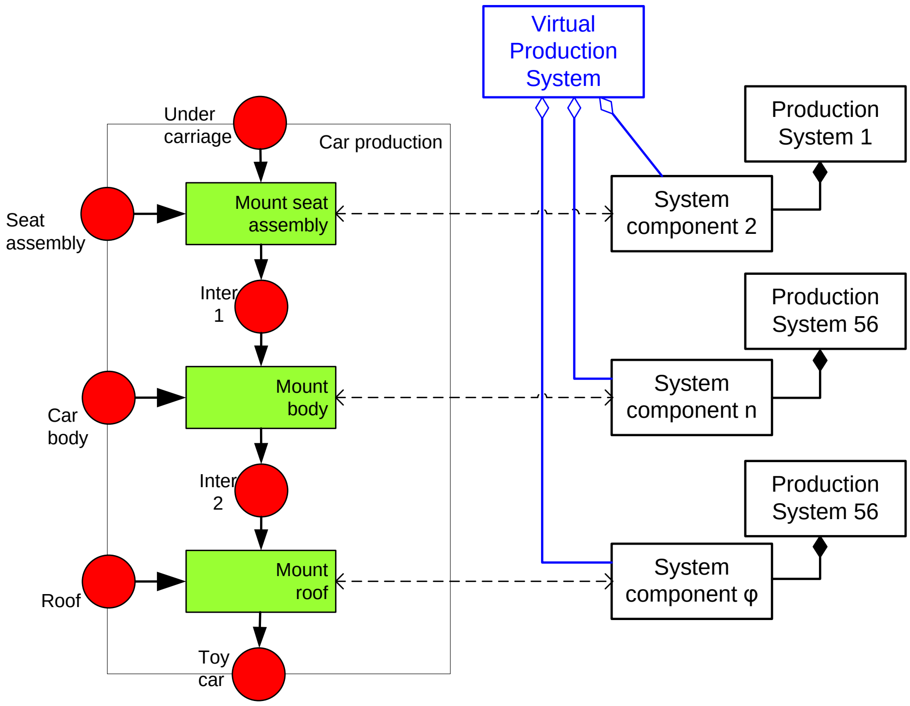

Figure 6. - Result of the orchestration

In order to orchestrate a useful integration of the different system components (production management services as well as involved production facilities) together with the option of extending the system functionality, a standardized, well suited, high-quality and unambiguous description of the different components is necessary. When looking at available technologies for describing industrial components, property descriptions are prominent and well accepted.

II. Property descriptions for equipment

Using properties for describing components of production systems is a well-established method used in industry today for comparison of automation components and used to support engineering decisions.

The property description was introduced to describe system components. An item described by properties is named "CharacterizedEntity". A property according to IEC 61360 may be used to characterize and classify the described item. Systems and system components may be considered as CharacterizedEntity and be described by appropriate properties.

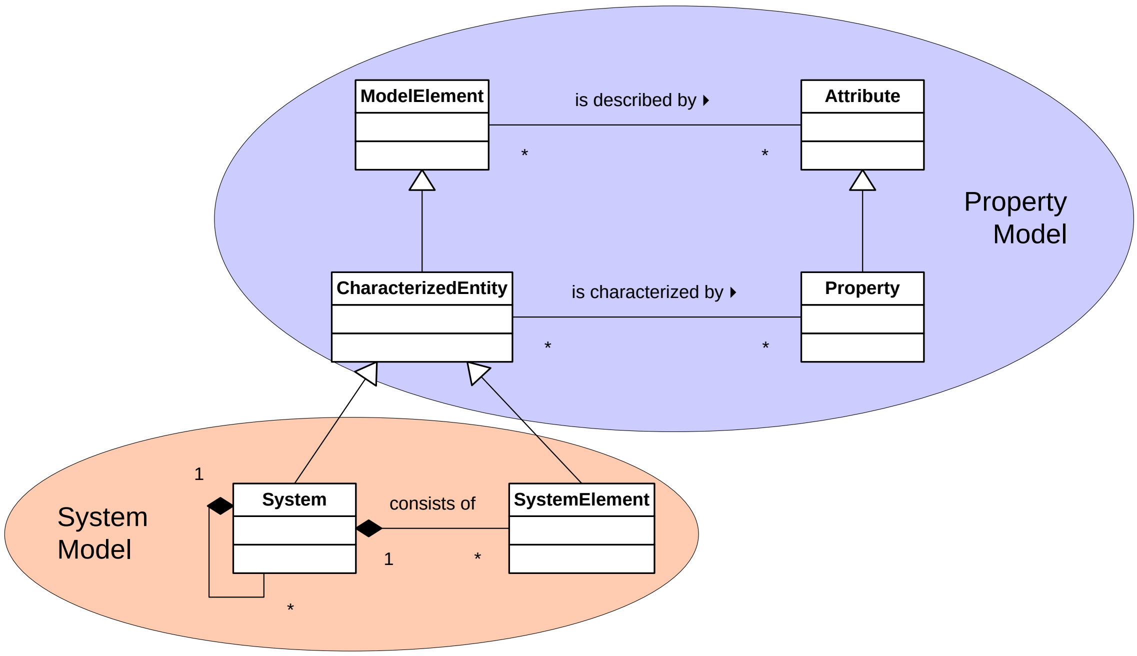

Figure 7. - Relation between property model and system model

Different organizations (e.g. PROLIST, eCl@ss) work on standards to describe specific components of production systems (e.g. NE100, IEC 61987-10). In such applications the property has a dual usage. On one side a property, which is defined semantically unambiguous (according IEC 61360-1), is used for description of the components. On the other side a property may be considered as data element with a clear definition of meaning, range of values and measurement unit (according IEC 61360-2).

The standard IEC 61987-10 based on IEC 61360 defines different concepts for property based descriptions, for instance "Lists of Property" (LOPs), cardinality and polymorphism. LOPs are used for grouping of properties, which describe a specific aspect of the system component, for example all properties for description of an interface or all properties for description of a contact address. Cardinality is used to describe aspects of a system component that can have multiple instantiations, for instance if a component has multiple times the same interface. For description of a cardinality aspect, a counting property is defined (e.g. count of process interface) together with an LOP, which is instantiated as often as defined by the counting property (e.g. for describing each process interface). Polymorphism describes the possibility to describe different implementations of an aspect. For example if there are different types of process interface, for each type a different LOP may be provided. A condition property controls which type of the aspect will be described. According to the value of the condition property the respective LOP is used for description of the aspect. This approach to describing components of production system is widely accepted and has been applied in several international standards, e.g. several parts of IEC 61987 describe process measurement equipment and actuators and several parts of IEC 62683 describe starters, switches and circuit breakers.

Hadlich et.al. proposed in [24] an extension of the property model to support development of systems. This extension allows describing the relations between system components. For this extension a component relation is considered as a CharacterizedEntity, which is described by its own set of properties. This proposal now is integrated into the current draft of IEC 62832 [25].

For orchestration of cyber physical systems the problem is that the full description of the production facilities is too complex and contains too much unnecessary information.

In this contribution we propose to extend the property model to the description of system functions. This extension supports the functional modeling of CPS.

III. Extending the property descriptions to functions

In this contribution we propose to extend the property model in a way to support also description of system functions. Full description of a system function includes the description of input as well as output of the function. For production systems input and output may be described as CharacterizedEntities ‘information’, ‘product’, and ‘energy’.

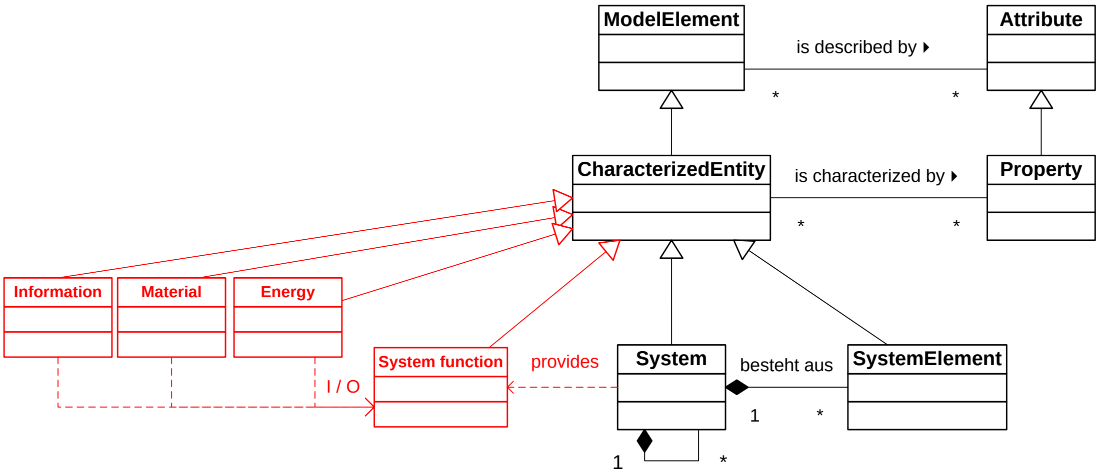

Figure 8. - Extension of the property model

With this extension it is possible to describe system functions with semantically unambiguous properties.

According to IEC 61360 system functions, information, material and energy may be described as CharacterizedEntity (“ItemClass”) and each class will be described by a specific set of properties.

The super class “system function” will be described by a set of properties, which is applicable to all system functions. From this super class, different classes may be derived, describing system functions of discrete manufacturing industry, process industry and logistics. Figure 9 shows an example for classification of manufacturing functions according to Groover[26]. According to this classification, properties may be defined at different levels of the class hierarchy and sub-types of functions may inherit properties from super-types of functions.

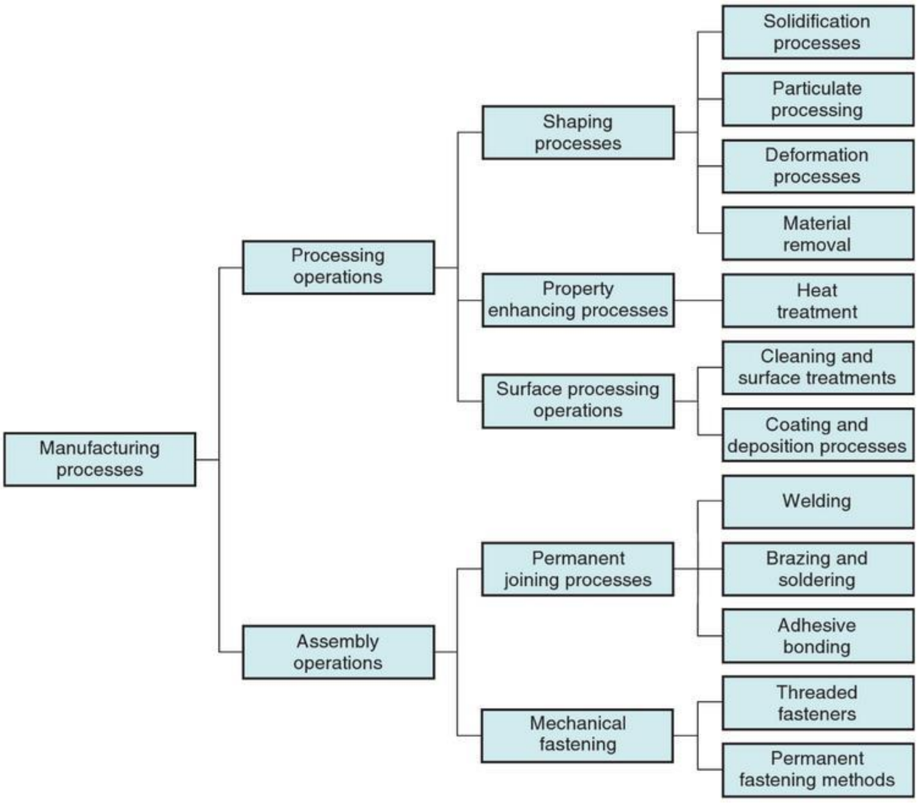

Figure 9. - Classification of manufacturing functions [26]

Proposals for properties of the super-type "system function" as shown in TABLE II. :

TABLE II. Properties of system functions

ID	Short name	Definition	Unit
THA001	Availability	Ratio of operating time to planned production time.	%
THA002	Execution time	Time for execution of the system function for a defined amount of input.	e.g. seconds per piece, hours per ton
THA003	Throughput	Maximum amount of input that can be processed within a certain time span.	e.g. pieces per hour, gallons per second

In general it would be useful to consider key performance indicators as defined for instance by IEC 62264 [27] for general properties describing the capability of production facilities to execute system functions.

TABLE III. shows examples for properties which are specific to certain system functions. Drilling is considered as one type of material removal functions according to Figure 9. Based on the shown properties it is possible to define properties that support selection of the correct equipment. For instance the required dimensions of the drilling hole are important for selecting the correct drilling equipment and the weight of the work piece is important for selecting the correct handling equipment.

Third line and fourth line of TABLE III. show that the same properties may be used to describe different functions. – The property THA021 actually is a property of material and applies to all discrete manufacturing functions.

TABLE III. Specific Properties of system functions

ID	Function	Short name	Definition	Unit
THA011	Drilling	Drilling hole diameter	Diameter of the whole that is created by drilling.	mm
THA012	Drilling	Drilling hole depth	Depth of the whole that is created by drilling	mm
THA021	Assembly	Material weight	Weight of a workpiece that is handled in an assembly function.	kg
THA021	Transport	Material weight	Weight of a workpiece that is handled in an assembly function.	kg

When the elements of the functional model and the system functions provided by available production facilities are described by property descriptions, selection of the most fitting production facilities becomes simple. Considering for example Figure 4, if mounting of seat assembly, mounting of body and mounting of the roof of the toy car have different requirements in regard to weight of the work piece, dimensions of the work piece or accuracy of placement, different production facilities could be selected for execution of the respective function.

Since property-based descriptions are semantically unambiguous and independent of natural language, it would be possible to use the same description system for all production facilities in the world, thus allowing to select the most appropriate facility for execution of a production task. Using the mechanisms of IEC 61987-10, such as polymorphism, cardinality etc. it also will be possible to describe the decomposition of functions.

IV. Summary

This contribution proposes to introduce property-based descriptions for functions provided by production systems. Property-based descriptions for production equipment are well established in the market and have proven their advantages for worldwide trade as well as for support of engineering decisions. These advantages will also apply to orchestration of CPS, providing a standardized and unambiguous means of communication between service providers and clients.

While this contribution focuses on properties of functions of production systems, similar descriptions might be provided for other functions. Similar function descriptions may be provided for all levels of the equipment hierarchy (e.g. site, line, machine, and control device), enabling service orchestration on different levels of the hierarchy (depending on the respective use cases). However for definition of properties for system functions the participation of domain experts will be necessary.

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