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# Asset Administration Shell and Knowledge Graph-based Production Logistics Planning in Fluid Manufacturing Systems

## Verwaltungsschale und Wissensgraphen-basierte Planung der Produktionslogistik in einem Fluiden Produktionssystem

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**Shorter product life cycles, increased product variety and volatile sales figures are some of the main challenges of manufacturers nowadays. In order to deal with these challenges and maintain a competitive edge, changeable production systems such as Fluid Manufacturing Systems (FLMS) with corresponding production logistics become particularly important. FLMS provides the required flexibility and changeability to meet continuously changing requirements. Traditionally, production logistics planning is conducted holistically and designed after the factory and production planning stage with monolith software applications e.g. ERP, CAD or with conventional office tools. This procedure is suited for production environments with nearly constant and predictable production conditions. However, it is limited in terms of interoperability and insufficient for changeable production systems. Therefore, integral, knowledge- and software-based approaches are necessary. This paper presents an approach for the planning and reconfiguration of production logistics in FLMS by using Asset Administration Shells (AAS) and knowledge graphs.**

*[Keywords: changeable and reconfigurable production systems, Asset Administration Shell, knowledge graph, ontology, production logistics]*

**Kürzere Produktlebenszyklen, zunehmende Produktvielfalt und schwankende Absatzzahlen gehören zu den größten Herausforderungen der Hersteller in unserer Zeit. Um diese Herausforderungen zu bewältigen und die Wettbewerbsfähigkeit zu sichern, sind wandelbare Produktionssysteme, wie beispielsweise die Fluide Produktion, mit einer entsprechenden Produktionslogistik besonders wichtig. Die Fluide Produktion bietet die nötige Flexibilität und Wandlungsfähigkeit, um den sich ständig ändernden Anforderungen gerecht zu werden. Traditionell wird die Planung der Produktionslogistik ganzheitlich nach der Fabrik- und Produktionsplanung mit monolithischen Softwareanwendungen wie z. B. ERP, CAD oder mit herkömmlichen Office-Tools durchgeführt. Diese Vorgehensweise eignet sich für nahezu konstante und vorhersehbare Produktionsbedingungen. Jedoch zeichnen sich bisherige Lösungen - durch eine begrenzte Interoperabilität aus und sind unzureichend für Wandelbare Produktionssysteme. Aus diesem Grund sind integrale, wissens- und softwarebasierte Ansätze erforderlich. In diesem Beitrag wird ein Ansatz zur Planung und Rekonfiguration der Produktionslogistik in einer Fluiden Produktion unter Verwendung der Verwaltungsschale und Wissensgraphen vorgestellt.**

*[Keywords: Wandelbare und rekonfigurierbare Produktionssysteme, Verwaltungsschale, Knowledge Graphen, Ontologie, Produktionslogistik]*

## 1 INTRODUCTION

Recent events such as the semiconductor crisis, Suez Canal obstruction or the COVID-19 pandemic have led to material shortages in production all over the world. Consequently, manufacturers have needed to react and adapt to the new circumstances. One example is re- or nearshoring the production back to Germany or sourcing material from suppliers in Germany or closer countries to reduce dependence on supply chains [1], [2]. However, this is quite complex and requires additional investments in capacities and resources for manufacturers and suppliers. Alternative solutions are therefore in demand. Novel approaches such as Matrix-structured Manufacturing Systems (MMS) or FLMS are suitable solutions for this, by enabling the manufacturing of different products and variants within the same factory. Furthermore, these production systems offer reconfiguration, by adjusting the functionality and capacity of a production system to respond to unexpected events. Nevertheless, the planning and reconfiguration of a production system as well as the corresponding production logistics are associated with increased planning effort, since current practice involves the manual execution of the

  

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associated tasks by experts [3]. In production planning and control, different approaches and software tools have already been established to support the outbound logistics process. However, there is a lack in the field of production logistics. Therefore, comprehensive and software-based approaches for production logistics planning for changeable production systems are necessary.

The remainder of this paper is organized as follows: Section 2 provides an overview of the state of the art. Section 3 outlines the planning approach. Following this, Section 4 presents the framework for implementation and execution. Section 5 concludes with the main points of this paper and provides an outlook.

## 2 STATE OF THE ART

### 2.1 PRODUCTION SYSTEMS

In the past, production technology was primary defined by **Dedicated Manufacturing Lines (DMLs)** or product-specific machines [4]. The DML is a production system which relies on the sequential organization of rigid dedicated production modules in a unidirectional flow [5]. Each DML is typically designed to produce a specific part at a high volume, ensuring cost efficiency. Over the years, however, the increasing variety in products and the demand for flexibility led to overthinking conventional production systems. In this context, the term "changeability" was introduced. Changeability refers to a system's capability to expand its system corridors through changeability enablers such as modularity, universality, neutrality, scalability, compatibility, and mobility. This enables the swift adaptation of production system functionality and capacity. Since its inception, this concept was the driving force for the development of various novel production systems [6], [7].

The **Flexible Manufacturing System** is a comprehensive system, which integrates production modules and material handling equipment. It addresses various aspects of flexibility in routing, processes, volumes, machines, products in a pre-defined flexibility range [5], [8], [9].

The **Reconfigurable Manufacturing System** (RMS) is a highly dynamic and evolvable system suitable for unpredictable events [14]. Furthermore, it resolves the limitations of DML and FMS by enabling hardware and software adjustment beyond fixed flexibility boundaries.

The **MMS** consists of flexibly-linked and usually dedicated production modules, usually with pre-defined technological functionalities essential for production. MMS introduces innovative production control capabilities by empowering products to independently determine their unique production path [10], [11].

The **FLMS** is an evolution of the MMS. In FLMS, the different process modules are mobile and are comprised of mobile cyber-physical systems (CPSs), which allow the ad-hoc combination to be adjusted to changing requirements [12].

The presented changeable production systems are characterized by reconfigurability to changing production environments and market demands. Although the vision of reconfiguration has existed for several decades, the desired degree of implementation has not yet been realized as the status quo in the industry [13], [14]. This has resulted in a research gap for the planning of the reconfiguration process in production and logistics systems.

### 2.2 LOGISTICS-ORIENTED RECONFIGURATION OF FLMS

According to Koren, reconfigurability is defined as the ability to change and evolve rapidly in order to adapt productivity, capacity and functionality. The reconfiguration process is mentioned and discussed regarding different productions systems such as FMS, RMS and MMS [5], [15], [16]. However, the reconfiguration process in an FLMS is more extensive and sophisticated due to the additional degrees of freedom and involves different levels of a production system as can be seen in Figure 1.

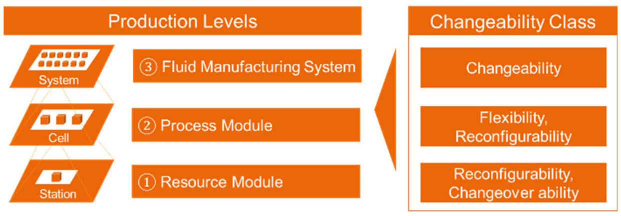


*Figure 1. Production levels with corresponding changeability classes, extract, based on [15], [16], [17]*

The adaption categories of reconfiguration involve, in different hierarchies, the ability, sequence and capacity of a production system, which are taken from Trierweiler, 2011 [16] and extended for this paper. The reconfiguration of an FLMS and the corresponding logistics is further described in Table 1 and 2.

*Table 1. Options for Adaption in FLMS on Production System Level, based on and extended from [18]*

| | **Production System level** |
|---|---|
| Ability | Add/remove/combine process modules with diverse capabilities |
| Sequence | Change position of modules |
| Capacity | Increase/decrease number of modules |

*Table 2. Options for Adaption in FLMS on Process Modules, based on and extended from [18]*

| | **Process Module** |
|---|---|
| Ability | Add/remove/combine resource modules with diverse capabilities |
| Sequence | Change position of resource modules inside process modules |
| Capacity | Increase/decrease number of resource modules |

In contrast to MMS, where the reconfiguration is only limited to certain capabilities, the reconfiguration has diverse capabilities in an FLMS with high changeability [12]. Besides, there are also flexibility and changeover options in the reconfiguration of an FLMS. More detailed information can be found in [15], [18].

*Table 3. Options for Adaptions of the Logistics System in an FLMS*

| | **Logistics Systems** |
|---|---|
| Ability | Add/remove/combine resources with diverse capabilities |
| Sequence | New source-sink relationship, layout changes |
| Capacity | Add/remove and combination of resources |

The reconfiguration of logistics resources can be accomplished by changes in hardware, for example by calibrating sensors or software via reprogramming or adapting the software [19].

- Smart Load Carrier: reconfiguration of different parts and products
- AGV/AMR: rerouting, rescheduling or new source-sink relationship
- Buffer/Storage System: for the stock of different parts and products

The reconfiguration can have many configuration options. For this reason, the best option must be weighed up, based on parts inventory, system productivity, reliability, and cost of the system [8].

### 2.3 Production Logistics for Changeable production systems

Production planning is responsible to ensure the correct procedure of material retrieval and assembly. Logistics, in contrast, has, according to REFA, to ensure the provision of the necessary materials in the appropriate quantity and type, to the designated point of use, at the correct time, in order to facilitate subsequent processing [20]. This process could be very complex and costly, due to the constantly changing production conditions and increasing number of materials. In the past, with the proven approaches Just-in-time and Just-in-sequence, and the introduction of the supermarket concept, manufacturers were able to handle this situation economically [10].

The development of changeable production systems with the reconfiguration options for different products and variants, led to overthinking these strategies. As a result, more logistics approaches for a changeable production system, especially for MMS and FLMS, have been developed in recent years.

Popp, 2015 developed and introduced various concepts for material supply with technical solutions for MMS. This includes logistics concepts such as the set-concept, the autonomous guided vehicle concept (AGV-concept) or the rack-concept [21]. Filz et al., 2019 presented an approach for material supply for MMS by considering multiple delivery locations, capacity planning and flexibility [22] [26]. Fries et al., 2019 examined a concept for MMS by defining decentralized and centralized material buffers to deliver material to different production modules [23]. Furthermore, it was evaluated in terms of complexity and flexibility. Müller et al. 2020 explored the effects of different levels of similarities in different order sequences on the logistics performance [24]. In addition, he explored a concept for an in-plant frozen period for orders and analyzed the effects.

Hagg presented an approach for short-term-oriented material supply which supports checking and ensuring material availability in FLMS [25]. Additionally, Bozkurt, Hagg and Schulz presented new control mechanisms for the material supply [26]. In addition, Bozkurt et al. provided a technical solution for the event-based, decentralized control of material flow [27]. Munzke et., 2021 presented a planning approach for an optimal logistics system, which supports the iterative optimization of the flexibility corridor [29]. The presented approaches are validated with simulations or are tool-based solutions.

In summary, all these strategies focus on material provision and order management. As previously mentioned, these strategies are typically designed to be applied in the operation stage. However, there is still a research gap concerning a holistic approach for planning production logistics integrated with the production planning process.

### 2.4 Information modelling

#### 2.4.1 Product, Process and resource Model

For the greenfield planning and reconfiguration process of a production and logistics system, various pieces of Information are needed [13]. These data are necessary for the planner’s understanding and knowledge about the process, products, software and hardware resources with their individual capabilities, constraints and possible interactions [19], [28]. Usually, these pieces of information are provided from heterogeneous data via models and metamodels within the product-lifecycle e.g. engineering, purchasing, production or logistics [29]. However, to avoid ambiguity and ensure that all actors have the same understanding of the data, uniform rules and standards are needed. In this context, interoperability is a primary aspect. According to IEEE, interoperability is defined as "the ability of two or more systems or components to exchange information and to use the information that has been exchanged" [30]. In the literature, there are many more definitions in different contexts [29]. To ensure interoperability in the context of smart manufacturing and CPS, various approaches, rules and models for information modelling have been developed over the years [31] , [32], [33]. Some of these approaches are discussed in the following.

In capability-based (continuous) engineering and operation management, the data is structured into the relevant domains of product, process and resource, which are also known as PPR-Triples [34], [35]. Each domain has its own design data and rationale [36]. The interaction between the different domains are shown in Figure 2. A process initiates the product, which has to be produced, while one or more resources perform the process. The product has requirements for the technology, while the resources need material to produce the product [28], [37].

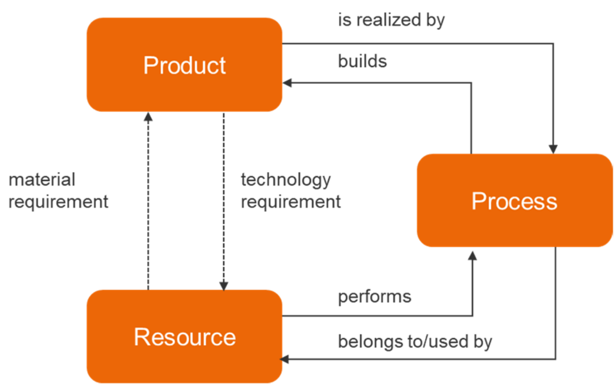


*Figure 2. Product-Process-Resource-Model [28]*

The main advantage of this approach is interoperability between the different areas of engineering, production and management [38]. Furthermore, it is applied in the plant planning with AutomationML for the exchange of asset information and machine interpretation or in the context of Product-Lifecycle Management (PLM) [35], [38]. Another advantage is that it provides a solution for integral planning with the integration of logistics.

### 2.4.2 AAS

The German "Plattform Industrie 4.0" introduced the AAS to create a standard for a digital twin and cross-vendor communication standard for Industry 4.0 components [39]. In addition, it outlines an entity, which can be a physical object or a software artifact, and an individual or sophisticated system, or a process and its digital representation in the form of an AAS [40]. In this context, an AAS exists individually or in the context of the nesting concept with several AASs in a network. The degree of granularity depends on the particulars of the use case [38], [39]. AAS enables an exchange of information such as operational states and the provision of functions such as Industry 4.0 component control. AAS provides interoperability and data transparency across all operating equipment and process steps involved in the value chain [6], [39], [27].

#### SUBMODELS

Submodels allocate the technical functions (capabilities) and information related to an asset. Each aspect of an Industry 4.0 component can be defined independently [41]. Against this background, it specifies the properties associated with an attribute, which include occurring events ("events"), provided operations ("operations"), and additional data and information [41], [42]. The individual properties, events and operations are defined as follows:

In an AAS, a submodel can be defined by any number of **properties**. A property describes a static or variable attribute, e.g. a position, color or serial number. The specification of properties of an Industry 4.0 component remains valid until the asset communicates a change. Uniqueness is ensured via the description and data type. The data types are based on JavaScript Object Notation (JSON) [39].

**Events** have a unique time reference compared to the properties by means of a timestamp. Examples of this include the arrival of an AGV at its destination, or the completion of an assembly process or similar. Events have a unique name and are able to publish other data elements. Each data element is specified in a manner similar to properties [39], [42].

Properties and events describe the nature of outgoing communication, while **operations** define the services that may be invoked by other components. An example of this is a transportation process [42]. The sum of all submodels results in the digital representation of the asset, which is visualized by the AAS and extended by data value-added services [40].

According to Plattform Industrie 4.0, there are currently three categories of AAS based on their interaction patterns. The passive pattern operates with static files or file packages, which are included with asset information in a standardized data format like XML or JSON. The reactive pattern has the same information content as the passive pattern, with the difference in its ability to exchange information with other AASs or software applications such as PLM or ERP systems via an Application Programming Interface (API). The API can utilize web-based transfer protocols like the Hypertext Transfer Protocol (HTTP) or Message Queuing Telemetry Transport (MQTT). The pro-

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active pattern is capable of protocol interaction between different AAS by utilizing the common Industry 4.0 semantic, as specified in VDI/VDE 2193. The purpose is to design decentral organized processes that build on a certain autonomy or decision-making ability of the AAS [43], [44].

### 2.4.3 Ontology and knowledge graphs

#### Ontology

The term "ontology" first appeared in philosophy in the 18th century, where ontology is a systematic account of existence [45]. Furthermore, it describes the "science of being" with the focus on the significance of classifying and categorizing the interactions of existence. In computer science, it is especially used by artificial communities, to structure and exchange information. According to Gruber, ontology represents a domain, with its related objects, and the describable relationships between them in a declarative formalism [45]. Additionally, ontology is the common understanding of information between people, machines or software agents. Additionally, it enables the reuse of domain knowledge, to separate knowledge in order to analyze it with the domain knowledge, as well as to make domain assumptions explicit [45], [46]. Meanwhile, ontologies have found a wide range of application and offer various advantages and have consequently arrived on the desks of domain experts, e.g. in the categorization of products or websites with taxonomies to describe the hierarchical structure.

The main advantages of ontologies are [45], [47–49]:

- use, reuse and maintainability of information
- shared use of expertise through uniform semantics
- flexibility for the definition of classes, properties and relationships
- integration of reasoning rules through different engines
- use of natural language queries, which simplifies the search for information
- integration of knowledge from different sources

Different standards have been defined over time for the development of ontologies. The WWW Consortium (W3C) developed the Resource Description Framework (RDF) as a standard model for data interchange on the web. Furthermore, it is used for decoding knowledge on websites to make it machine readable to electronic agents searching for information [46]. A recent specification is the "web ontology language" (OWL), informally OWL 2 with so-called "axiomatic triples". The structure of axiomatic triples are organized as follows:

```
(1)rdf:type rdf:type rdf:Property.
(2)rdf:type rdfs:domain rdfs:Resource.
(3)rdf:type rdfs:range rdfs:Class.
(4)rdfs:Datatype rdfs:subClassOf
rdfs:Class.
(5)rdfs:isDefinedBy rdfs:subPropertyOf
rdfs:seeAlso.
```

The part of the ontology to which the designation of a vocabulary term belongs is in (1). In the case of a property, the domain (2) and range (3) are specified. Additionally, (4) describes the hierarchical relationship between classes of properties (5) [51].

Ontologies are used in many different domains in the production environment e.g. Manufacturing, Product, Remanufacturing and Reconfiguration [52–55]. In the area of production, many frameworks for ontologies are already available. However, there is a lack in the area of internal logistics ontologies. Individual solutions are available in the area of warehousing and storage with an insufficient level of detail. In addition, a satisfactory description of the relationship between the elements of product, processes and resources, as well as the taxonomies for a logistics ontology in a PPR model, is still missing [56], [57].

### 2.4.4 Knowledge Graphs

Knowledge graphs (KGs) are a type of graph that use nodes connected by relationships to provide context to the underlying data through rules for structure and interpretation [48]. Furthermore, KG provides semantically-structured information with properties, in a machine- and human-readable form [58].

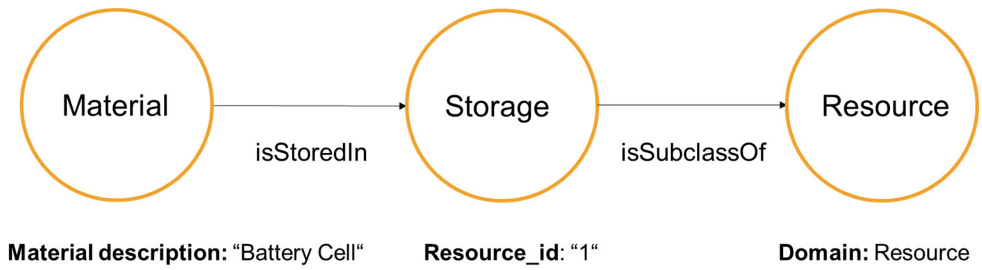


*Figure 3. Nodes and relationships based on [50]*

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In contrast to ontology, KGs are the manifestation of the ontology of a specific subject [59]. The ontology, in connection with the information of the database, results in a KG. Additionally, it consists of the logic of linked data using an ontology. [60]. Figure 9 presents an example of a node with the entities of material, storage and the domain Resource.

KG have been implemented for different domains, to increase the usage and discovery of data [61], [62]. Furthermore, KG and graph databases are used for graph statistics, by determining statistical measures about the graph. Graph analytics and reasoning are determined by analyzing graph data to provide answers, the utilization of queries or graph algorithms. For example, if the KG contains a fact like (Material x isStoredIn, Load Carrier_1), (Load Carrier_1 isLocatedIn, shopfloor), the missing link is obtained as (Material x isLocatedIn, shopfloor). The knowledge reasoning is not limited to attributes and relationships between the different entities, but also includes the values associated with entity attributes and the hierarchical structure within the ontology [63].

## 3 Production Logistics Planning for Fluid Manufacturing Systems

The term "planning" finds a large application in practice and is the prerequisite for the economic performance in production [64], [65]. According to REFA, planning is the systematic search and definition of goals as well as tasks and the means to achieve the goals [20]. A reference to the future is evident in all definitions [64], [65].

The object of the planning is a system, consisting of a set of elements that are connected to each other by relationships in the form of a hierarchy or structure. Additionally, a system can be described by its system boundaries, elements, relationships, input and output and its purpose [66], [67].

The first aspect is the development of a planning system, which enables the integral planning of the production and logistics. Integral approach means that all aspects of the overall system are necessary to perform holistic and effective planning and to exploit the full potential of the overall system. Therefore, in addition to logistics, the bordering areas of product development, factory and production must be included in the planning.

The second aspect is the consideration of production system specific requirements such as the reconfiguration and mapping of a cyber-physical production system as well as the consideration of the different levels of freedom in an FLMS. Finally, the requirements in information modelling are considered such as the application of uniform rules, standards and the interoperability of CPS [68].

### 3.1 Factory and Production Planning

Besides organizational and economic decisions, the product and its bill of materials (BOM) have a decisive strategic influence on the engineering, production and logistics processes. Together with the associated BOM, and the corresponding resources, it represents the starting point for the factory, production and logistics planning processes [22].

Planning starts with product engineering (1), which is responsible for the design of a new product. Afterwards, the product is broken down in a BOM and into components to be manufactured. Subsequently, either the factory planning (2) begins or, if a factory already exists, production planning (3) is started directly, which is divided into the following phases according to VDI 5200, as presented in Figure 4.

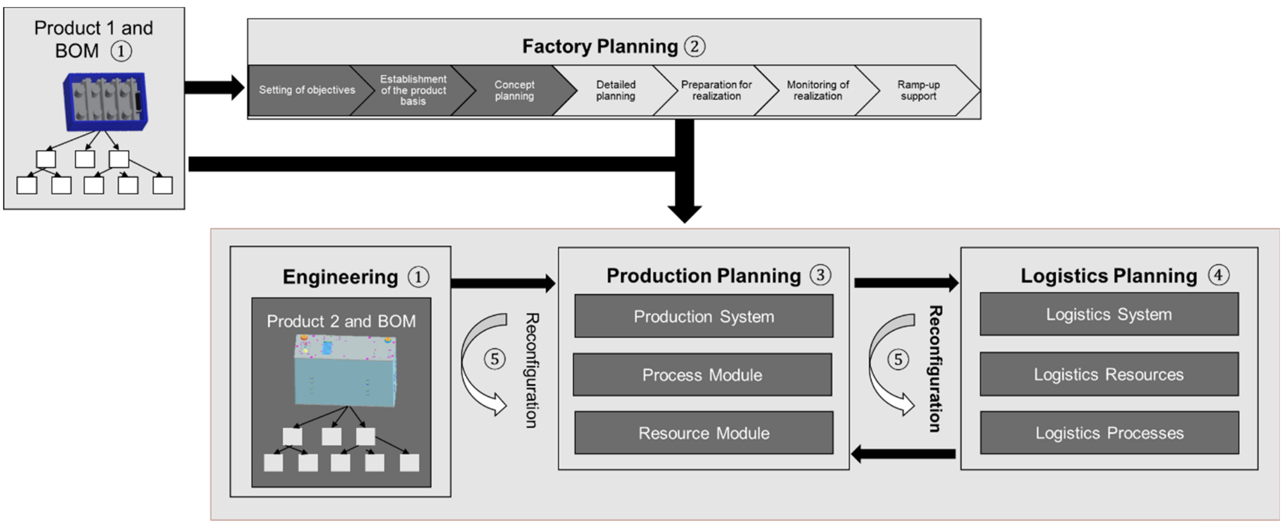


*Figure 4. Approach for an integral factory, production, and logistics planning and reconfiguration.*

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In the first and second phases of factory planning, the relevant objectives are defined and the basic principles are determined e.g. boundary conditions and constraints are defined [69].

In the third phase, the "concept planning phase", a holistic design for the factory is developed. The goal is to create a feasible factory concept based on the results obtained in the previous phases and to achieve the objectives [69]. The focus of this paper is on rough planning, which considers the phases 1-3.

In phase 3, the production planning (3) also takes place. The determination of a changeable production system, e.g. FLMS, includes different planning parameters such as process modules, capabilities, layout and employees. By defining the planning parameters and objects, the changeability framework, as well as the flexibility corridor of the production system, is determined, which can only be changed by extending the system boundary, e.g. by structural or technical measures such as the expansion of the production network or new acquisitions [23]. Theory by Hinrichsen et al. complements this step by focusing on production planning and control (PPC) with the tasks, capacity planning and checking of the material availability from the order management perspective [70].

### 3.2 Production logistics planning

Logistics planning (4) encompasses different areas of logistics, such as procurement, transportation, warehousing, production network, distribution and disposal logistics [71], [69]. In the literature, there are many approaches for logistics planning e.g. 7-step planning system from Jünemann or ten Hompel [71], [72]. Logistics planning (4) is the presented concept that focuses on material supply. Production logistics extends across all manufacturing and assembly systems [73].

Therefore, the aim of this approach is an integral planning approach, to fulfill the potential of an FLMS. The planning of material supply requires the selection of resources, the definition of organizational material provision strategies (processes) for the individual materials (products). Various systematics are used, which suggest suitable supply principles on the basis of the product characteristics [74].

### 3.3 Reconfiguration of the production system

If the reconfiguration (4) of a production system is triggered, e.g. by a new product or product family, this represents an iteration step in the planning. The new product with its new specifications represents a new input variable in the planning of production and logistics. In the production process, it results in the change of the process modules and resource modules as described in Section 2.2.

First, the logistics planner has to check the availability of the required material along the supply chain, plan it for the new product and control it in the subsequent planning process. Subsequently, which load carrier is suitable for the transport process must be checked. In the next step, whether the material supply is compatible with the existing logistics concepts and equipment must also be checked. Otherwise the reconfiguration of the logistics system takes place via the adaption of the logistics system.

## 4 The Framework for AAS and KG-based Production Logistics Planning in FLMS

In this chapter, the framework for the software and hardware implementation of the AAS and KG-based logistics planning for FLMS is illustrated. The framework is intended to support steps 1-3 of the planning process to perform rough planning. The framework is structured in four stages as shown in Figure 5.

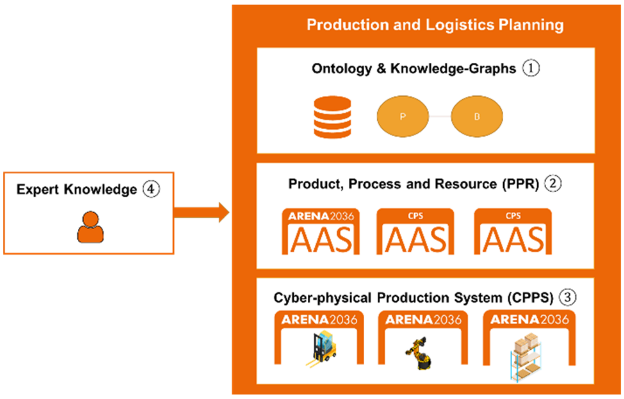


*Figure 5. The Framework for AAS and KG-based logistics planning in FLMS (own representation based on [70])*

In the first step, an FLMS ontology was implemented in Ontotex GraphDB, based on the specification of the web ontology language (OWL). As a conceptual layer of the planning system, it is used for the definition, integration and multi-criterial decision-making of the relevant domains (product, process and resource) and the corresponding information as metadata. In Figure 6, an excerpt of the information for PPR is illustrated.

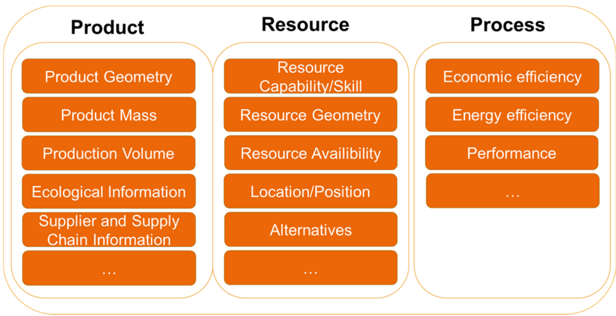


*Figure 6. Excerpt of PPR Information and Metadata*

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In this context, KGs are used for knowledge representation and reasoning of the relevant domains [6], [7]. It shows the hierarchy and the relationships between the different objects.

### 4.1 Integration of PPR

The AAS is implemented for the semantic self-description of the different CPSs. At the beginning of the planning phase, the AAS and the ontology initially contain only statistical data and have a low information content. For example, information about the product through the AAS with the necessary CAD models and BOM. In the production and logistics, the different resources are already produced or provided from the OEM with an AAS. The AAS contains the necessary information such as capabilities/skill or resource geometry. Meanwhile, standardized submodels, e.g. for electrical equipment based on IEC61360, or product carbon footprint are provided, through different initiatives like Industrial Digital Twin Association (IDTA).

In the subsequent stages of the planning process, the informational content progressively grows until the operational phase. In this phase, the informational content remains constant, as illustrated in Figure 7. For instance, details such as status, sensor data, or location can be ascertained [27].

At the beginning of the planning process, information about the product and the relevant parts e.g. product geometry, product mass, (see Figure 6) are provided from product engineering in a product-AAS with the necessary CAD models and BOM. In the operating phase, information about the current location, position, sensor data or resource availability is added [6]. Reconfiguration planning contains extensive information about the existing production and logistics system. This information can be used at this point for fast and efficient reconfiguration.

### 4.2 Integration of CPPS in Ontology

In the next step, the CPSs are integrated with the ontology database by using AAS with various patterns through the representational state transfer application interface (Rest-API). Through MQTT requests, messages containing the most recent values are received and inserted into the Endpoint URL of the ontology. For more resource flexibility and efficiency, the different services e.g. Ontology, Grafana, Dashboard, Node-RED run as virtualization solutions in virtual machines and containers [27]. Moreover, this makes the simultaneous planning of different processes possible, whereby each ontology instance is utilized on a different container. The Third stage is the execution of the planning process of the logistics system in an FLMS, which involves the generation of planning variants and the selection of the suitable solution. In the next sections, the execution of the production logistics in FLMS is shown through different use cases.

#### 4.2.1 Products

The first product is a "dummy battery box" consisting of a small load carrier (KLT) with individual wooden components as inlayers with different variants (cylinder, cuboids and bag in the shape of T (T-bags)) see Figure 8.

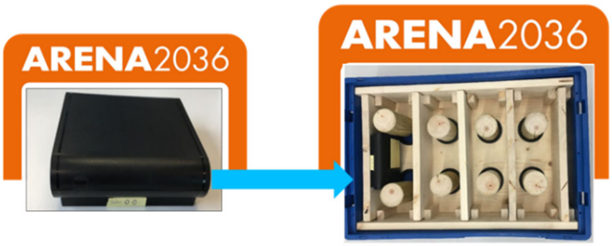


*Figure 8. Dummy Product and BMS*

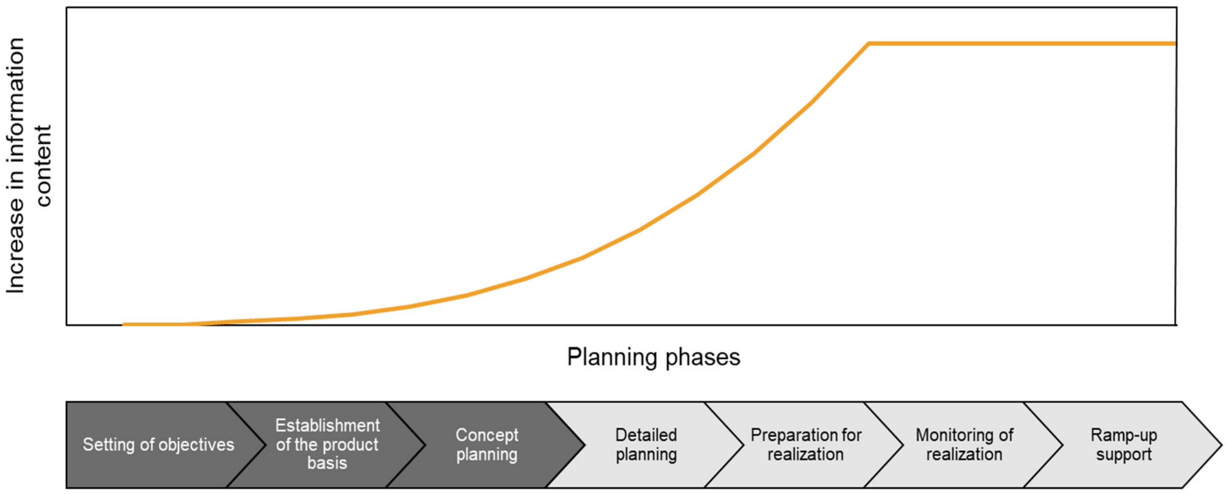


*Figure 7. The information content in the individual planning phases*

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The structure of the dummy battery box is based on a plug-in hybrid (PHEV2) battery. In addition, the dummy product consists of a battery management system (BMS), see Figure 8. The BMS is inserted into the "dummy battery box" and consists of a microcontroller, an acceleration sensor and a battery. Through the integrated infrared transmitter with the control unit of the battery box, it is able to communicate with the Raspberry Pi in the battery box. This allows the status information of the BMS to be provided via a pro-active product-AAS.

The second product is provided by the FlexCar project, which is a fully-functional battery, as shown in Figure 9. The information is provided through a passive pattern product AAS.


*Figure 9. FlexCar Battery*

#### 4.2.2 Resources

For the implementation of the use cases, various CPSs were included as resources. The individual CPSs have their own pro-active AAS. The first resources are smart load carriers in different sizes s, m and l [27]. Figure 10 shows a smart load carrier in size L.


*Figure 10. FlexCar Battery*

The second resource is the Autonomous Mobile Robot (AMR) Poseidon from Bär, which is shown in Figure 11. The AMR is provided via the AAS and the corresponding submodules, which are based on the specification of VDA5050 [6].


*Figure 11. AMR "Poseidon"*

The third resource is a Smart Storage System (SSS) and is based on the rack concept [21], [75], as shown in Figure 12. In this version, it features Balluff Smart Reordering System Sensors, which can determine the occupancy of each storage location.


*Figure 12. Smart Storage System*

The AAS provides information on the presented resources via different submodels. The available information for each CPS is shown in Table 4.

*Table 4. Information on the CPS via AAS*

| | Smart Load Carrier | AMR | SSS |
|---|---|---|---|
| Status | ● | ● | ● |
| Dimensions | ● | ● | ● |
| Position or Location | ● | ● | ● |
| Sensor data | ● | ○ | ● |
| Payload | ● | ● | ● |
| Energy efficiency | ● | ● | ● |
| Costs | ● | ● | ● |

Legend: ○ Not Available ● Available

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#### 4.2.3 USE CASE 1

The first use case is a load carrier planning process for components of the initial product called “Dummy product”: Therefore, a suitable load carrier is selected. The graph-based query language SPARQL is used to identify the specific entries (objects) of the ontology that fulfill the requirements.

The initial product has the "T-bag right part" component. The excerpt of the query below identifies all “empty” and suitable Smart Load Carriers, taking into consideration the specified constraints on dimensions and weight.

```
SELECT ?Smart_Load_Carrier ?h ?w ?l
?weight
WHERE {ex:T-Bag_Right_Part_DP
   ex:hasWidth ?tBagWidth ;
   ex:hasHeight ?tBagHeight ;
   ex:hasLength ?tBagLength ;
   ex:hasWeight ?tBagWeight ;
   rdfs:subClassOf ex:Dummy_Product .

?Smart_Load_Carrier
rdfs:subClassOf ex:Smart_Load_Carrier ;
   ex:hasWidth ?w ;
   ex:hasHeight ?h ;
   ex:hasLength ?l ;
   ex:hasWeight ?weight ;
   ex:hasStatus "empty" .

FILTER (?h >= ?tBagHeight && ?w >=
?tBagWidth && ?l >= ?tBagLength && ?weight
>= ?tBagWeight)
}
```

Alternatively, the expression of dimensions and weight can be used instead of the variables (w, h, l, weight). Additionally, the location can also be set as a filter. As a result, all possible M- and L-sized “Smart Load Carriers” are accessed. To distinguish the different resources, each resource has a unique ID. Furthermore, it is also possible to extend the search with conventional “Load Carriers”, but in this case “Smart Load Carriers” are the specific entries e.g. status has to be exempted.

In the context of the present use case, a reconfiguration process is performed from the original product to a second product, which also involves the corresponding components. Fig. 13 shows the reconfiguration process of a different component.

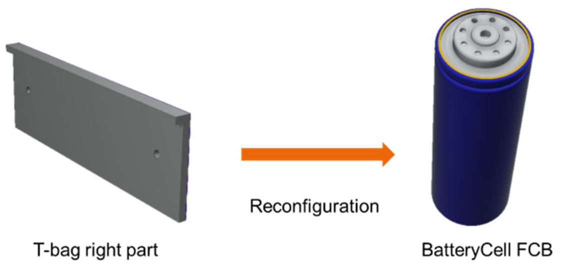


*Figure 13. Reconfiguration from Product 1 to Product 2*

The excerpt of the following query is for the identification of suitable load carriers for the component “BatteryCell FCB”, which belongs to the FlexCar Battery Cell.

```
SELECT ?Smart_Load_Carrier ?h ?w ?l
?weight
WHERE {
  ex:BatteryCell_FCB
    ex:hasWidth ?batteryCellWidth ;
    ex:hasHeight ?batteryCellHeight ;
    ex:hasLength ?batteryCellLength ;
    ex:hasWeight ?batteryCellWeight .

?Smart_Load_Carrier
    rdfs:subClassOf ex:Smart_Load_Carrier;
    ex:hasWidth ?w ;
    ex:hasHeight ?h ;
    ex:hasLength ?l ;
    ex:hasWeight ?weight.

FILTER (?h >= ?batteryCellHeight && ?w >=
?batteryCellWidth &&
?l >= ?batteryCellLength && ?weight >=
?batteryCellWeight)
}
```

In contrast to the first query, it can be seen from the result that all three sizes S-, M- and L-sized Smart Load Carriers are possible.

#### 4.2.4 USE CASE 2

In the second use case, the "Dummy case" has to be transported to the final assembly, where the BMS is installed. The first step is the planning of a transportation process for the “Dummy Product” with the dimensions of 600x400x280 mm. Thus, the subsequent excerpt of the query was executed to retrieve all "available" resources belonging to the class "AGV" with the skill of "transportation" and location "FluPro Area," while also applying present restrictions. The location “FluPro Area” is the location of the FLMS.

```
SELECT ?agv ?skill ?h ?w ?l
WHERE {
    ?agv rdfs:subClassOf ex:AGV ;
        ex:hasSkill ?skill ;
        ex:hasLocation "FluPro Area" ;
        ex:hasStatus "active" .
    ?agv ex:hasLoadDimensions ?o1 .
    ?o1 ex:hasHeight ?h ;
        ex:hasWidth ?w ;
        ex:hasLength ?l .
    FILTER (STR(?skill) = "transport" &&
?l = 600 && ?w = 400 && ?h = 280)
}
```

The result shows that only the object “Poseidon” in the class “Resource” fits the requirements. It is also possible to perform the planning process via a graph-based solution. In Figure 14, an excerpt of the resource “Poseidon” in a KG is shown.

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URN: urn:nbn:de:0009-14-58065

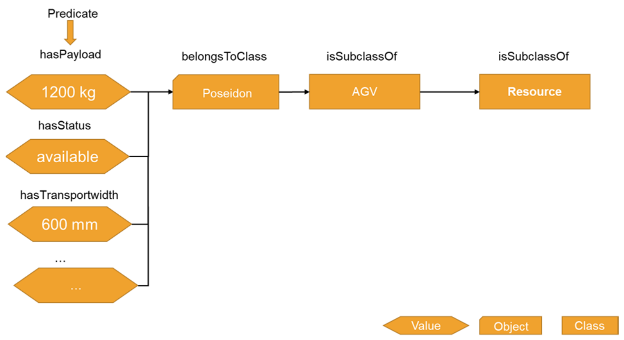


*Figure 14. KG of the AMR based on [76]*

The component "Battery Cell FCB", from the second product has to be stored at "Smart Storage System", which is named "Riegel_1" after the assembly process. Consequently, the query refers to all "empty" storage spaces in "Riegel_1".

```
SELECT ?subclass
WHERE {
  ?subclass rdfs:subClassOf ex:Riegel_1 .
  ?subclass ex:hasStatus "empty".
  ?subclass ex:hasLocation "FluPro Area" .
}
```

The result is the available "Storage Space" in "Riegel_1", which is located at "FluPro Area".

### 4.3 Expert Knowledge

Stage (4) describes the use of expert knowledge. The presented framework provides the planning process of the necessary data and information about PPR. Furthermore, it supports the planner and enables this person to quickly generate several solution variants with different restrictions and to compare them with each other. However, due to the high complexity of the FLMS, expert knowledge with an understanding of the processes is still required. The planner is only supported, if this person explicitly requests certain solutions. The dimensioning and evaluation of the solutions must be carried out by the planner [77].

The planning process can be performed based on various preferences of the planner. For this purpose, as already described, various information is provided by the system. For example, planning can be carried out on the basis of the following preferences and requirements:

- ergonomics: height of the respective resources (equipment and workforce)
- fulfillment of efficiency: processing time of the production module, acceleration (speed in m/s * distance)
- economic efficiency: required space, operating costs of the resources in (€/meter), cost in € for each logistics concept [78]
- energy efficiency: energy consumption in (kW per h)

The information can be provided through the AAS and can be considered through queries or filters in the ontology.

## 5 Conclusion and Outlook

The presented approach allows fast and efficient planning and reconfiguration of the production logistics in an FLMS. AAS and ontology are applied for the planning of the production logistics in an FLMS. FLMS ontology is used for the definition, integration and multi-criterial decision-making of the relevant domains (product, process and resources) from different bordering areas. Further data were provided through the integration of AAS. Based on the data, the rough planning of the production logistics was executed. Thereby, different levels of freedom such as mobility, location flexibility, various capabilities of the resources were considered. Furthermore, the developed approach allows the reconfiguration on a second product, which is unknown at the start of production. The reconfiguration process was shown via two use cases with different processes, products or resources. Therefore, the perquisite of the FLMS was fulfilled. Finally, the presented approach was tested and validated at the ARENA2036 research campus with a resources pool and two products with different parts. The execution and speed of planning in a complex system such as FLMS is highly dependent on the planner's individual experience and knowledge base. Therefore, there is a need for development on further solutions that will make it easier for the planner to query solution variants without a deep understanding of the system.

As Industry 4.0 drives the digitization of production and logistics, more data and information will be available across companies along the supply chain. Consequently, future research will focus on the integration of heuristics and the further implementation of engines for reasoning rules, which will further reduce the amount of planning variants and accelerate the planning process. The presented framework provides the possibility to be extended for the application on a production network or supply chain. It can be enriched with data from previous planning stages e.g. Building Information Modeling (BIM) to integrate further knowledge domains, factory and building or further used in the detailed planning stage with simulations [79, 80].

Finally, the presented paper also shows the execution of a reconfiguration process. In the present example, this is still very much dependent on manual execution. For future research, autonomous systems are necessary, which determine the best solution variant in advance during the ongoing PPC and logistics for the new product.

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