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Towards an ontology-based dictionary for production planning and control in the domain of injection molding as a basis for standardized asset administration shells

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ABSTRACT

The use of digital technologies in the industrial environment enables great potential for increasing efficiency in manufacturing. One building block are production environments that plan and control their production flow autonomously and decentrally. To this end, all machines and systems (so-called "assets") need to communicate with each other and derive suitable actions based on the exchanged information. Therefore, all assets need to be represented in the virtual world. This can be realized with digital twins. A concrete implementation of digital twins is the asset administration shell, which comprises all the assets' properties and the endpoint of the corresponding asset, so intercommunication is possible. Here, the challenges comprise establishing a manufacturer-independent vocabulary that standardizes the assets' properties and enabling the machines and systems to interpret this vocabulary semantically. Existing standards and information models represent only a fraction of the information requirements (i.e., terms) in this domain, making autonomous production planning and control (PPC) challenging to implement. Furthermore, the information requirements of the machines and peripheral assets as well as the corresponding information flows are insufficiently defined. Therefore, this contribution aims to build a comprehensive vocabulary for the domain of PPC, which serves as a basis for standardized asset administration shells that realize machine-to-machine communication. In particular, PPC processes concerning the injection molding domain's characteristics are considered since the interaction between the domain's assets, i.e., injection molding machines, molds, peripheral assets, raw materials, and operators, are especially complex. For this purpose, the relevant input and output information within the injection molding domain was first collected for each process step in PPC. After that, a UML class diagram was modeled under consideration of established standards. The result of this work is an ontology, which can be used as a dictionary for the PPC in the injection molding domain and as a foundation of standardized digital twins in the form of asset administration shells.

1. Introduction

Global production and supply networks characterize today's markets. Due to globalization, the barriers to manufacturing goods in low-wage countries to decrease production costs are lower than a few decades ago. From a customer's perspective, globalization allows buying goods from almost all countries with low effort, so customers are not bound to the local market. This leads to increased competition and a change of the production philosophy, e.g., shorter product launch processes, fulfilling individual product demands towards lot size one, or an enhanced considering of resource efficiency. In order to compete in a global marketplace, companies in high-wage countries are forced to reduce their production costs but ensure high product quality simultaneously [1–3]. To overcome this challenging task, the fourth industrial revolution, also known as Industry 4.0, was introduced in 2011, which promises more efficient production processes using digital solutions. One potential for more efficient production processes lies in the establishment of autonomous communication between the individual assets on the shopfloor and overlaying information systems [3]. The main benefits of autonomous communication on the shop floor are faster coordination of the whole production process (particularly by handling disruptions) and relieving or supporting of employees in complex tasks [4]. Realizing this potential requires digitizing the assets in a sufficient level of detail, i.e., representing the asset's relevant characteristics regarding a specific domain in the digital world. This coexistence of production-related physical assets and their digital counterparts is named Cyber-Physical Production System (CPPS) [5].

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One element for an integrated digitalization of production assets is realizable with digital twins, or more specifically, with the asset administration shell (AAS) as a concrete implementation of digital twins. The AAS contains all relevant asset properties and enables the connection to its environment. The vision that is concomitant with AAS is autonomous asset communication.

An autonomous communication needs a common vocabulary that the assets understand and use. One building block towards autonomous communication is to establish a standardized dictionary that includes the relevant vocabulary for the regarded domain [6]. This vocabulary comprises the asset's properties (e.g., its current temperature) and correlated semantics like unit, datatype, synonyms, or valid ranges and enumerations. Furthermore, not only the vocabulary is essential, but also the relation between the assets. Highlighting assets' relations helps identify which assets need to communicate with each other. Both, the vocabulary and relations of a domain, are representable by ontologies [7], which is an "explicit specification of a conceptualization" [8]. Ontologies indeed exist, but nowadays, a widespread application is missing. Furthermore, already built ontologies mainly cover a particular and company-specific domain, so the reusability of those ontologies is not reasonable [9]. This hinders extensive autonomous communication between assets, which currently is rarely implemented.

The demand for a common vocabulary for autonomous asset communication results in multiple challenges. With the rise of production related software tools (i.e., ERP, MES, CRM) and production assets manufactured by different vendors, multi-vendor communication may be difficult. The reason is that software tools often operate on different databases, and hence, a connection of each data interface to a separate database is given. In a worst-case scenario, there is no digital solution at all [10]. Likewise, inconsistencies of different vocabularies from different vendors are present since single vendors have a different understanding and interpretation of their domain that leads to a different form of the domains' vocabulary [11]. Examples are given by *Legat et al.* [9], where combining different vocabularies describing batch control processes is not possible since the semantics of the units are not consistent reciprocally, or *Gönnheimer et al.* [12], where the proprietary semantic definition of vendors hinders the identification of needed parameters. Here, establishing a widely used vocabulary inside a domain requires the acceptability of competitors within the same industrial sector. Thus, exchange and discussions across multiple companies are mandatory to reach an agreement concerning a suitable vocabulary [13,14]. Summarized, enabling the communication between software tools and machinery from different vendors is difficult since relevant properties differ from each other or are not implemented as data point [15].

This work focuses on the production planning and control (PPC) process within the injection molding (IM) domain since an ontology that depicts PPC in the injection molding domain currently does not exist. In general, PPC covers all necessary steps in the order fulfillment process that comprises the management of customer orders, their translation to production orders with the allocation of material, workforce, and machinery, and dispatching. As PPC emerged in the 1980s, practices, methods, and algorithms, e.g., for determining the optimal order quantity, or models, e.g., for the demand planning of resources (MRP II), are state of the art. Furthermore, corresponding software tools like enterprise resource planning (ERP), manufacturing execution systems (MES), customer relationship management (CRM), and much more are available [16,17].

In the field of injection molding, enabling autonomous communication enables great potential for more efficient manufacturing. A challenge regarding autonomous communication in the injection molding domain is the variety and process-related interconnection of the domain's assets, e.g., injection molding machines, molds, dryers, or handling devices. Often, those assets are composed of different vendors, thus finding an optimal or suitable asset configuration can be complex due to different property definitions, so conducting smooth production planning and control is difficult. Other examples considers the quality of the molded parts. Since manufacturing the same part on different injection molding machines can lead to different results, machine-specific characteristics, e.g., machine components' wear information, should be considered autonomously within PPC [18]. Furthermore, the knowledge of the right condition of the plastics raw material is essential, especially for hygroscopic raw materials, as moisture affects the quality of the finished part [19]. In this case, the dryer autonomously can request a transportation order to forward the raw material when the required drying level is reached to reduce the overall jobs' lead time.

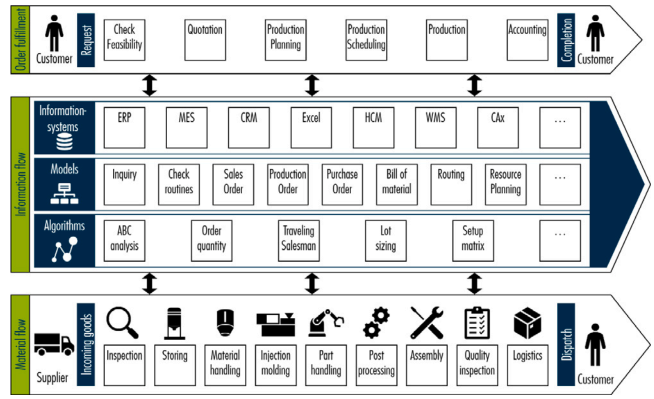

Fig. 1. Typical order fulfillment, internal material flow, and information flow in an injection molding factory.

This work aims to provide a first but comprehensive ontology for PPC in injection molding (PPCinIM ontology) as a basis to tackle the issues mentioned before. The contribution of this paper enables a step towards semantic shopfloor interoperability as one core topic of Industry 4.0 in injection molding factories. Because injection molding factories often are equipped with machinery from multiple manufacturers and utilized with various peripheral assets (e.g., material dryers), a common vocabulary for this domain is beneficial.

Therefore, this contribution addresses the following research question: *Which classes, their relations, and properties in the domain of PPC in injection molding are essential for building a consistent ontology as a foundation for autonomous asset communication?*

The remainder of this paper is organized as follows: Section 2 gives a detailed introduction to the PPC scenario in injection molding. In Section 3, related work regarding ontologies, dictionaries, and standards is pointed out. Section 5 explains the methodology. In Section 6, the ontology is presented and subsequently discussed in Section 7. A conclusion and outlook complete the paper.

2. Background

This section introduces the tasks and interfaces within PPC in the domain of injection molding. Fig. 1 shows the general order fulfillment process on the top and the corresponding material flow on the bottom level. The information flow in between connects the order fulfillment process with the material flow through used information systems, models, and algorithms that are relevant for PPC in injection molding. This work focuses on internal business processes and does not consider external material and information flow.

The general steps in the order fulfillment process on the top level are independent of the enterprise's manufacturing processes since the type of manufacturing is make-to-order or make-to-stock. In the beginning, the manufacturer checks the general feasibility of the incoming inquiry from the customer. If the general feasibility is given, the manufacturer creates a quotation. After the customer accepts the quotation, the manufacturer generates a sales order that leads to the dispatch of one or more production orders. The production orders are the central elements in the production process since they contain the relevant information required for manufacturing the product (e.g., bill of materials, routings, quantities, or scheduling information). Hence, rough production planning and scheduling for the exact allocation of the resources are usually inevitable. Once the production process is completed, the manufacturer creates a delivery note and an invoice to complete the process from an accounting perspective [20].

The bottom level of Fig. 1 shows the material flow. The flow contains all possible production and handling steps so that some steps can be omitted or performed several times regarding the customer's requirements. First, a supplier delivers the required raw materials. After inspection, the manufacturer usually moves the goods into storage. Suppose the material is required for the manufacturing of a product. In that case, it has to pass through various (optional) stations, marked as material handling, to prepare and provide the raw material for the injection molding process. The material handling includes tasks such as conveying the raw plastic granulate to the injection molding machine and preprocessing the raw plastic granulate (e.g., drying, mixing, or crystallizing). After the injection molding process, part handling is inevitably required to transport the produced parts to the next workstation. Subsequent postprocessing tasks are possible, e.g., separating the sprue from the injection molded parts. If the injection molded part is a component (semi-finished product) or finished product, an assemble in one or more steps follows. After the final quality control and packaging, the finished part is ready for dispatch [21].

The scenario in Fig. 1 demonstrates that many information interfaces and hence, a plurality of data and information exist in both the order fulfillment process and the material flow (production process). Multiple information systems like ERP or MES are established that contain several models (e.g., the production order or the bill of material). In addition, algorithms for improving business processes like suitable lot sizes or scheduling are available. Because of this variety of interfaces, data, and decision-making processes, a common vocabulary is helpful, so the single assets are able to communicate. An autonomous communication between the single assets enables a variety of benefits for businesses that manifest in faster and more robust production and order fulfillment processes.

3. Related work

This section presents related work of digital twins, in particular AAS, ontologies, and class diagrams in the field of injection molding and PPC that are suitable as a basis for standardized AAS. Relevant and used dictionaries as well as standards and guidelines to establish the PPCinIM ontology will be introduced in Section 6.

At first, related work about digital twins for PPC will be presented. *Novák et al.* [22] concept a production system control. Within this concept, digital twins of the physical assets are connected with a production planning system and supply feedback regarding the current asset status. *Biesinger et al.* [23] present a case study for the automatic creation of digital twins that support production planners in accelerating the integration process of new vehicles for manufacturing. In [24], *Agostino et al.* propose a data exchange framework of digital twins for PPC. Digital twins within the injection molding domain are not widespread. *Modoni et al.* [25] control and monitor the injection molding process with digital twins, while *Lacueva-Perez et al.* [26] use digital twins for failure identification. An architecture for implementing digital twins in injection molding is made by *Wang et al.* [27]. *Bibow et al.* [28] offer an approach for model-driven development of digital twins that is applicable in the injection molding domain.

Research on AAS for PPC domain shows that they still need to be implemented. *Park et al.* [29] build an AAS application for reinforcement learning-based production control, in [30], *Park et al.* develop a cyber physical logistics system (CPLS) based on AAS. The CPLS controls the inventory and operational capabilities of a supply chain in the make-to-order process to gain resilience. *Komesker et al.* [31] make a design approach for resilient production planning and execution with the help of AAS in dynamic, multi-level production environments. All contributions listed before do not consider standardized properties. Within the domain of injection molding, no AAS implementation can be identified, and thus is an open research gap.

Related work concerning models and ontologies about injection molding will be presented next: In [32], a detailed listing of relevant quality parameters, their priority, their measure point, frequency, and period for enabling an industry 4.0 injection molding factory is given. They focus on the injection molding process, so PPC in injection molding plants has minor consideration. *Zhang et al.* [33] tackle the challenge of selecting a suitable material in the engineering process of plastic parts in an efficient way. Because selecting the right material requires deep knowledge, the authors developed a comprehensive, ontology-based knowledge framework for this issue. *Meylheuc and Goepp* [34] pointed out that defining the shape, the material, and the process for injection molding simultaneously is crucial. They established a UML class diagram that connects the product and process parameters with the properties of the injection molded part to identify the relations between those parameters and properties. *Nyanga et al.* [35] design a multi-agent system for selecting a suitable injection molding machine regarding required manufacturing parameters (i.e., clamping force, due dates, or mold dimensions). Therefore, they present some relevant assets in a UML class diagram but not in a comprehensive manner for conducting a comprehensive PPC. *Hwang* [36] controls and monitors the status of the raw material and the relating equipment during the drying process by enabling the data flow through sensors and gateways. For this purpose, Hwang models the dryer and corresponding assets in the form of an entity-relationship diagram.

Related work regarding the general shopfloor configuration that is independent of any manufacturing method will be presented below. *Seyedamir et al.* [37] have developed an ontology based on the ISA-95 standard (Enterprise-Control System Integration) that is suitable as a basis for the new PPCinIM ontology from this work. In contrast to *Seyedamir et al.*, the PPCinIM ontology provides more attributes and adds some customer classes. Another upper ontology comprising general shopfloor assets is the MAnufacturing's Semantics ONtology (MASON), presented by *Lemaignan et al.* [38]. Although some classes and their relationships can be reused, their attributes are not yet determined comprehensively, and some details, e.g., storage and orders, are missing. *Schleipen et al.* [39] built an MES-ontology that has been incorporated into VDI Guideline 5600 (Part 3) [40]. The ontologies' main building blocks are the product, the production order, the process, resources, time synchronization of assets, and general data points that do not belong to the categories before. Although some classes (e.g., bill of materials, customer order) are missing, the results can be integrated or adapted to the PPCinIM ontology. A UML class diagram that models business elements in manufacturing is made by *Dakic et al.* [41]. They give a comprehensive overview of relevant classes and their interconnection, but not in a standardized manner. Other models of the manufacturing domain in general were made in [42–45].

An important issue in PPC is to check the capabilities of assets concerning technological aspects or with regard to deadlines. The following ontologies were built for this purpose. *Järvenpää et al.* [46] built the manufacturing resource capability ontology (MaRCO) that represents the functionalities and constraints of manufacturing resources. In case of changed market settings or customer demand, MaRCO helps to realize a fast and semi-automatic shopfloor reconfiguration. A reference ontology for process and production planning was introduced by *Šormaz et al.* [47]. This ontology focuses on typical manufacturing processes (e.g., drilling, milling) and their related machinery to find a suitable manufacturing process. Organizational aspects like production orders are not included. *Tsai et al.* [48] model an agile production planning and control system (APPCS) as a UML class diagram with the

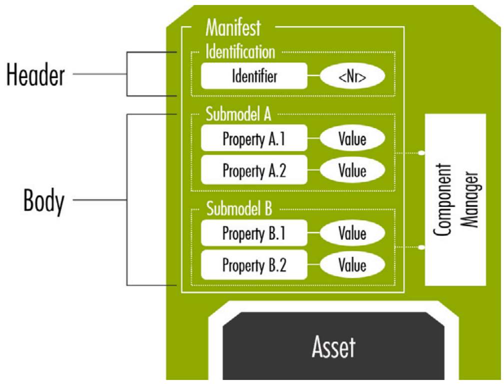

Fig. 2. The general structure of the Asset Administration Shell.

production order as the central element. With the help of this model, classes, properties, and functions that support immediate planning and scheduling of production orders are provided. Another ontology-based resource reconfiguration method is given by *Wan et al.* [49], while *Fumagalli et al.* present a model of the logistic system [50]. An ontology where the product is the central point is pointed out by *Vegetti et al.* [51]. They introduce the PRoduct ONTOlogy (PRONTO), which provides a product model to cope with the vast number of product variants in specific industries, e.g., automobiles. The manufacturing process is not considered. Hence, the PPCinIM ontology covers another domain. Another product-related ontology was developed by *Dassisti et al.* [52] which is based on the IEC 62264 standard (enterprise-control system integration) and focuses on the handling of the material. The ontology only comprises a few PPC-related classes and properties. Hence, a comprehensive vocabulary for PPC purposes is not given.

In summary, several ontologies for PPC exist. Because some of them are already based on standards (e.g., IEC 62264), the results will be partially transferred into the PPCinIM ontology. In the perspective of injection molding, no ontology that models the domain extensively exists. Thus, an comprehensive ontology that unites the injection molding domain and PPC yet does not exist and hence is a research gap this paper is going to close.

4. The asset administration shell as an enabler for industrial information integration

This section introduces Asset Administration Shells as a concrete implementation of the digital twin and demonstrates the eligibility of AAS as an enabler for industrial information integration. Fig. 2 illustrates an AAS structure schematically..

The AAS is divided into two partitions: the header and the body. Moreover, an AAS comprises two main parts: the manifest and the component manager. In general, the manifest contains the assets' properties and auxiliary data, e.g., technical drawings, while the component manager provides the corresponding endpoint to interact with the AAS. Within the header, the manifest only provides properties for uniquely identifying the AAS, an index of the AAS' submodels, and its functionalities. Within the body, the manifest includes the assets' properties and auxiliary data like technical drawings. The body also includes the component manager. Properties and auxiliaries with the same function can be grouped into single submodels, which can be nested arbitrary [53,54]. A detailed overview of the AAS' building blocks is provided in [55] in the form of a meta-model. Generally, AAS are applicable either for physical assets, e.g., machines and periphery, or virtual assets, e.g., bill of materials or routings [53]. The purpose of an AAS is to provide a digitally available representation of every asset that is characterized by standardized, static properties (e.g., name or identifier). The values of these properties can be provided by vendors (static, immutable technical property values, e.g., the maximum clamping force of an injection molding machine), or be gathered by sensor data, plant or machine data acquisition [54]. The AAS acts as a single source of truth since it concentrates all relevant asset information within one central point. The asset information can either be stored exclusively on the corresponding AAS or provide the endpoint to enterprise systems, e.g., ERP or MES, so users and other software systems need not know the exact location of the information source [54,56,57]. Hence, an update within the AAS leads to an updated software system and vice versa.

AAS' behavior can be passive, active, or proactive [58]. Passive AAS are only described as a data structure (e.g., single JSON or AASX file). Passive AAS cannot communicate with its environment directly; communication is realized by transferring the file to its destination. Passive AAS are specified in [55]. If the passive AAS has a communication interface, e.g., a REST API, the passive AAS turns into an active AAS, which is introduced in [59]. For implementing passive and active AAS, open source solutions already exist[1] However, proactive and autonomous communication between single AAS is not yet specified. Due to its structure, "the concept of the AAS is highly suitable for standardization without interfering with the entity's functionality" [53]. The properties of the manifest can be obtained from a standardized dictionary. A first attempt was made in DIN EN IEC 63365 that specifies the identification properties of the headers' manifest (Digital Nameplate) [60]. Furthermore, metadata regarding IEC 61360 should be considered to describe the meaning of single properties [54,61,62]. Hence, ontologies are suitable for building a semantic foundation for AAS [63,64]. Further considerations, e.g., security aspects, were not introduced in this contribution but are considered within the AAS [65].

After this short introduction to AAS, its elements, purposes, and specifications, an analysis of the AAS' suitability as an enabler for industrial information integration is proposed. A general definition of industrial information integration (III) and its engineering (IIIE) is made by *Xu* [66]. Thus, "IIIE comprises methods for solving complex information integration problems" [66] by applying and improving enterprise systems. The main goals of enterprise systems are handling intra and inter-communication within a globalized supply chain, managing business processes, and ensuring an enterprise's efficiency, competency, and competitiveness. The prerequisites for enterprise systems are data and information added with semantics. Derived from that, III is the progress for providing the relevant data and information with suitable tools and technologies. In this context, AAS are an adequate solution for III since they fulfill the prerequisites mentioned before. Due to their character, they bundle relevant asset information from different enterprise systems, e.g., parts' master data from the ERP, current production orders from the MES, or technical drawings from the CAD. In literature regarding industrial information integration, AAS are addressed indirectly. *Chen* [67] reviews drivers for industrial information integration engineering by sorting them into different research categories. In comparison to digital twins that first originated in 2010 in [68], AAS are a relatively new concept that arose in 2016. However, this review does not consider AAS directly, but digital twins and the reference architecture model industry 4.0 (RAMI 4.0) are mentioned. Fig. 3 shows the RAMI 4.0 architecture model.

The RAMI 4.0 architecture model is a tool for comprehensively classifying assets in the virtual world. Within RAMI 4.0, an asset can be contextualized through its entire life cycle by specifying its data, information, communication protocols, and business functions, differentiated by the enterprises' hierarchy level according to IEC 62264. Furthermore, RAMI 4.0 allows the integration of other standards and guidelines, e.g., for communication protocols. RAMI 4.0 is specified in DIN SPEC 91345 [62] and introduces the core idea of AAS without

[1] For example: AASX Package Explorer for building passive AAS and AASX-Server for hosting passive AAS to make them active. Source: https://admin-shell-io.com/

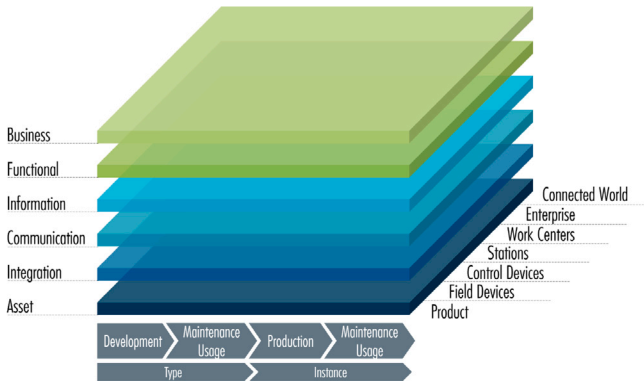

Fig. 3. The RAMI 4.0 architecture model, according to [62].

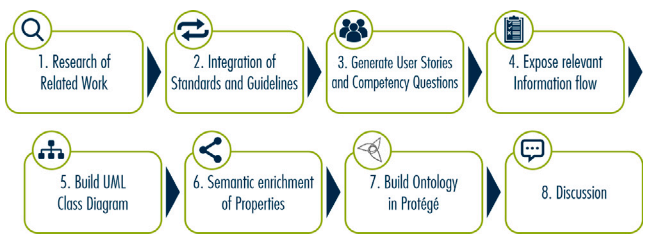

Fig. 4. Illustration of the applied methodology.

going into detail. *Corradi et al.* [69] summarizes that information and communication technologies (ICT) are compliant with RAMI 4.0 and hence AAS. The main reason is that RAMI 4.0 is capable of modeling the overall value chain or the life cycle of assets. This requirement is applicable to AAS. Furthermore, RAMI 4.0 matches the requirements for IIIE since, with the help of this tool, methodical development of IT infrastructure for industrial information integration, namely AAS, is possible.

As AAS matches the prerequisites for industrial information integration, they should be considered as a possible source for this purpose. Furthermore, the concept of AAS currently is in an international standardization process (IEC 63278 - Asset Administration Shell for industrial applications) [70] that indicates the significance of AAS as an implementation of the digital twin. Since the AAS' manifest should be based on standards and include semantics, ontologies are appropriate as their foundation. Due to the identified lack of an ontology for the production planning and control domain in injection molding, this contribution provides an ontology enriched with metadata and could serve as a basis for AAS in the corresponding domain.

5. Methodology

This section presents the methodology for building the PPCinIM ontology as illustrated in Fig. 4.

First, a comprehensive literature research has been performed covering existing ontologies, models, dictionaries, and standards in the field of injection molding, PPC, semantics, and the cross-sections of these topics. Besides the literature research, interviews with domain experts in the field of PPC and the domain of injection molding have been performed. Then, to specify the usage of the PPCinIM ontology, some user stories and competency questions were pointed out to ensure the ontology fits the typical requirements a production planner or production controller needs within the PPC process in the injection molding domain. Afterward, in step four, the relevant information flow for PPC in the injection molding domain was pointed out to identify the corresponding assets and the subsequent attributes. In step five, a mapping of the standards and the conducted information flow is made to identify missing attributes and combine the two domains, PPC and injection molding. On this basis, a UML class diagram containing the relevant assets, their attributes, and the correct data type was designed. To ensure a semantic and unique interpretation of the exposed attributes, semantic enrichment of the properties in a standardized pattern is proposed in step six. In the next step, the UML class diagram serves as the basis for an ontology built in Protégé as a tool to design ontologies. Finally, the results are discussed.

6. Ontology for production planning and control in injection molding

6.1. Integration of standards and guidelines

Section 3 pointed out some relevant ontologies and models. However, most of those ontologies do not take standards and guidelines into account. The benefits of using standards and guidelines are a commitment of several stakeholders regarding their communication and the reuse of accepted and established processes [71]. Also, using those predefined terms and processes is reasonable for the later acceptance of a newly built ontology. Moreover, relevant terms in the field of PPC in injection molding that are not present in a standard or guideline can be figured out to fill the open vocabulary gaps. This section presents the used standards in this work and their interconnection (derived from their normative references and bibliography). Moreover, this section points out why to use a specific standard for building the PPCinIM ontology. Fig. 5 presents the used standards. To reduce the figures complexity, standard and guidelines with multiple sub-parts were treated as one document.

To build the PPCinIM ontology, four main categories of standards and guidelines have to be considered. The orange category depends on production planning and control fundamentals, while the teal-colored category comprises injection molding and plastics processing documents. The green category faces semantics and data definition topics, and the dark blue category encompasses foundations of digitalization and Industry 4.0.

Building the PPCinIM ontology originates from VDI 4499 and DIN SPEC 91345. VDI 4499 (Digital Factory) points out the necessity for the digitalization of the manufacturing domain. In addition, this guideline provides tools for enterprise data management [72]. For building the PPCinIM ontology, the recommendations to model the current information flow (Section 6.3) and to design an UML class diagram for the domain, were adopted (Section 6.4). While the scope of VDI 4499 regarding digitization is more general, DIN SPEC 91345 connects the production planning and control with the semantics and data definition domain. The core topic of DIN SPEC 91345 is the reference architecture model for Industry 4.0 (RAMI 4.0) that was introduced in Section 4. Within RAMI 4.0, the PPCinIM ontology is located on the integration layer that represents the asset's properties and dependencies. Hierarchically, the connected world, enterprise, work centers, and stations over the entire life cycle is indicated by the PPCinIM ontology.

The hierarchy level of RAMI 4.0 are mentioned in IEC 62264 - Enterprise-control system integration. IEC 62264 provides all relevant information for manufacturing goods on the enterprise level and the manufacturing operations level and specifies the level's objects and their attributes [73–77]. The PPCinIM ontology makes use of the objects and their attributes. More standards regarding required information and data for the production planning and control domain are ISO 18828–2 which presents a reference process for production planning [78], VDI 5600 as a guideline for manufacturing execution systems [40,79,80], IEC 61512 that provides terms regarding batch control [81–84], DIN IEC 60050-351 for terms regarding control technology [85], ISO 22400 that includes key performance indicators (KPIs) for manufacturing operations management [86–88], and VDI 2815 (terms regarding production engineering and control) [89–95].

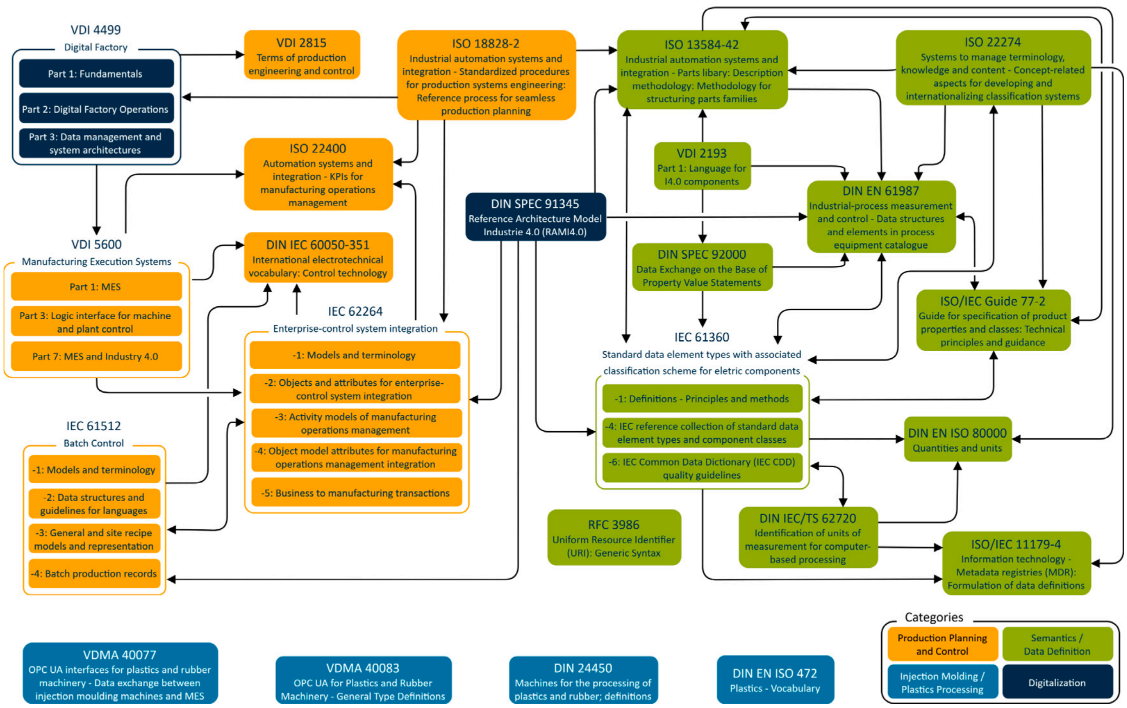

Fig. 5. Most relevant standards and their interconnection considered in this work.

In the domain of plastics processing, the following standards and guidelines regarding vocabulary and definitions were used: DIN EN ISO 472 (Plastics - Vocabulary) [96], DIN 24450 (Machines for the processing of plastics and rubber - Definitions) [97], VDMA 40077 (OPC UA interfaces for plastics and rubber machinery - Data exchange between injection molding machines and MES) [98], and VDMA 40083 (OPC UA for Plastics and Rubber Machinery - General Type Definitions) [99] (also known as EUROMAP 77 and 83).

An elementary goal of the PPCinIM ontology is the consideration of metadata that ensure a semantic definition of the data element types. One of the most important standards for this issue is applied by IEC 61360. This standard models the building blocks for designing single properties (e.g., units, semantic attributes, or translations) and defines criteria for a compliant development of dictionaries. Furthermore, IEC 61360 provides a dictionary for electronic components.[2] [100–102] The PPCinIM properties adopt parts of the mentioned components of IEC 61360, especially in the area of semantical interpretation. Realizing interpretable semantic properties requires unambiguous semantic identifiers. In Section 6.5, an eligible semantic id pattern concerning the recommendations of VDI 2193 (Language for I4.0 components) [103], RFC 3986 (Uniform Resource Identifier (URI): Generic Syntax) [104], and ISO Guide 77-2 (Guide for specification of product properties and classes - Part 2: Technical principles and guidance) [105] was created. In addition, standardized and computer readable quantities and units from DIN EN ISO 80000 [106–108] and DIN IEC/TS 62720 [109] were considered. Besides, the general structure of classes and properties is essential in the modeling process. General rules for modeling the PPCinIM ontology consistently, comprehensively, and extensible were extracted from ISO 22274 [110] and DIN EN 61987-10 [111]. ISO 11179-4 describes the correct wording of data (e.g., singular, concise), the PPCinIM ontology follows [112]. More technical principles for modeling dictionary components are given by ISO 13584-42, e.g., id, short name, version, and their necessity for a specification (mandatory/optional) [113]. DIN SPEC 92000 describes the general data exchange via properties [114] in the manufacturing domain. The PPCinIM ontology integrates those recommended structures, datatypes, and mandatory attributes to realize such an exchange.

6.2. User stories and competency questions

An ontology represents the classes, attributes, and their relations for a specific domain. With the help of an ontology, complex queries are executable for gaining deep insights into the behavior of the single assets and their correspondence. Thus, the final ontology should focus only on this specific purpose. To avoid building neither a comprehensive nor a limited ontology, user stories and competency questions support defining the scope of the ontology and the expected queries. A user story, in general, describes functionalities a software product has to provide. Hence, a user story helps software developers to meet the customers' requirements. Usually, user stories were structured as follows, supplemented by acceptance criteria:

As *type of user* I want *some goal* so that *some reason.* [115]

In this case, the customers are the users (i.e., production planners and controllers) of the PPCinIM ontology. Fig. 6 illustrates a user story for a production planner, whose scope is rough planning.

In Fig. 7, the user story of a production controller is presented. Compared to the planner, the controller focuses on detailed planning tasks like scheduling.

In addition, gathering competency questions such as typical queries an ontology has to answer is the second foundation for building ontologies [116]. The following list registers some competency questions for the PPCinIM ontology:

- Which injection molding machine is capable of manufacturing the customers' product that needs a clamping force of *n kN* with mold dimensions of *(a,b,c) mm*?
- Is the stock of *product XY* sufficient to satisfy the customers' demand?
- Is it possible to complete the *production order PO-XX* to the desired due date, and is the stock of raw material for manufacturing this production order sufficient?
- Which and when are machinery and operators capable of conducting *production order PO-XX* that requires a certain minimum or special qualification?

[2] URL: https://cdd.iec.ch/

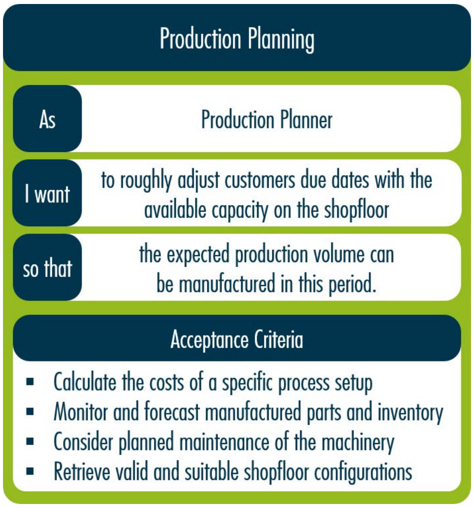

Fig. 6. User Story for a production planner as user of the PPCinIM ontology.

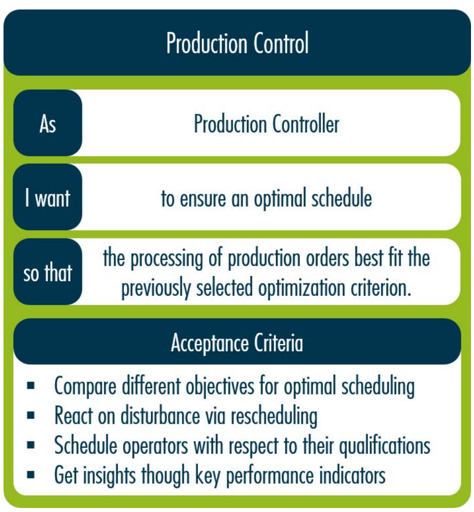

Fig. 7. User Story for a production controller as user of the PPCinIM ontology.

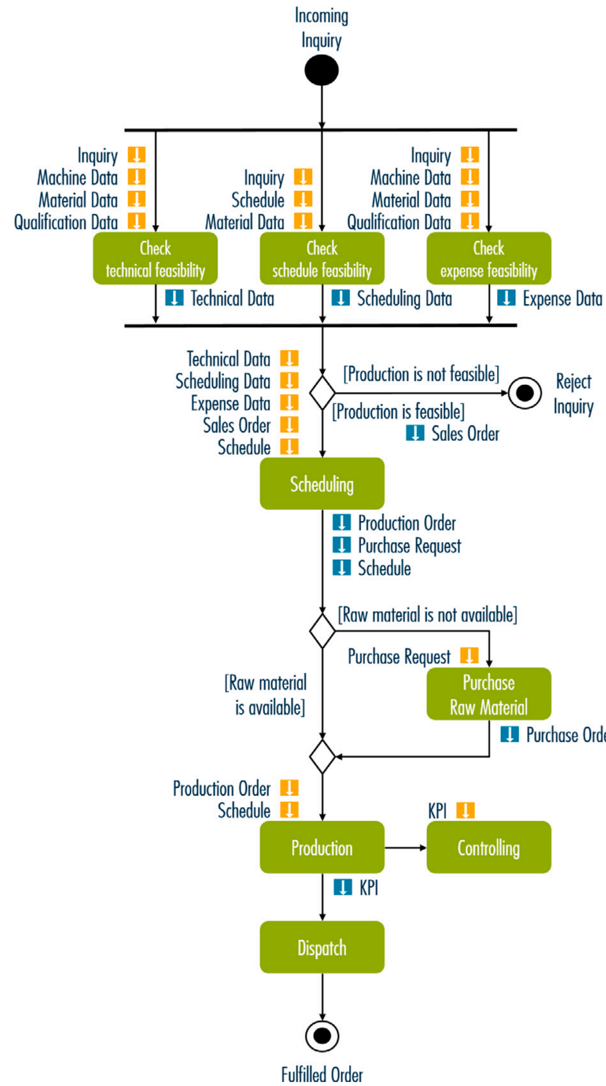

Fig. 8. Document and information flow to fulfill a customer's order.

- Which injection molding machine has the best OEE[3] for manufacturing *production order PO-XX*?
- What is the expected scrap rate of *product XY* on which injection molding machines?
- Is it possible to reschedule *production order PO-XX* due to a change in the customer's due date?

With the accentuation of the user stories and competency questions, a foundation for purposefully building the PPCinIM ontology is made. The information flow for PPC in injection molding will be determined in the next subsection.

6.3. Information flow for production planning and control in injection molding

According to VDI guideline 4499 - Digital Factory - (part 3), a central building block for an integrated data management in a digital factory is the definition of the right information and its appearance in the process. Therefore, the guideline recommends the creation of an information model that contains the process steps and the corresponding input and output information [117]. This information model is the basis for the data model introduced as a UML model in Section 6.4. The information model that describes the document and the information flow in the PPC in the injection molding domain is depicted in Fig. 8. Input documents and information are declared with an orange box while the outgoing ones are blue.

One identified lack of the pointed out PPC models as related work is the missing connection to the customer. This is highly relevant because their demand is the origin of the shopfloor utilization and allocation of production assets to the corresponding production and customer order. The PPCinIM ontology takes this into account. The process starts with an incoming inquiry of the customer. The inquiry includes the technical attributes as also the required due date and expense data [118]. In the injection molding domain, it is common that the enterprise that receives the inquiry is a third-party manufacturer. That means that the customer does not inquire about a specific product the manufacturer offers. Instead, the customer asks for the capability to manufacture the customer's product with the manufacturer's resources [119]. If the manufacturer is a third-party supplier, the technical, schedule, and expense feasibility of the inquiry need to be checked. The check for the technical feasibility can be omitted if the customer asks for an offered product, so this feasibility check is unnecessary. To check the

[3] OEE = Overall Equipment Effectiveness, a key performance indicator that predicates the utilization for a manufacturing operation.

feasibility, the requirements from the inquiry are compared with the manufacturers' data. The information that have to be checked may be:

For the technical feasibility:

- Machine data: clamping force, max. mold fixing dimensions, suitable handling units, etc.
- Material data: restricted material (e.g., transparent), suitable machines, etc.
- Qualification data: know how of special processes, etc.

For the schedule feasibility:

- Schedule: machine utilization, priority of present production orders, etc.
- Material data: inventory, replenishment time, etc.

For the expense feasibility:

- Machine data: setup and manufacturing costs
- Material data: material costs, storing costs, transportation costs
- Qualification data: labor costs

If one of the feasibility checks is negative, the production is not realizable under these conditions. Hence, the manufacturer rejects the inquiry. The customer can adjust its inquiry, search for a solution jointly with the manufacturer, or search for another manufacturer that fits the customer's specifications. If the production is generally feasible, the manufacturer generates a sales order.[4] The sales order contains the part(s) to manufacture, the costs, and the due date, but also information about the priority and status of the sales order. Next, within the scheduling step, the sales order is transferred to one or more production orders under consideration of the technical, scheduling, and expense data pointed out before. The production orders comprise the bill of materials where the raw material and its amount for production are listed and the single operations necessary for finishing the product (routing). The resulting production orders were allocated to suitable resources and included the planned times for each operation. Furthermore, an availability check of needed raw material is executed. If the manufacturer detects missing raw material a purchase request is generated that later becomes a purchase order. As soon as all raw material is available, the production starts under consideration of the determined schedule. After the production is finished (and dispatched), the order is fulfilled. Relevant key performance indicators (KPI) that were calculated during the production should be used for controlling purposes, i.e., for optimization for further production orders. A shortcoming of the information flow is that it does not consider further documents. For example, a production order initiates the production of a part and consists of a bill of materials and a routing. The routing again consists of one or more operations. Furthermore, the information flow does not present the cardinality of relations and the properties of the single documents or process steps that are necessary. Thus, the information model will be transformed into a UML data model that comprises all relevant classes, their properties, and their relations in the next section.

6.4. UML class diagram

Building a UML model is helpful as a blueprint for the later ontology created in an expert software tool. An identified gap within related work is that no comprehensive model (and subsequently no ontology) exists that represents the manufacturing information flow under consideration of technical injection molding assets. The UML model in Fig. 9 shows the relevant classes, their properties, their interconnection, and their cardinalities for the PPC in the injection molding domain to close this gap. In this contribution, the term "property" is a synonym for the terms "attribute", "characteristic", and "data element type".

The modeling of the PPC classes is lean on typical information carriers in the order fulfillment process and comprises the four manufacturing principles, so all types of manufacturing are considered: Make-to-stock, assemble-to-order, make-to-order, and engineering-to-order. If the part is make-to-stock (MTS), the production of the parts is decoupled from the direct demand of the customers. Hence, a sales order does not lead to a production order because the demand is fulfilled from stock. In contrast, when make-to-order (MTO), the part's manufacturing only starts if the customer places an order, so one or more subsequent production orders arise. Compared to the MTS principle, MTO normally leads to higher delivery times but reduces inventory costs. Because the production of injection molded parts is always connected to a mold, MTO in injection molding has to differentiate between conventional manufacturing and subcontracting. In contrast to conventional manufacturing, where the manufacturer uses its machinery and equipment for subcontracting, the manufacturer requires the mold from the requester for production. Thus, routines for checking the feasibility of the subcontractors' technical assets, e.g., the required clamping force that is needed for fulfilling the production order, are mandatory. Assemble-to-order (ATO) combines both principles, MTS and MTO. Typical injection molded parts that are ATO are assemblies whose semi-finished parts are identical (e.g., housings) but customized in a further process step (e.g., colorizing or individual prints). If a customer requests the production of a part that the manufacturer does not have in the portfolio, the scenario calls engineer-to-order (ETO). Within ETO, other machinery or equipment is necessary before manufacturing can start. In the injection molding domain, all four principles are a common business, and therefore it is necessary to provide the relevant UML classes. For MTO, ATO, and ETO, the customer triggers the process by initiating an *Inquiry*. In the case of subcontracting or ETO, the inquiry contains the required technical parameters that have to be compared to the available capabilities of the *TechnicalAssets*. Ideally, a comparison between the required and available technical parameters is made automatically. The technical asset class provides general properties that are valid for all technical assets, e.g., status or hourly rate. Derived subclasses are the *InjectionMoldingMachine*, *Mold*, *MoldInsert*, *Dryer*, and *TemperatureUnit* as IM specific classes and *TransportContainer*, *Conveyor*, *Scale*, and *HandlingDevice* as assets in the PPC domain. If the technical feasibility as well as the time and cost conditions are given, the inquiry turns into a *SalesOrder*. The sales order is the origin of one or more production orders. In a multi-stage scenario, the *ProductionOrder* consists of one or more suborders. The *ProductionSchedule* contains the production orders in a sequence, normally with respect to an objective like minimal adherence to due dates. The scheduling under consideration of optimization objectives is fulfilled by suitable *OptimizationModels*. A production order contains the relevant information for manufacturing a *Part*. The needed manufacturing steps are centralized in a *Routing*, whereas one single manufacturing step is an *Operation*. Besides the needed manufacturing steps, the *BillOfMaterial* (BOM) lists the required *BOMPositions*, i.e., raw material, assemblies, and semi-finished products. BOM positions can be connected to a specific operation, so the demand for components is synchronized with the execution of the operation. From the data perspective, either the *Routing* or the *BillOfMaterial* only are present when the related *Part* exits. The *RawMaterial* is a subclass of a part. Because *PlasticsGranulate* comprises domain-specific properties (e.g., particle size or granular type), plastics granulate is separated from the raw material class. Since small derivations in the raw material specification significantly affect the part quality, the management of *Batches* plays an essential role, in particular in injection molding. Hence, a corresponding class is introduced. The procurement of raw material is realized by a *PurchaseOrder*. For monitoring the stock of Parts and BOMPositions, *InventoryData* exists. Therefore, single *Storage* and their

[4] Normally, the manufacturer first offers a quotation. After acceptance of the customer, it turns into a sales order. In this case, quotations will not be considered because they do not provide further information in the order fulfillment process.

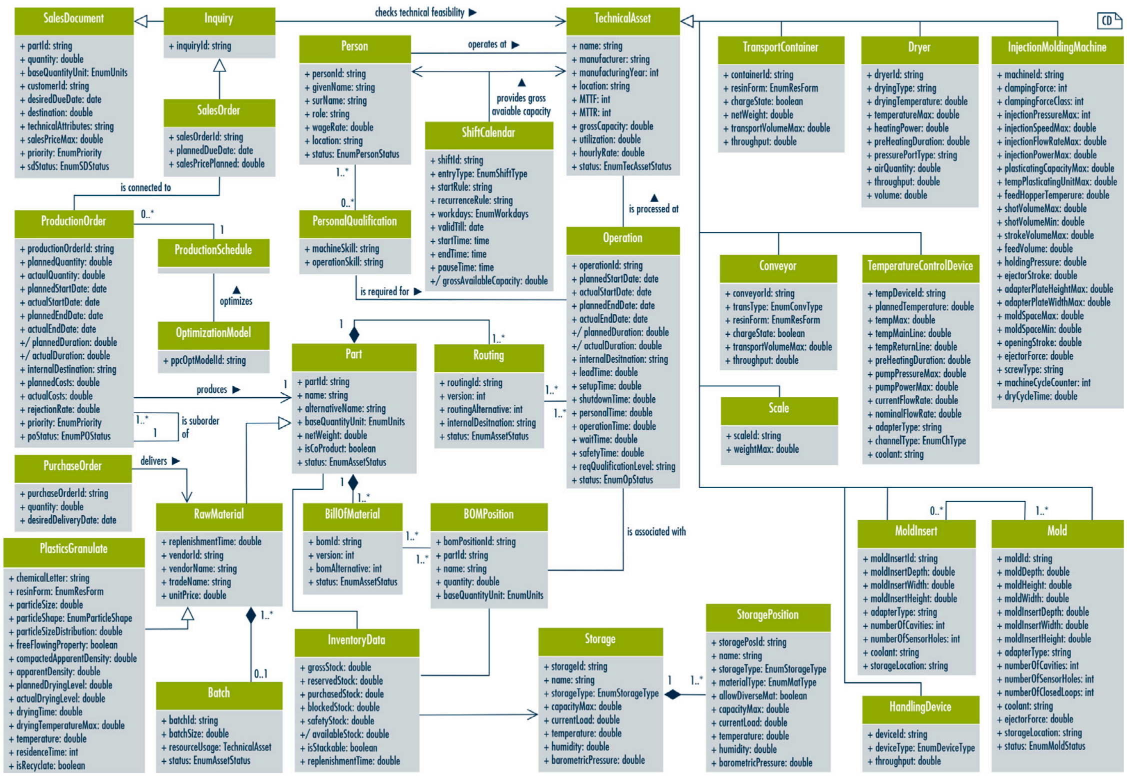

Fig. 9. Relevant classes and their relations for production planning and control in the domain of injection molding.

StoragePositions are modeled. Operations were conducted by technical assets and *Persons*, that operate at those assets or are instructed for their setup, teardown, or maintenance. Regarding the *PersonQualification*, persons can conduct different tasks. For determination of a person's or technical asset's capacity and working times, a *ShiftCalendar* exists.

Different sources were used to name the classes and their properties. As the first source, standards and guidelines for both domains, PPC and injection molding, were considered (see Section 6.1). Moreover, for PPC-related classes, the naming, content, and relation of classes are oriented to SAP ERP as the software with the highest market share in this segment [120–122]. To complete the naming, vocabulary from [123,124] were included. Important IM properties that are relevant for PPC were derived from different sources: *Bourdon* [125] presents a calculation for an optimal utilization regarding single parameters for injection molding machines, where the level of the machine's utilization in relation to the machine's maximal possible performance is evaluated. *Custodis* [126] provides a method for finding the best injection molding machine regarding pre-defined criteria, e.g., clamping force, shot volume, or prize. Other relevant properties were derived from different injection molding handbooks [127,128] and institutional research work [129,130]. Because some work defines the properties in German, the terms were translated with the help of a plastics processing dictionary [131]. The developed UML class diagram contains all assets and their properties without integrating semantic properties. Thus, the next section presents the enrichment of those assets and properties with semantics.

6.5. Semantic enrichment of assets and their properties

Realizing autonomous communication in an Industry 4.0 environment needs standardized dictionaries that contain all assets and their properties of a domain since they are a key to enabling a common understanding. In contrast to a conventional dictionary, semantic dictionaries enrich the single terms with meta-data, e.g., synonyms, descriptions, units, or the datatype. Therefore, standards like DIN EN

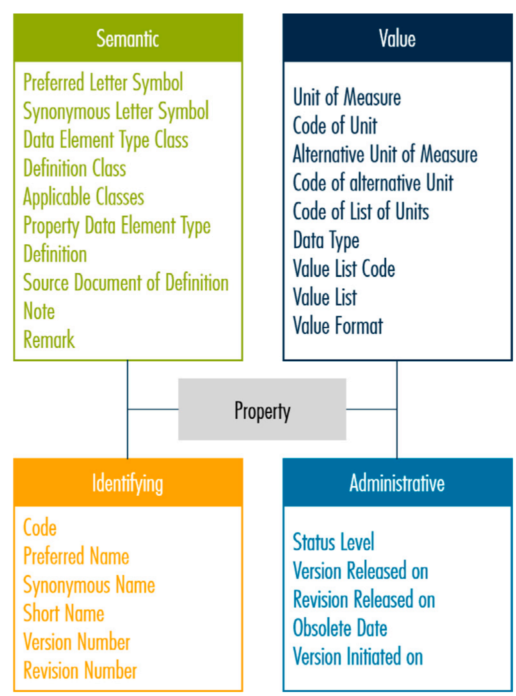

Fig. 10. IEC 61360 meta-data within PPCinIM ontology.

61360 provide these meta-data, their usage in dictionaries, their necessity (mandatory or optional), and guidelines for their implementation. An example of a standardized dictionary is eCl@ss, which comprises terms for the specification of products and services [132]. Fig. 10 shows the meta-data from IEC 61360 considered in the PPCinIM ontology.

Meta-data properties can be differentiated into four groups: Identifying, semantic, value, and administrative attributes [100]. Identifying attributes ensures unique and unambiguous identification of a property. The PPCinIM ontology makes use of the *code* as unique identifier, the *preferred name*, the *synonymous name*, and the *short name* of the property. In addition, *version* and *revision* identify a single definition of a property within its life cycle. Semantic attributes ensure a common understanding by adding meaning to a property. The PPCinIM ontology includes the *preferred letter symbol* and *synonymous letter symbol*. The letter symbols conform with ISO 80000 (e.g., ϑ for temperature). The *Data Element Type Class* groups similar properties, e.g., all properties that stand for a temperature. Meta-data that offer the context of a property's location are given by *Definition class* (root class) and *Applicable classes* (list of classes that contain the property). To ensure the properties understanding for humans, a *Definition* (ideally from a standardized or established *Source Document of Definition*, is provided. The meta-data *Note* and *Remark* add further information to the properties. The third group of meta-data comprehends value attributes. The PPCinIM ontology comprises the *Unit of Measure*, an optional *Alternative Unit of Measure*, the corresponding *Code of Unit* and *Code of Alternative Unit*, and the *Code of List of Units*, that encompasses similar units (e.g., °C and K are related to temperature), following DIN IEC/TS 62720 [109]. Further meta-data specify the *Data Type* of a property and the *Value Format*. The value format defines the structure of a property (minimal and maximal length, number of characters, position of comma). Enumerations are defined separately by a single *Value List Code*, the *Value List* presents all values of this enumeration as code. For administrative purposes, attributes concerning the *Status Level*, *Version Released On*, *Revision Released On*, *Obsolete Date*, and *Version initiated on* are integrated in the PPCinIM ontology.

Corresponding to DIN EN 61360–1, one important and mandatory meta-data is the *code* that represents the unique identifier of a property. Different standards characterize the pattern of the identifier. VDI 2193 (Language for I4.0 components) suggest two conventions to generate the *code* [103]. The first convention recommends ISO/TS 29002 [133], which defines a pattern under consideration of an international code designator (ICD), that is specified in ISO/IEC 6523-1 [134]. Compared to a city's zip code, the ICD classifies the organization that creates a property within four digits[5]. Currently, the International Organization for Standardization (ISO) manages those ICDs. In industrial practice, it will not be realizable that all companies first register at ISO to get an ICD to specify their assets and properties. Thus, the second convention VDI 2193 suggests offers a more flexible generation of identifiers. Based on RFC 3986, VDI 2193 suggests using uniform resource identifiers (URI). The PPCinIM ontology follows the second convention, so the *codes* in of all assets and properties is as follows:

Listing 1: Code pattern of identifiers used within the PPCinIM ontology.

```
http://www.iop.rwth-aachen.de/{PPC,IM,
    IEC-61360}/<version>/<revision>/<
    preferred_name>
```

The leading organization as the origin of the PPCinIM ontology is http://www.iop.rwth-aachen.de. Due to modularization aspects, three different subdomains exist: PPC covers only assets of the production planning and control domain, whereas IM consists of all assets in injection molding. IEC-61360 comprises the meta-data. Assuming VDI 2193, the number of the version and revision follows. The URI ends with the preferred name of the data element type. Future domain ontologies can be attached by abbreviating the faced domain. The entire data-set is attached in the appendix and is also available from GitHub.[6]

[5] A list of currently allocated ICDs is provided here: https://docs.peppol.eu/poacc/billing/3.0/codelist/ICD/

[6] URL: https://github.com/psapel/PPCinIM

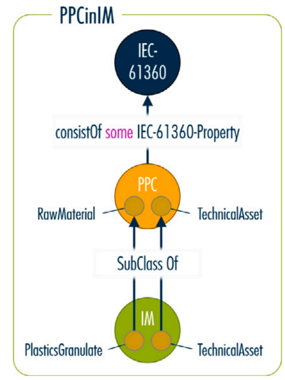

Fig. 11. Hierarchical structure and connections that results in the PPCinIM ontology.

6.6. The PPCinIM ontology

For modular reasons, the PPCinIM ontology is a composition of three single ontologies (see Fig. 11). For the ontology building process, Protégé (Version 5.5.0) was used.

First, an ontology for PPC purposes as mid-level ontology is established. The advantage of a separate PPC ontology is the independence of the underlying manufacturing process since most information and documents (e.g., BOM, production order, technical assets) are generally involved in production processes. Second, a domain-ontology for injection molding (IM) is provided. This ontology covers the technical assets in the injection molding domain as well as a class for the raw plastics granulate. For connecting the IM to the PPC ontology in Protégé, the TechnicalAsset class of the IM-ontology is the *SubclassOf* the TechnicalAsset class of the PPC ontology. Analog to this, the IM-ontology's PlasticsGranulate class is the *SubclassOf* the PPC's RawMaterial class. Third, an ontology of IEC-61360 meta-data was built (the structure is shown in Fig. 10). This ontology is applicable to every class and properties of other ontologies, regardless of the domain. Hence, IEC-61360 is a top-level ontology. In Protégé, the PPC ontology *consistsOf some IEC-61360-Property* that enrich its classes and properties with meta-data. Since IM is a subclass of PPC, the meta-data inherit from IEC-61360 to IM. Both the PPCinIM ontology and the three single ontologies were provided on GitHub[5]. Finally, this ontology and meta-data can be used as a foundation for implementing asset administration shells based on common vocabulary.

7. Discussion

Semantically described production domains are a core necessity of Industry 4.0. The major challenge for implementing the vision of a seamless and autonomous communication of all production assets is that the corresponding enterprises need to agree to one standard and, subsequently, one single identifier for a property. One problem may exist in the different definitions and understanding of single properties and their meta-data (e.g., different units). Since unification is necessary, companies (even competitors) must collaborate and discuss to find an alignment. Hence, one or more market leaders can define the vocabulary as pioneers so others can follow. This requires a non-proprietary characteristic of the defined vocabulary as it is intended with the standardized manner of the AAS to be developed.

Due to the numerous amount of shopfloor use cases, it is not possible to build a holistic ontology or dictionary that is able to cover all properties. Therefore, the PPCinIM ontology does not claim to be a fully comprehensive vocabulary but provides a first and widespread foundation for this purpose. Another challenge is the reuse of ontologies instead of building new ones. The threat lies in multiple ontologies for the same domain that overlap. It is challenging for domain experts to identify whether mid or domain-level ontologies exist and how existing and suitable ontologies can merge. To overcome this challenge, the PPCinIM ontology, corresponding properties, and semantic enrichment are provided on GitHub and allow a transparent view and reuse. Another major challenge is that production engineers as domain experts are often unaware of semantic modeling. Especially standards and guidelines (e.g., IEC 61360) mainly address software specialists rather than production engineers. Hence, tools are necessary that allow production engineers a straightforward building, merging, and implementation of ontologies for their domain. Current work in the "Internet of Production" faces these challenges by developing and providing several semantically tools and training for their usage. In the field of AAS, no standard exists but is currently under development. In particular, the modeling of proactive AAS is not specified, but proactive AAS are one key factor for interdisciplinary information exchange. Furthermore, manufacturers have to equip their products with AAS comprehensively. Similar to the reuse of ontologies, the reuse of AAS submodel patterns, e.g., the nameplate of machinery, needs to be forced to avoid different submodels with the same meaning. In summary, the PPCinIM ontology can be used as the first foundation for the injection molding domain and provides semantic meta-data and documents for PPC purposes, regardless of the underlying manufacturing process.

8. Conclusion and outlook

Digitalization offers enormous possibilities for more efficient production, i.e., through autonomous asset communication. The critical factor is data, information, and knowledge that have to be integrated into the manufacturing domain and that have to be provided to all stakeholders. The digital twin is a suitable and beneficial technology for industrial information integration. This paper discusses the asset administration shell as a concrete implementation of the digital twin and points out that AAS are eligible for III since AAS provides all relevant information about an asset in a standardized manner in one central location. Thus, the AAS acts as a single source of truth. One prerequisite for autonomous asset communication is a uniform vocabulary enhanced with semantics. This paper presents the first holistic dictionary in the form of an ontology as a foundation for AAS. The dictionary comprises PPC purposes focusing on the injection molding domain under consideration of semantics regarding IEC 61360, named PPCinIM ontology. PPCinIM is a composition of three single ontologies: IEC-61360 as a top-level ontology that is applicable for every production use case, PPC as a mid-level ontology that faces the management of the manufacturing process, regardless of the underlying manufacturing technology, and IM as a domain-ontology that fits for the injection molding domain. The benefit of this modular composition is the reusability for other domains, particularly for the top and mid-level ontology. Furthermore, the IM ontology can easily be expanded by adding other injection molding assets. One prerequisite for building the PPCinIM ontology was the consideration of standards and guidelines. This contribution merges standards of different fields and demonstrates that in an Industry 4.0 environment, a cross-domain collaboration between domain experts and software engineers is strictly required.

Following this requirement, future work needs to develop tools that domain experts can easily use to build, enhance, and integrate their vocabulary on existing dictionaries and ontologies. Regarding the PPCinIM ontology, the built vocabulary is planned to transfer into a standard or a guideline in the form of standardized asset administration shells for the injection molding domain. Moreover, a tool that efficiently enriches a property's meta-data corresponding to IEC 61360 will be built that supports domain experts and software engineers. For production control in the injection molding domain, a model catalog will be established. This model catalog contains scheduling models that can be applied under consideration of the current shopfloor configuration for receiving a suitable schedule regarding a specific objective, e.g., adherence to due dates. This contribution focuses on establishing an ontology for PPC in the injection molding domain and the eligibility of AAS for III as a basis for autonomous asset communication. Important further work will concern the application of the PPCinIM ontology for performing autonomous communication with the built AAS.

Abbreviations

AAS	Asset Administration Shell
ATO	Assemble-to-order
BOM	Bill of Material
CAD	Computer Aided Design
CAx	Computer Aided *x*
CRM	Customer Relationship Management
CPLS	Cyber Physical Logistics System
CPPS	Cyber Physical Production System
ETO	Engineer-to-order
ERP	Enterprise Resource Planning
HCM	Human Capital Management
ICD	International code designator
ICT	Information and Communication Technologies
III	Industrial Information Integration
IIIE	Industrial Information Integration Engineering
IM	Injection Molding
IMM	Injection Molding Machine
K	Kelvin
KPI	Key Performance Indicator
MTO	Make-to-order
MTS	Make-to-stock
MES	Manufacturing Execution System
MRP II	Manufacturing Resource Planning II
OEE	Overall Equipment Effectiveness
PO	Production Order
PPC	Production Planning and Control
RAMI 4.0	Reference Architecture Model Industry 4.0
UML	Unified Modeling Language
WMS	Warehouse Management System

Data availability

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.jii.2023.100488 and https://github.com/psapel/PPCinIM.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.jii.2023.100488.

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