prostep ivip

Recommendation

# Bridging the Gap – Seamless Information Transfer in Production Environments

prostep ivip PLiM Recommendation 2021 PSI 26

## PLiM Recommendation

Bridging the Gap - Seamless Information Transfer
in Production Environments

# Abstract

The demand for customized products, shorter product lifecycles and cost pressures require increased efficiency and flexibility in the development and operation of production systems, which are becoming increasingly complex. Digital tools and models are being used for end-to-end model-based engineering in this context. Exploitation of their full potential is currently being hindered by discontinuities in the flow of data and information, e.g. during collaboration between different internal and external departments, which leads to high subsequent costs. The evaluation of a recent survey indicated a significant impact on projects in terms of material and time. The apparent lack of data standards underscores industry's pressing need for the information model being put forward. Continued media discontinuities in the companies' data management systems, however, make it imperative that a universal information model, which includes products, processes and resources (PPR), be standardized.

Companies, however, often make insufficient use of current standard models, due in large part to their strongly generic character, and users struggle in the face of their abstraction and complexity. The prostep ivip Association's Production Lifecycle Information Management (PLIM) group has developed an application-related data model based on two different industrial use cases. Unlike existing standards, this model does not fully cover all use cases, but it is more clearly structured and more practice oriented. Transfer to ISA-95 and export to a generic exchange format (AML) as an existing industrial data interface demonstrated that the information model can also be used for tool-unspecific applications. With focus placed on achieving a high level of usability, it will be necessary in the future to investigate whether additional use cases could be used to derive a standard that a large number of companies could integrate.

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# 1 Introduction

## 1.1. Background and objective of the group

The Production Lifecycle Information Management (PLIM) project group examines the end-to-end multidirectional flow of information from product development to production planning all the way through to production with the aim of developing and validating a generic information model. This is done based on real processes and demonstrators used in companies and research institutions.

The project group was launched in 2011 with the aim of defining and establishing generic and interchangeable planning processes. While developing and standardizing concrete recommendations for action (ISO 18828), it was determined that the increasingly dynamic nature of industry meant static processes could not easily meet new requirements such as fluctuating demand and short product lifecycles and innovation cycles. Consequently, the series of standards had to be expanded to include manufacturing change management. The result is planning processes that qualify the change in production, but which exhibit a weakness in that the exchange of information at the handover points in and between these processes needs to be efficient. The objective of defining an information model led to the name of the project group being changed to Production Lifecycle Information Management (PLIM).

Because plant engineering companies, users, system integrators and software companies recognize the need for international standards, the group intends to develop the information model on the basis of existing standards, such as ISA-95, AutomationML (AML) or OPC UA, rather than develop a separate standard of its own. This includes, among other things, participation in the standardization activities relating to ISO 16400 being carried out by ISO/TC 184/SC 5, which is developing an Equipment Behaviour Catalogue (EBC) that would support the configuration and simulation of virtual production systems before they go live.

## 1.2 Motivation

Current trends such as the growing scarcity of resources, increasing competitive pressures and the individualization of demand are presenting manufacturing companies with new challenges. To survive in this dynamic environment, flexibility and resilience are being added to the competing target variables quality, costs and time that apply to all business processes. The operation of flexible production systems that can be adapted to a wide variety of different production requirements by reconfiguring them efficiently is a key success factor.

Numerous industrial standards that support the physical flexibility and adaptability of technical systems already exist today. Flexibility, however, depends not only on the hardware but on all the processes within the lifecycle of a system. In particular, efficient planning and commissioning processes that span company and departmental boundaries within the machinery and system supply chain are of vital importance.

Efficient production system planning is currently hindered by inadequate data continuity between the IT tools and insufficient documentation of the wealth of experience-based knowledge that the individual experts involved possess. Another problem when it comes to reconfiguration in particular is the fact that existing databases do not usually correspond to the actual systems.

Data consistency cannot be guaranteed across departmental boundaries, company boundaries or process boundaries, which results in the loss of information, redundant data storage and delays. As this has long been a problem, one objective of the CIM approach was to introduce a company-wide IT infrastructure that enables the end-to-end flow of data. Broad-based introduction however failed and isolated solutions continue to be used today.

Increasing levels of digitalization mean that production systems are complex mechatronic systems with a growing proportion of software, which makes not only planning but also commissioning crucial when it comes to efficient reconfiguration. Simulating the behavior of a newly configured system during operation, in terms of virtual commissioning, offers the greatest potential in this context. To do this, an integrated view of product, process and resource (PPR) information is essential. However, this must not be limited to static data from the development processes alone but should also contain dynamic data from current operations, thus providing a basis for developing digital twins of real products as well as processes and resources.

The highly heterogeneous data and intertwined system and process worlds mean that PPR data can only be integrated to a limited extent. Dependence on the knowledge and experience of engineers when it comes to designing and reconfiguring production systems also prevents deeper PPR integration.

Standardization of a universal information model is essential for making interoperable PPR views possible not only in real terms but also virtually at an early stage. The use of this type of information model must not result in additional effort. On the other hand, data security, in particular the protection of intellectual property, must be guaranteed, which means that the exchange of partial models must also be supported. If the effort involved is to be reduced, the model also needs to be able to map all the relationships between entities in the production system domain without having to launch this comprehensive effort at the outset.

# 2 Survey results

## 2.1 Introduction

In cooperation with Fraunhofer IPK and IPS Dortmund, a survey was devised within the framework of the prostep ivip Association's PLIM group with the aim of examining key hypotheses relating to the information model developed. An information model was created as part of the group's work with the aim of reducing discontinuities in the data flow in companies. Focus is placed on the planning, development and operation of production systems. The survey results will be used in the following to examine whether a derived metamodel can reduce media discontinuities, discontinuities in data flows and related problems. In this context, the metamodel serves as an interface to established implemented models and is primarily intended to improve usability.

The survey provides a look at how things work in practice. The insights gained can be used in the context of the information model to determine to what extent the group's activities meet the requirements of industrial users and which aspects need to be given special consideration. Industry representatives were asked which problems with discontinuities in data flows occur in companies and how they assess these, with focus placed on production. Interrelationships, ramifications and existing solutions such as data standards and organizational regulations were also examined. A combination of multiple choice and text questions was used in the questionnaire. Response-based questions were used to obtained detailed information about specific groups of responses.

## 2.2 Evaluation

The evaluated sample comprises N= 57; the response-based questions means that the sample is smaller for some questions and not all of the 40 questions could be seen by all the participants. It can therefore be concluded that the participants in the survey comprise a heterogeneous group. Their affiliation is fairly evenly distributed across different department and company sizes, with a slight tendency toward larger companies. Primarily employees from R&D and IT departments participated. Departments such as manufacturing, systems planning and work planning are also represented, although there were fewer responses from engineering. All levels in the hierarchy are represented from employees to team leaders, departmental mangers, division heads and managing directors, although it should be noted that all the managing directors come from small companies (1-20 employees). The composition of the survey participants should be kept in mind when interpreting the responses.

It is clear that the issue being examined is relevant. Approximately 90% of the respondents said that they experience media discontinuities at their company. The remaining 10% of respondents belong to small companies, where the number of data management systems tends to be a more manageable. The vast majority of the participants share data with each other across departmental boundaries – which is a basic prerequisite for the occurrence of the problems being examined. According to the respondents, the main reasons for media discontinuities include the inordinate amount of effort invested in documentation, overly complex and specific solutions, and the lack of a framework. Particularly worthy of note here are process optimizations, which are held responsible for the vast majority of media discontinuities in individual organizational entities

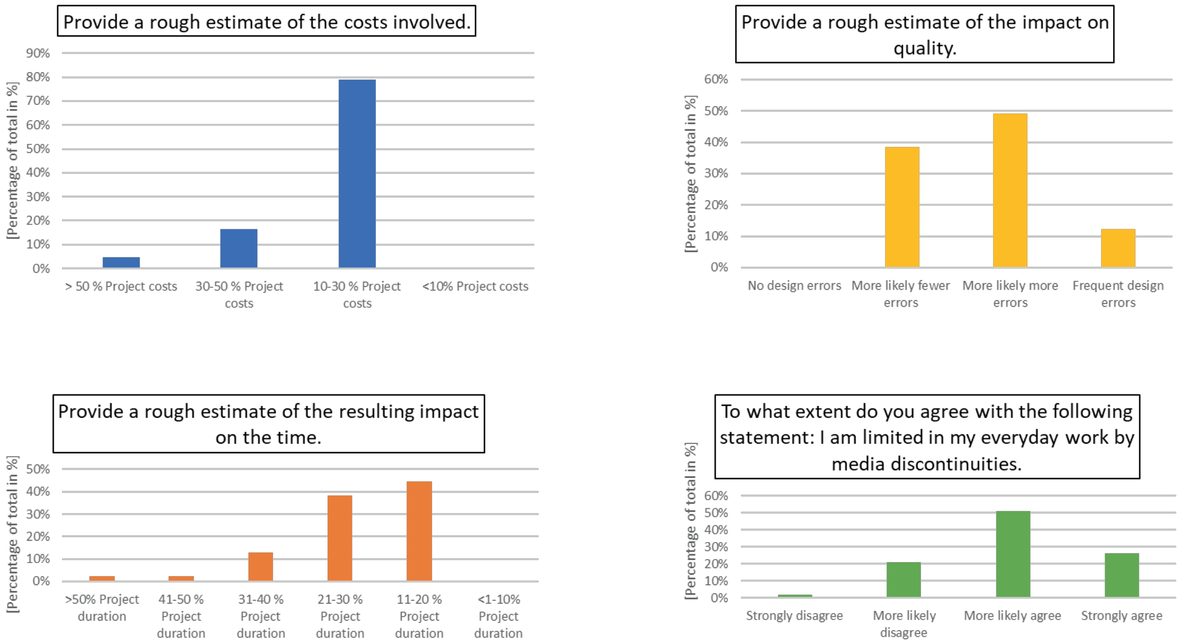



Figure 1: Excerpt of the survey results regarding the negative impact of media discontinuities

The majority of the respondents indicated that project costs increase by up to 50% and project duration by an average of 10-30% as the result of discontinuities in data flows and that design errors are more likely to occur, which means that significant financial ramifications for the companies concerned can be expected. The figures indicate a high degree of relevance and reach a level at which significant ramifications (e.g. with regard to profitability) for the projects and companies can be expected. This suggests that these values will on average increase if no measures are taken in the companies in the future. This is due to the fact that the reasons for discontinuities in data flows, such as the complexity of products and production systems to be developed, are increasing. The high figures are also reflected in the day-to-day work of the respondents, almost all of whom said that media discontinuities place limitations on them in their everyday work. This indicates that discontinuities in data flows result in significant problems, for which an information model provides a possible solution.

When people receive data from other departments, the majority of these people are not responsible for the quality and recency of the data they receive. The extent to which responsibility for data is regulated with the organization was not clear to approximately half of the respondents. In many cases, it is the data producers who are responsible without there being any further organizational regulation. This leaves room for individual interpretations and misunderstandings. In many cases, the quality and recency cannot be assessed by the person in question, but there is no known central responsible authority from which the missing information can be obtained. At times, the need to search for information results in additional effort and inefficiency. This is accompanied by design errors and a certain amount of additional effort if work is performed using obsolete data. An easy-to-understand information model as the basis for collaboration can provide a transparent representation of responsibilities and make it possible to verify inconsistencies. Organizational changes are also needed, for example to provide training courses or communicate the need for data standards.

It should be noted that the survey results indicate that there is a greater tendency to assume that the responsibility for the actual quality of the data lies with the recipient than is the case for the extent to which the data is up to date. The reason for this may lie in the fact that specialist staff are in a better position to quantify quality requirements (e.g. for a 3D model of a component). The information model must cover identification of the current (document) version in particular. The majority of participants in the survey do not use all of their company's data storage systems (about half). The number of systems is highest among respondents who work in companies with more than 1000 employees. Those respondents were also the most likely to agree that there are too many data storage systems. Not all data management systems are relevant for all employees in their day-to-day work. On average, there are around 20 different systems in the companies.

Only half of the companies surveyed have a separate department for data management. Almost all the respondents however see a need to establish such a department – there is a need for action in many cases. Studies need to be carried out to investigate the specific reasons for this absence, especially when the financial impact is actually a strong driver. Those who indicated that a central department already exists stated that, in addition to providing organizational and technical support, the primary role played by this type of department was in the context of change management for future digitalization projects. Only one third of the respondents stated that this department provides them with specialist support. A distinction was made between specialist support (50% agree) and organizational support (84% agree). It is possible that specialist support is no longer possible, particularly if there is a large number of data storage systems and departments (in large companies), and that the wide-ranging complexity cannot be managed efficiently, something that is also indicated by the survey data. The information model could provide an interface for a mechanism, provided that it reduces the level of complexity for the users and moves user-friendliness and comprehensibility firmly to the foreground – both for end users and implementers.

Almost half of the respondents have no data standards, but they clearly feel that such standards would help them. However, one third of the companies that have introduced data standards do not put them into practice, mainly due to the fact that employees lack an overview. An information model has to create as much transparency as possible, even if a large number of different divisions and departments are being mapped. It can be noted that the data standards used are frequently used for either products, processes or resources but are used less often in combination. When it comes to data standards, 90% of the respondents see potential for improvement in their companies. The main reason that they are not fully utilized is the fact that are too complex, especially in the context of simple tasks, and the added value is not apparent. If the amount of effort invested in documentation and complexity is to be reduced, it is important that usability be given due consideration. The information model places focus on usability to ensure the highest possible level of acceptance. In this case, this means that the information model takes account of user requirements. The following aspects were also equally important to the participants:

- A high level of usability in practice
- No extra effort needed for introduction and use
- High level of data security
- Reduction of effort involved in business processes
- Everything is mapped

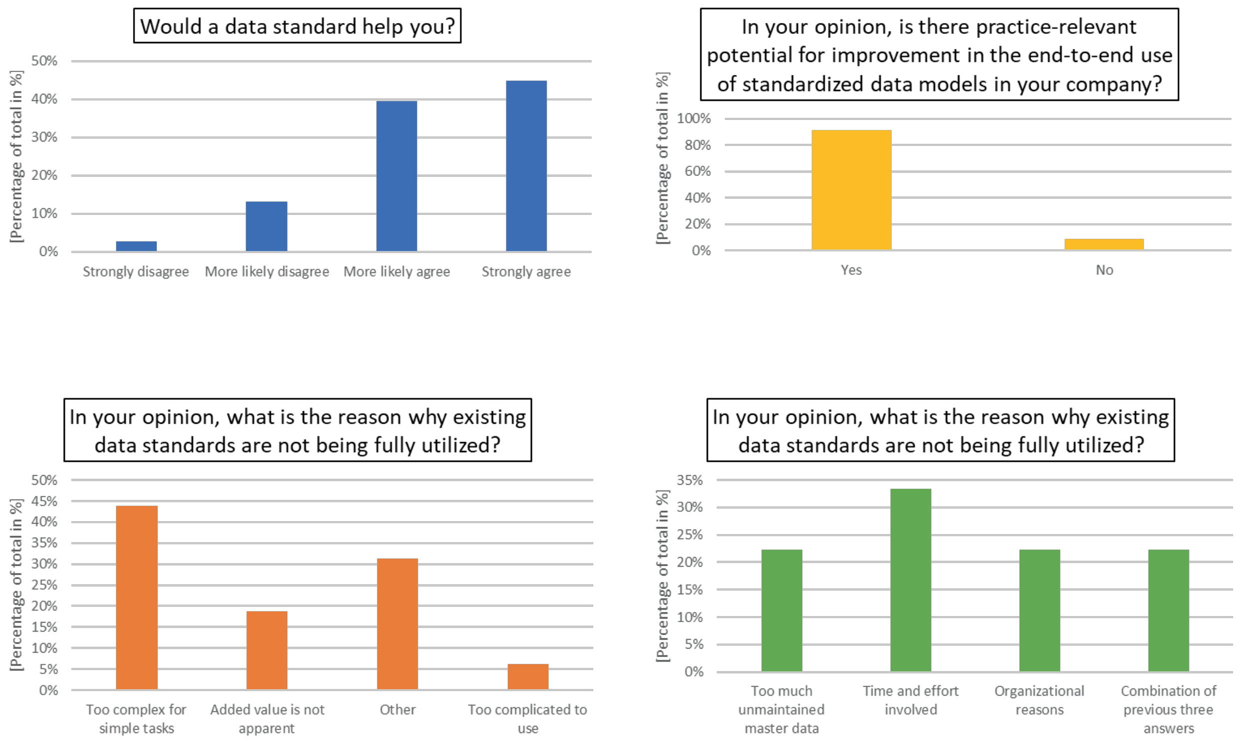



Figure 2: Excerpt of the survey results regarding data standards in the companies

### 2.3 Summary and outlook

It should be noted that the sample represents only a small and subjective slice of reality that is influenced by the composition of the survey participants. It is important to understand that the results are merely indicators. Furthermore, only a small number of the questions focused on specific aspects; the majority were more general. A future survey could, for example, take a closer look at individual aspects. Interviews with experts could also provide support.

The survey clearly indicates that problems arise in connection with discontinuities in data flows and that there is a need for the proposed information model. This is compatible with the objectives of the prostep ivip Association's project group since existing solutions are not used systematically. It is important that focus be placed on usability. The aim is to reduce complexity and the amount of effort users have to invest in documentation and achieve a high level of usability by means of appropriate implementation. Unlike established data standards, it is acceptable if it is not possible to map all the aspects of a company, provided that usability increases. This is something that the information model under consideration has the potential to achieve.

In summary, we can say that it was possible to verify the original hypothesis since the group's information model reflects the requirements of industry and its use can reduce discontinuities in data flows. A reliable assessment can only be achieved if the information model is developed further and analyses of implementation in a large company are carried out. It goes without saying that other aspects, which are not covered by an information model, are relevant to the issue. These include, for example, the way in which a company is organized as a whole and framework conditions.

## 3 Technical foundation

Numerous generic or specific information models are already being used for modeling and exchanging of information in industrial practice today. These models are also subject to ongoing further development. If the envisaged information model to be used widely in industrial practice and achieve a high level of acceptance, interchangeability and adaptability with the main models already established must be ensured. It is therefore intended that the group collaborate with international initiatives and standards for syntax and semantics. The open standards XML, ISA-95, BIM, AutomationML, STEP, JT, and OPC UA are particularly relevant in the context of PPR modeling in the lifecycle of production systems.

**ISA-95** in particular provides the basis for various versions of modeling production systems following the start of production (SOP). ISA-95 forms the basis for the international standard IEC 62264 and specifies the integration of enterprise and control layers in order to allow the homogeneous and consistent exchange of production data within companies, in particular for the process and resource views. To achieve this, it introduces terminology that is structured functionally on the basis of object models and attributes (IEC 62264-2:2013). The "automation pyramid" is another term commonly used. (Semmar et al. 2020).

The **extensible Markup Language (XML)** is a text-based data format (similar to .json, for example) and provides a basic framework that allows it to be adapted to a wide variety of use cases. It can be used to structure information hierarchically using a uniform syntax in a way that is machine-readable. It is formulated flexibly to allow extended specifications to be added. There are numerous interfaces for importing and exporting data as well as for integration into applications and tools. Document-centric representations can be created. These are easy for humans to grasp and tend to describe semantic information with a weak structure. Data-centric representations are optimized for machine processing and follow a schema consisting of entities and their relationships to each other together with attributes. These can in turn be used to form the basis of data storage facilities and file management systems. Alternatively, it is possible to derive pre-structured generic exchange formats that are optimized for a specific purpose.

**XML** derivatives play a very significant role in the modeling of production systems. Some examples of this are PLCOpenXML or Collada in control engineering and can be found in the exchange of 3-D data.

**AutomationML** provides a central XML-based standard for use throughout the entire design and commissioning phases of production systems (cf. Lüder and Schmidt 2015, p. 5ff). In the context of Industry 4.0, it represents a particularly promising approach for the standardized exchange of plant descriptions (Adolphs 2017, p. 116).

It addresses consistent and loss-free data exchange in the field of automation technology and beyond. AutomationML is an open, neutral, XML-based, free data exchange format. It allows design data to be transferred between different domains and companies, thus enabling the seamless use of heterogeneous tools. It follows an object-oriented approach and describes physical and logical plant components as data objects that form a hierarchy, i.e. which can be classified as subordinate and superordinate objects. It can, for example, be used to map the topology, geometry, kinematics and behavior. AutomationML has a modular structure and integrates and adapts various XML-based data formats under the CAEX IEC 62424 umbrella format. (Lüder and Schmidt 2015, pp. 12–13) This umbrella format passes objects for applications such as COLLADA or PLCopen XML in the native application formats (Weidemann and Drath 2010). Interoperability with the OPC Foundation's Unified Architecture (OPC-UA), a standard for platform-independent, service-oriented data exchange between machines and plants that also permits semantic descriptions (IEC 62541-1:2010), bridges the gap between data from the product and resource development processes and the dynamic process data (Henßen and Schleipen 2014, p. 297ff). The integration of ISA-95 and collaboration with the OPC Foundation, eCl@ss e.V. and prostep ivip Association are intended to establish AutomationML as an important building block of the IoT (Lüder and Schmidt 2016, p. 221).

**JT** is currently the most widely used exchange format for the visualization of 3D data and became an ISO standard in December 2012 (ISO14306). It is supported by a large number of (vendor) tools and is used as a de facto standard in industry, for example for mechanical design (CAD), computer aided quality assurance or computer aided process planning (CAPP). It is particularly notable for its low memory demands, which can be further reduced by also limiting the level of detail. At the same time, BREP (boundary representation) can be used to create exact copies of external geometries with a high level of detail. Specifically, sets of triangles, polygons, points, lines and implicit primitive objects (such as cylinders, cones and spheres) are supported to represent tessellated objects. It is possible to implement construction attributes and assemblies directly and link other information for visualization, such as materials, texture, lighting, as well as layers and filters. The balance between a high degree of compression and the accuracy of the data means that the format is mainly used as an interface format for collaboration in the world of CAD, for example to define the neighboring parts in a design. However, its full potential is only achieved in combination with the AP242 XML standard in order to link additional meta information (such as kinematics, hierarchy, etc.) with 3D information. The possibilities for linking using STEP are described in ISO/DIS 10303-242.2. In this context, Katzenbach et al. have highlighted a number of use cases that show that the format offers potential beyond visualization, first and foremost for digital mock-up. Examples include tolerance analysis and supplier integration, and context-sensitive design becomes possible if this information is stored in the XML part and passed independently of native data formats.

**STEP AP242 XML** is an XML-based exchange format that offers a wide range of options for structuring meta information describing the product in a machine-readable format and coupling it with 3D information. Focus is placed on representing the structure and providing context information. The standard was originally developed in the automotive and aerospace industries. It replaces AP203 and AP214 and thus provides a PLM backbone. Due to its generic design, the standard is used in a wide range of industries with very different requirements and has as a result also been implemented in most CAx and PDM tools. Domain-specific elements are constantly being added to the standard. The STEP tree provides the basis for this, linking context information to 2D or 3D data, for example. For example, the following data can be recorded: Compositions and the linking of kinematics to design conditions and constraints, information on product manufacturing, the quality of geometry data, as well as rules and requirements. AP242 provides a number of options for interoperability with PDM systems.

Architectural standards are also becoming increasingly important in the context of providing descriptions of all resources. When it comes to layouts and mapping resources within production halls, open standards (openBIM) are of particular relevance. They are standardized and established by buildingSMART, an international organization, based on the building information modeling (BIM) approach. The standards thus include three-dimensional geometry data for the digital representation of buildings throughout their entire lifecycle. Not only geometric information but also semantic information such as material information, cost information or information about the relation of two objects, for example, is stored. Zones and areas can also be saved in addition to volume objects. Focus is primarily placed on the interchangeability and extensibility of a file between different user groups. What sets these standards apart is the fact that all objects represent an instance of a specific object type, which facilitates their use for structural analysis or dynamic building simulation. (Borrmann et al. 2018)

# 4 Development of a functional data model

## 4.1 Motivation for the functional data model

We already have industrial standards and metadata formats that provide templates for data exchange within various process levels, e.g. for developing and operating a production system. Taking as our starting point a digitally developed product that is represented by means of models (3D assemblies, BOMs, etc.), it is possible to derive, plan and implement a production system that has to satisfy both technical (e.g. manufacturing and assembly processes, quality, etc.) and economic requirements (e.g. batch sizes, development and operating costs, etc.). During operation, the use of MES systems makes it possible to assign manufacturing orders to production systems that are prepared and ready for operation and to cycle through these efficiently. From initial planning through to operation, digital tools and models are used for technical engineering or planning processes, which in theory make consistent, end-to-end modeling possible.

In practice, however, there are frequent discontinuities in the information flow , for example, dueto the absence of the interfaces necessary for the use of exchange formats between different tools. The various individual models only map a selection of the aspects that are necessary for the corresponding process steps. A higher-level, industrially standardized model then establishes the relations between the individual models and is available for integration in development tools by means of exporters and importers. As a result, only the necessary information from the overall model is used and manipulated for any given individual process step before then being fed back into a consistent model. However, the simple presence of industrial standards is not sufficient if these are not implemented in business processes. In addition to the need to raise awareness of model-based (systems) engineering, in particular in the case of complex systems, industrial standards often fail due to issues of usability, since they frequently have to map a very large number of dimensions (e.g. development artifacts from different disciplines) and consequently possess a generic structure. If it is to be suitable for use, the model must be instantiated by specialists and adapted for the company in question.

It is therefore well worth examining whether, in the long term, it is possible to derive an industrial standard whose basic structure is as similar as possible to comprehensible, familiar business processes. For these reasons, the PLIM working group has followed a deductive approach in order to derive individual information models that reflect real-world practical application on the basis of actual use cases. Each of the derived models is exclusively tailored to the requirements, processes and entities of the use case originator and can very probably only be directly used by the latter in a practical application scenario. In order to derive a generic model, the next step consists in consolidating models from different use case originators within a single model. To this end, the main carriers of information were identified and analyzed in order to determine the extent of the overlap between the individual use case originators.

One aim of this examination is to determine whether it is possible to develop a middle way between a generic and an instantiated, application-specific model that can also be transferred to the greatest possible number of use cases. To do this, it is necessary to analyze as heterogeneous a range of use case originators (company size, sector, disciplines involved, etc.) as possible. This requirement is associated with a number of limitations. Nevertheless, this type of examination provides indications of how an iterative approach based on a growing number of analyzed user cases makes it possible to come closer to a solution that can be employed on the broadest possible basis in the future.

Following this, it is possible to examine whether a link can be established to existing standards in order to benefit from high levels of integration in development tools (e.g. existing importers and exporters in tools). The overarching aim is to create interfaces to the digital models that are used during the product lifecycle in the digital factory in order to reduce discontinuities in the information flow. Finally, it is necessary to at least discuss the level of usability when compared to existing industrial standards.

## 4.2 The development process

The process starts with the identification of use case originators, which ideally will already be using a model-based approach and be characterized by complex, interrelated processes and enterprise variables in order to permit the mapping of large quantities of information and dependencies that can be exploited within a functional data model. To this end, we chose two project partners from the automotive industry, which however differ in the details of the product type and disciplines involved.

Workshops were conducted with representatives of the various disciplines in order to map and merge individual domain-specific aspects. This form of observation at the level of the processes themselves meant that the employees were able to participate positively in the development of the model. To this end, the main processes were analyzed and modeled on a domain-specific basis in order to create a logical information model. At every stage during this operation, it was necessary to take account of contextual and data engineering perspectives and incorporate these within a balanced form of representation. However, it should be kept in mind that the developed individual models only ever place the focus on certain aspects and disciplines because the task of comprehensively mapping a major international company is extremely demanding.

## 4.3 Recording the functional data model

### 4.3.1 Use case: Audi

The first use case was provided by Audi AG. Following an initial analysis, we chose to focus on bodywork construction, which in the employed production solution, tends to be characterized by inflexible lines in large, sequentially structured systems. Isolated interpolated processes extend the rigid production workflows, for example by implementing configuration capabilities for vehicle bodywork. There are already numerous structures involving data storage and management systems and processes for digital development activities that have evolved over the years but which are not directly networked with one another. One particular challenge here lies in the fact that elements of the production system are generally provided by system integrators based on requirements defined internally by Audi AG

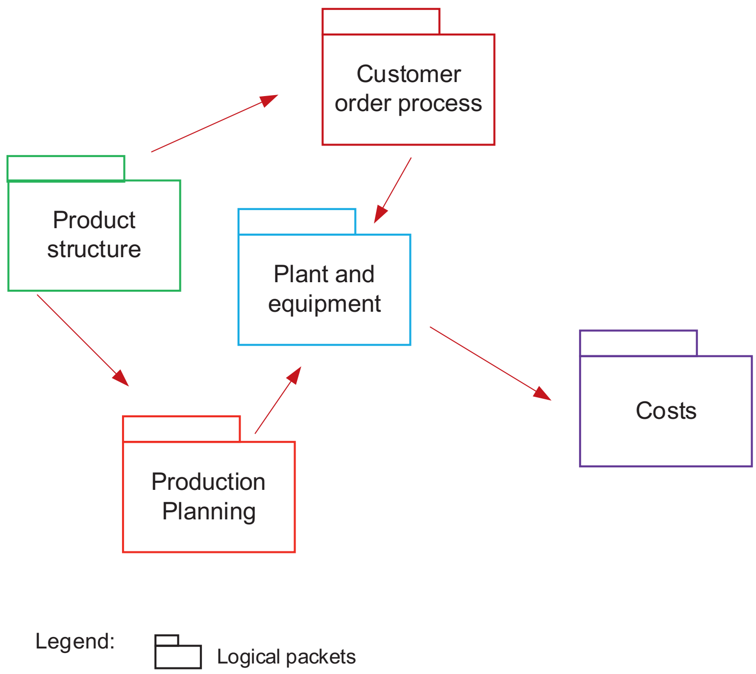



Figure 3: Overview of the information model for the use case at Audi AG

Problems arise if no digital models are fed back into the Audi data storage and management systems following commissioning – for example, if a system has to be overhauled. This made it clear that the domain-specific models of real-life production systems need to play a central role in the functional data model that we wish to develop. The functional data model is subdivided into five main components – Product structure, Production planning, Plant and equipment layout, Sales and Costs – which were further subdivided into logical packages (see Figure 3: Overview of the information model for the use case at Audi AG).

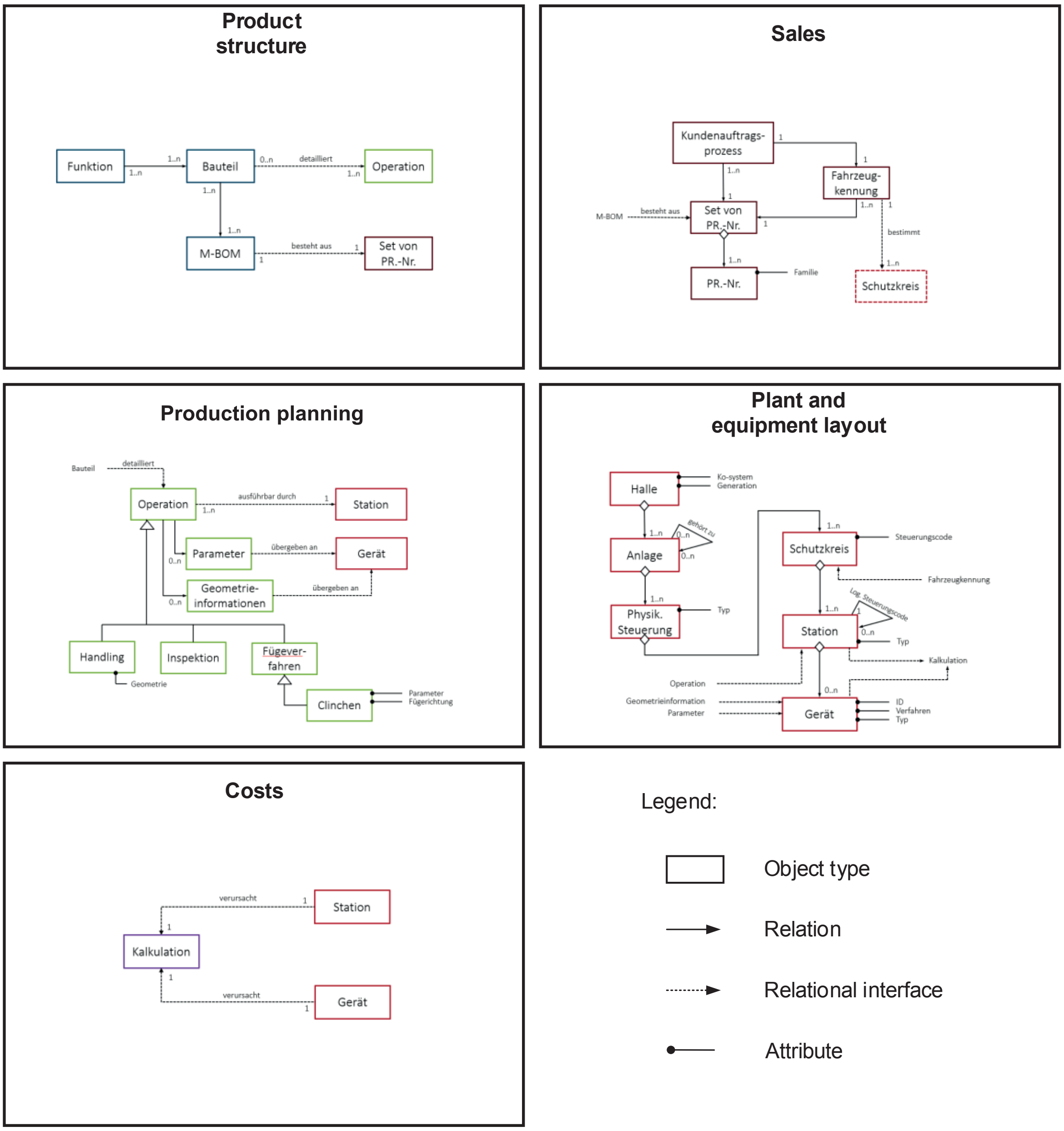



Figure 4: Detailed presentation of the functional data model for the Audi AG bodywork construction use case

### 4.3.2 Use case: ZF

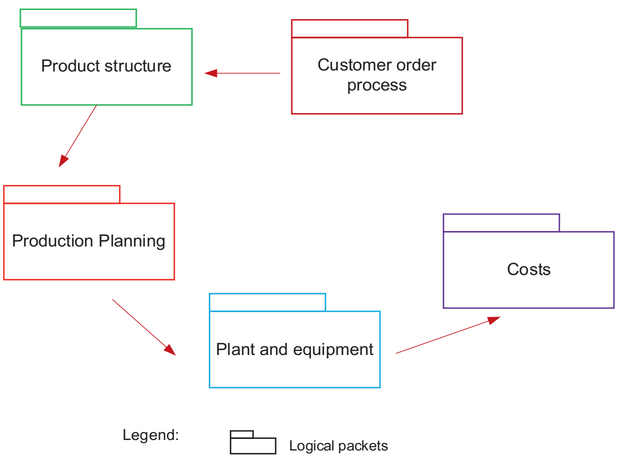



Figure 5: Overview of the information model for the use case ZF AG

The second use case was provided by ZF Friedrichshafen AG. Like the first use case, this was put together in cooperation with specialists from different departments. The segment under consideration, namely the production of transmissions, is characterized by a mixture of medium and small-run production orders that have to be planned and assigned within a large-scale production facility. The production systems can be flexibly networked for individual process sequences (e.g. for a small series). When compared to the Audi AG use case, a mix of component production and assembly processes are performed, whereas the tendency at Audi is to assemble supplied components. Due to the specific circumstances, the focus in the ZF use case is on production control, in other words the assignment of production orders to free resources (systems or human operators). The functional data model is subdivided into five main components – Product structure, Production planning, Plant and equipment, Sales and Costs – that are further subdivided into logical packages (see Figure 6: Detailed presentation of the ZF AG use case).

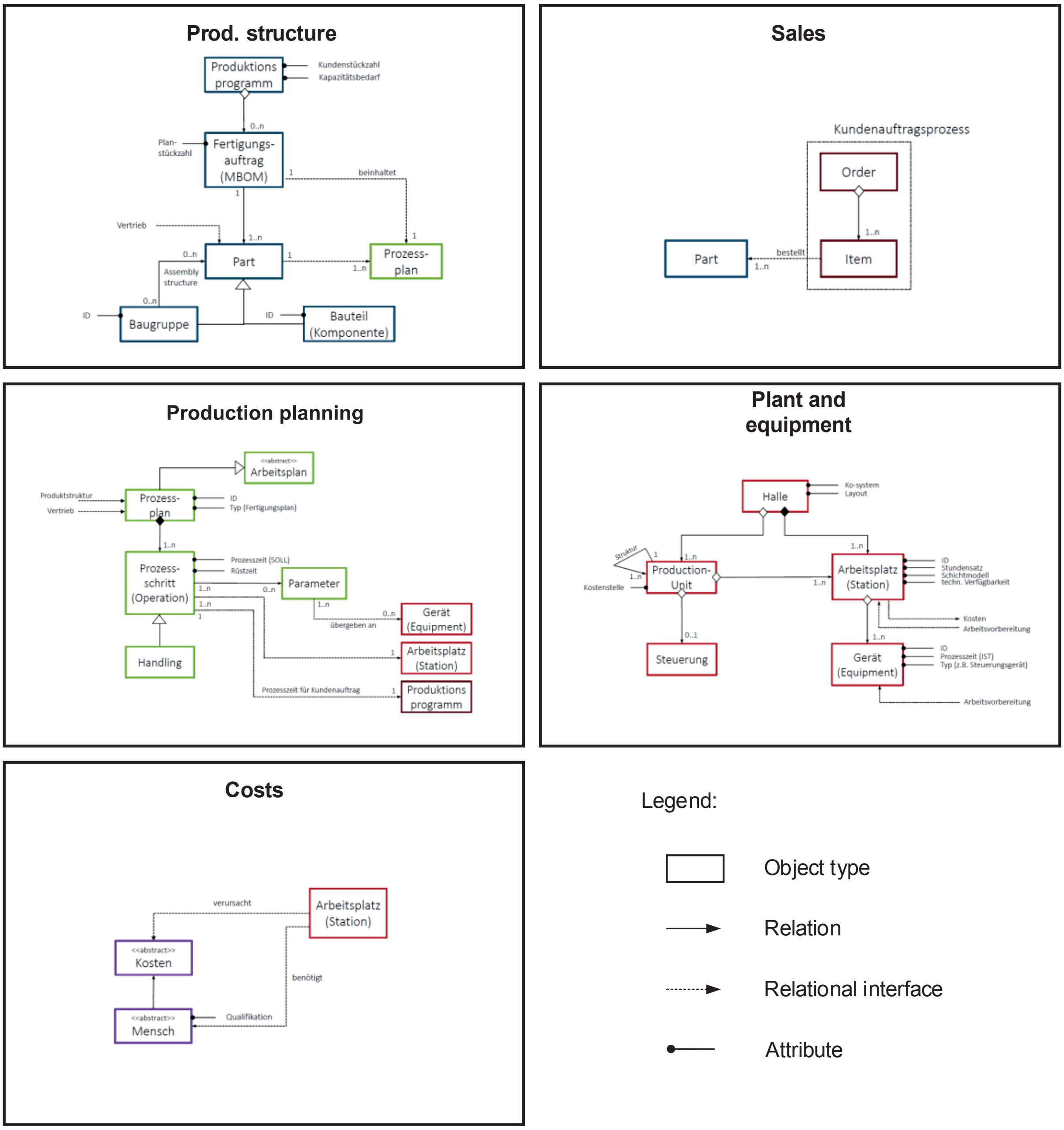



Figure 6: Detailed presentation of the ZF AG use case

Consolidated functional data model:

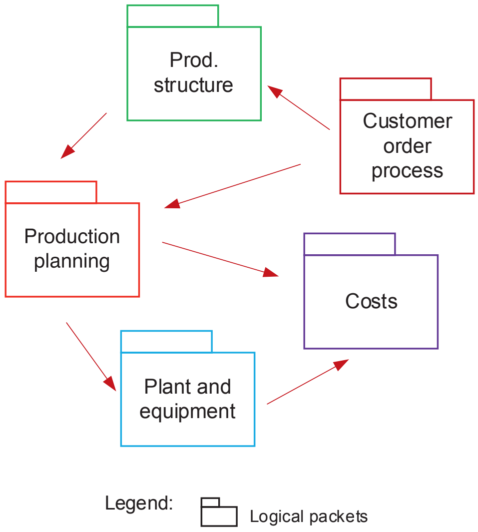



Figure 7: Overview of the consolidated functional data model

In the next step, the models from the two use case originators were compared and consolidated in order to create a cross-domain overall model. This revealed logical overlaps between the two models, which sometimes use different terminology to refer to the same entities. The result is that it is possible to assign a large number of object types. The functional data model possesses a high level of practical applicability for both enterprises.

During the customer order process, internal order and development processes (new development or series production) are generally initiated on the basis of purchase orders and these processes are composed of individual components, including the enterprise-specific identifications for the configured product. Starting from the definition of the product, it is possible to derive manufacturing processes and work plans that can then be assigned to implemented systems. A variety of different costs can be derived and calculated depending on the resources required in any given instance.

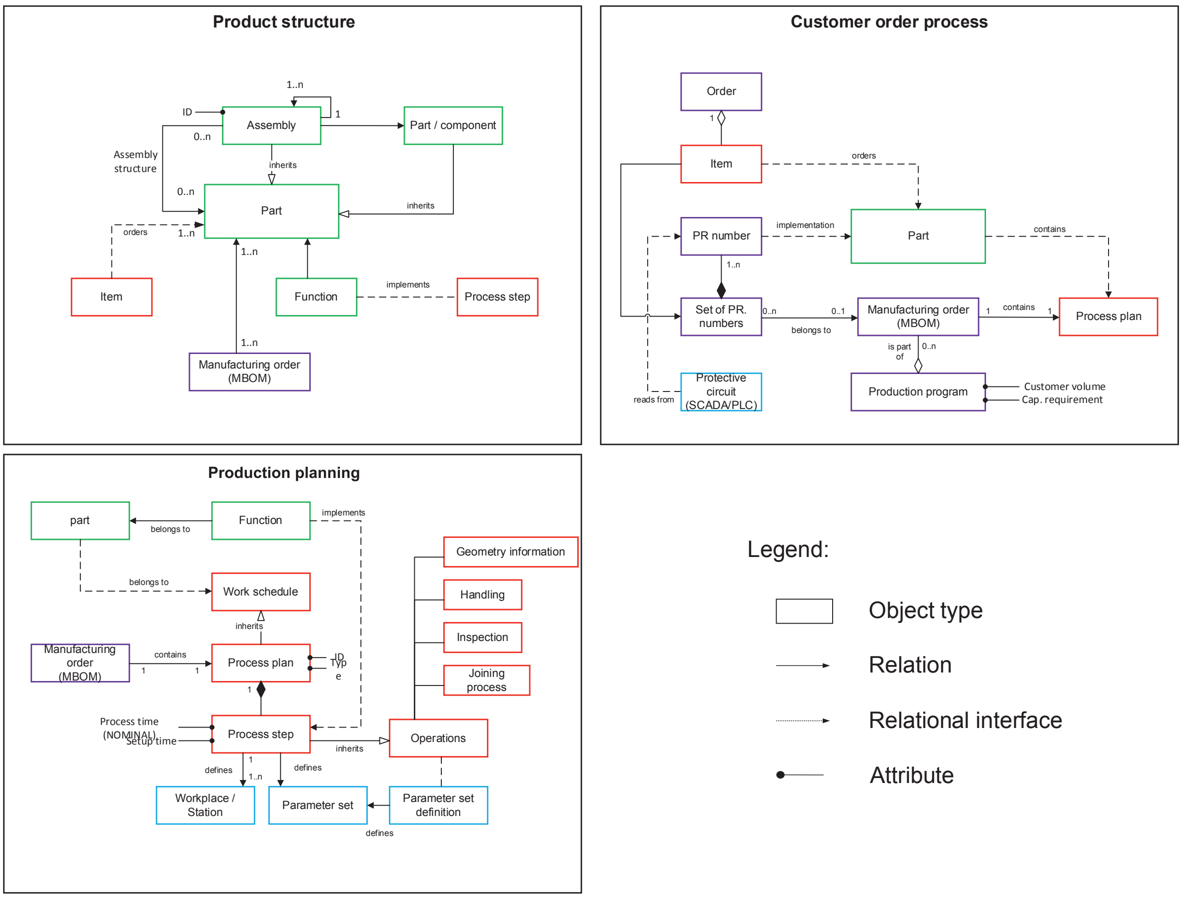



Figure 8: Subject data model consolidated. Detailed presentation of product structure, customer order process and Production planning

It is to be expected that the incorporation of further use cases will result in other changes to the model and that this will always be associated with a certain level of uncertainty. It has been derived based on the perspective of individual companies and/or their employees, who work with their own processes and were involved in the development of the model. The next step is to move from the information model to one that permits technical data processing. Ultimately, this will make it possible to standardize data and ensure implementation thanks to reliable mapping.

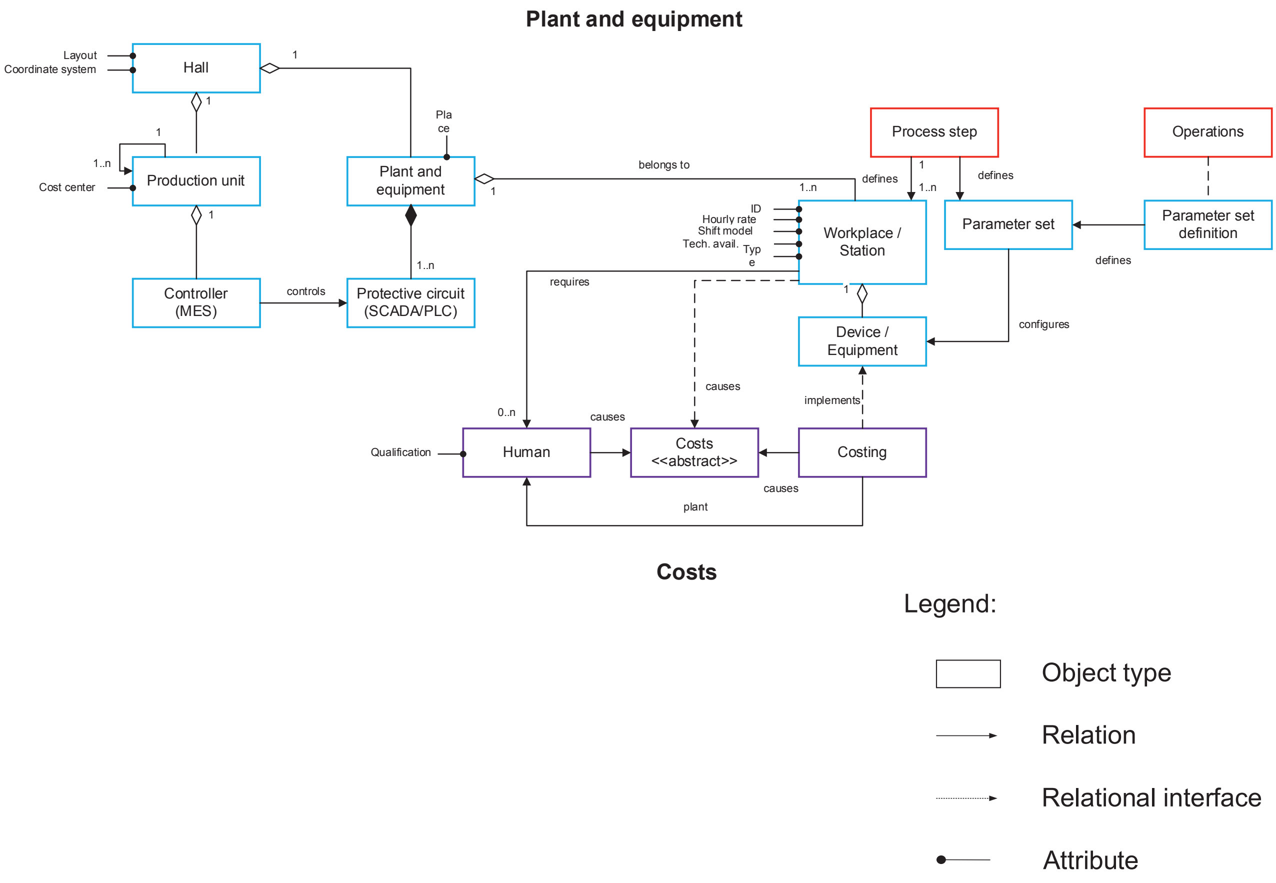



Figure 9: Subject data model consolidated. Detailed presentation of the plant and equipment and cost elements

### 4.3.3 Comparison with ISA-95

A comparison with ISA-95 was performed. ISA-95 is a widespread industrial data standard for which interfaces to other formats already exist (e.g. AutomationML). Thanks to its generic structure, it generally maps all aspects. This, however, also requires a high level of abstraction – and consequently hinders implementation. If the functional data model can be linked to ISA-95, then this conservative approach will make it possible to store and implement relational databases easily in combination with the UML data model. However, adaptations to the standard are difficult to implement and would have to be incorporated via the ISA. Alternatively, there are also other models (e.g. STEP AP242) that could also be considered in the equation and might even be more suitable.

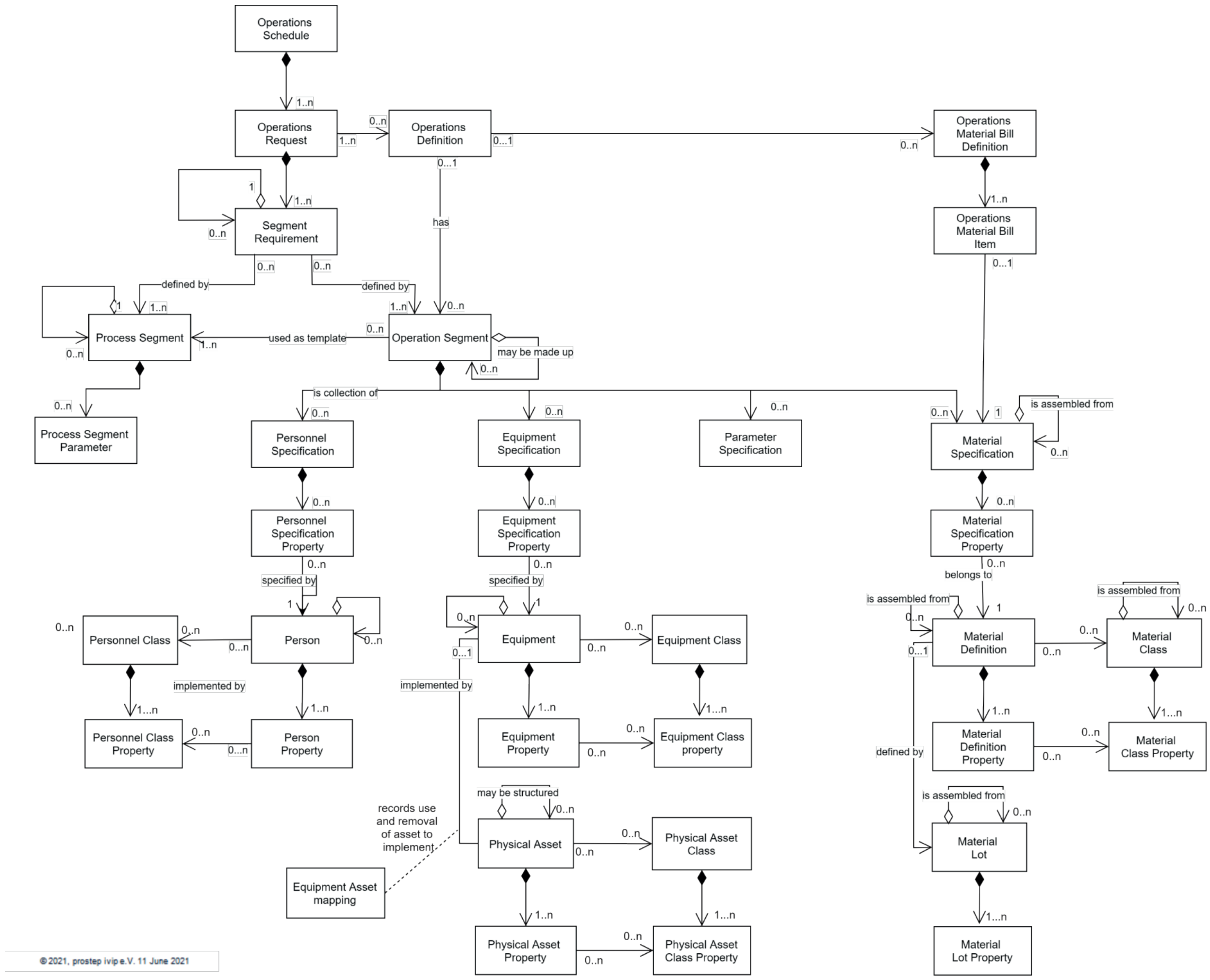



Figure 10: Result of transposing the functional data model to ISA-95

The individual components of the functional data model were described using the ISA-95 standard. To a very large extent, it resembles a part library. Instantiated object types are linked to a library part via relations, an approach that closely resembles asset mapping. The instantiated objects (e.g. a robot as equipment) can themselves be further nested (e.g. link with another piece of equipment: electrode holder). At a higher level, the equipment is assigned to the operation.

Everything that is mapped in ISA-95 can also be depicted in AutomationML and transferred using existing exporters. This would make AutomationML an important exchange format which can, for example, be implemented between company boundaries in order to trace back real planning and development activities and ensure the end-to-end multidirectional flow of information.

# 5 Exporters

The above-mentioned mapping procedure is currently being used to create an AutomationML model that is able to integrate or reference all the main specialized information objects of the original domain-specific models from the product and production lifecycle.

If the full potential of this model as a long-term solution for mastering complexity is to be achieved, it will be necessary to establish it as a standard for uniform information exchange throughout the product lifecycle.

This will require its across-the-board introduction into the IT systems used in the mechanical and plant engineering industry as well as those of manufacturing companies. This can only be achieved if the software providers enable their BDE, MDE, MES, PLM, ERP and other solutions to perform this information exchange by incorporating importers and exporters for the AutomationML model.

In the sections below, we present the technical feasibility, current prerequisites and specific challenges on the basis of individual practical examples of these interfaces.

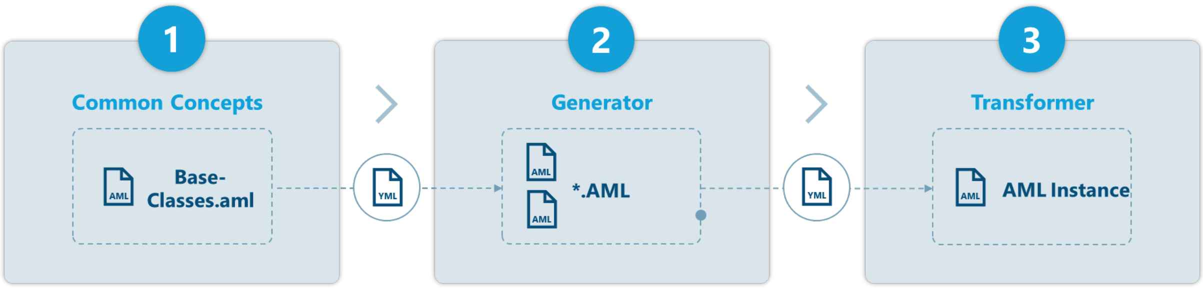
## 5.1 AutomationML generator

AutomationML possesses a transformation architecture for transforming various data formats, such as CSV or XML for example, which are often used for data storage in industrial companies. This architecture is used to convert local, domain-specific and cross-domain formats.

These so-called tool artifacts provide an abstract representation of the technical information. This information must be transferred to ALM-based formats, known as engineering artifacts, so that it can be integrated in an AML project file that is based on a global format and is used to represent the information. This latter file reflects the individual possible tool artifacts and is thus enterprise-specific.

The structure of the architecture can be described as a transformation chain, a simplified depiction of which is presented in **Error! Reference source not found.**. A CommonConcept.yml file and an AML file containing the required AML base class are required as inputs for the process chain. The **generator** represents the initialization stage, during which the libraries required in order to create the local and global data models are generated. The output is a set of *.aml files.

Figure 11: Structure of the AutomationML transformation architecture




The downstream transformer is data format-specific, although generic in terms of the internal data structure, and is used for the automated conversion of tool artifacts into engineering artifacts.

The transformer therefore needs the tool data in addition to the data from the previous step. Configuration is performed in two steps. The first step, or the first configuration file, defines how the object types can be identified from a tool artifact and transferred to a local AML unit class. In the second step, the source of the individual attributes is then referenced in a further configuration file. The output from the transformer therefore takes the form of *.aml files, which represent the engineering artifacts. In a final step, the engineering artifacts are then transformed from the local AML unit classes into a uniform, overarching, global language.

In a subsequent integration step, the various engineering artifacts, which are already present in a uniform language, can be iteratively merged to create a higher-level data model. This data model contains all the relevant objects together with their respective properties and interfaces.

Finally, a tracer addresses the dependencies of the individual attributes in the different domains or divisions and replaces missing values based on the uniform global language or structure. At the end of this process, the data is present in a uniform format, which can be used in different ways.

Thanks to the modular structure, files do not necessarily have to pass through the entire transformation chain. In addition, the modules or components can be executed independently of one another, thereby permitting fast, versatile adaptation. Other tool types can be referenced in the CommonConcept.yml file in order to update the execution of the generator of the AML1 transformers and integrators. All that remains to be done is add a new transformer with the data format-specific configuration. Individual main components are characterized by the detailed interaction of the generator, transformer, AML1 transformer, integrator and tracer (see Figure 12: Detailed interactions within the AutomationML transformation architecture).


Figure 12: Detailed interactions within the AutomationML transformation architecture

The AutomationML data logistics are based on a central architecture in order to make local domain-specific knowledge available to other disciplines. Unlike other integration strategies, no predefined data model is used for semantic harmonization. Instead, a specific view of each domain on an object is analyzed in order to make it possible to derive common concepts. The properties of concept views can then be transferred to one another by the data logistics in the light of the defined dependencies.

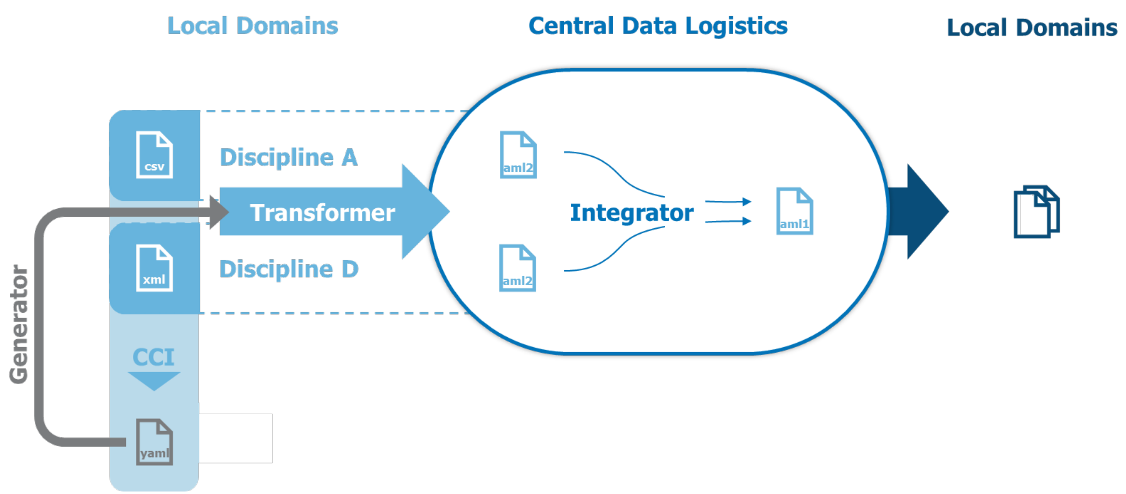



Figure 13: Presentation of the AML data logistics in the domain-specific view

It was found that due to the resource-intensive process, it is probable that no (online) data from Production can be transformed in this way, even though the AML data logistics offer potential in the field of asynchronous system integration, e.g. for planning data. To map production systems, it is necessary to detail the IEC 62264 elements. As a result, interoperability can be impaired by specific extensions, thus resulting in implicit limitations with terms of usability for the data logistics.

## 5.2 Delmia export:

The 3DEXPERIENCE suite from Dassault Systèmes is an example of comprehensive product data management in the lifecycle. Despite the suite's extensive functionality, there are no companies or supply chains in which it is the sole solution used for product, process and resource management. The reasons for this lie in the presence of IT structures that have evolved over decades, cost savings potentials offered by the use of lightweight individual solutions or the need for highly specific functions. This underscores the need for a uniform data interface.

Because this all means that the full integration of all processes in a single tool constitutes a challenge, at least for large enterprises, suitable import and export functions may offer considerable potential. Against this background, the corresponding possibilities are constantly being investigated. At present, two approaches appear relevant in the context of data exchange in AutomationML:

1. Querying of data from Delmia via REST API in JSON format:
2. Direct (integrated) XML export

The REST API makes it possible to query and process all the required data from engineering and manufacturing/ process planning in JavaScript Object Notation (JSON) format. Thanks to the simple text format and independence of any specific programming language, JSON is particularly suitable for data transfer between applications and formats and can be transposed in full to an XML structure. As a result, data can be queried from engineering or manufacturing and process planning and made available in JSON. In the next step, this data can be taken over into the AutomationML structure by means of mapping or the AutomationML transformer.

# 6 Use case: Mars Rover (best practice)

## 6.1 Introduction

As a cross-project group and therefore enterprise-neutral use case, part of the PROSTEP AG's Mars Rover model was mapped in a fictitious production network involving the other stakeholders: IPS, IPK and an external customer. In this scenario, the various subcomponents are mapped in different engineering and PLM tools (e.g. Delmia). This artificial use case permits a proof-of-concept for the end-to-end mapping of object types within the information model by using the neutral AML (Automation Modeling Language) exchange format. Thanks to AML's export and import capabilities, it is possible to integrate structured information in the information model using the presented interfaces on the basis of the ISA-95 standard. The use case presented here is intended to demonstrate the benefits on the basis of a progressive application example and clarify which data can be implemented in the AML standard. The use case not only addresses the problems that companies currently face, due to the face that the use of AML reduces discontinuities in the engineering data flow, but also indicates new potential by making new Industry 4.0 business models possible and providing the basis necessary for technologies (e.g. digital twins or automation in the engineering field). In this context, the continuity of the data and information flow via central systems is essential.

## 6.2 Structure of the example

In the example employed here, data exchange is optimized across all company and process boundaries for a special case involving a variable Industry 4.0 production network. The higher-level use case starts with the award of the contract: The flow chart below involves four stakeholders: IPK, IPS, a cooperation platform for open production networks, and the customer, who wants to order the Mars Rover. The platform generates a customer order process and information is then passed on to the two participating production systems (Fraunhofer IPK and IPS TU Dortmund) using a generic interface format.

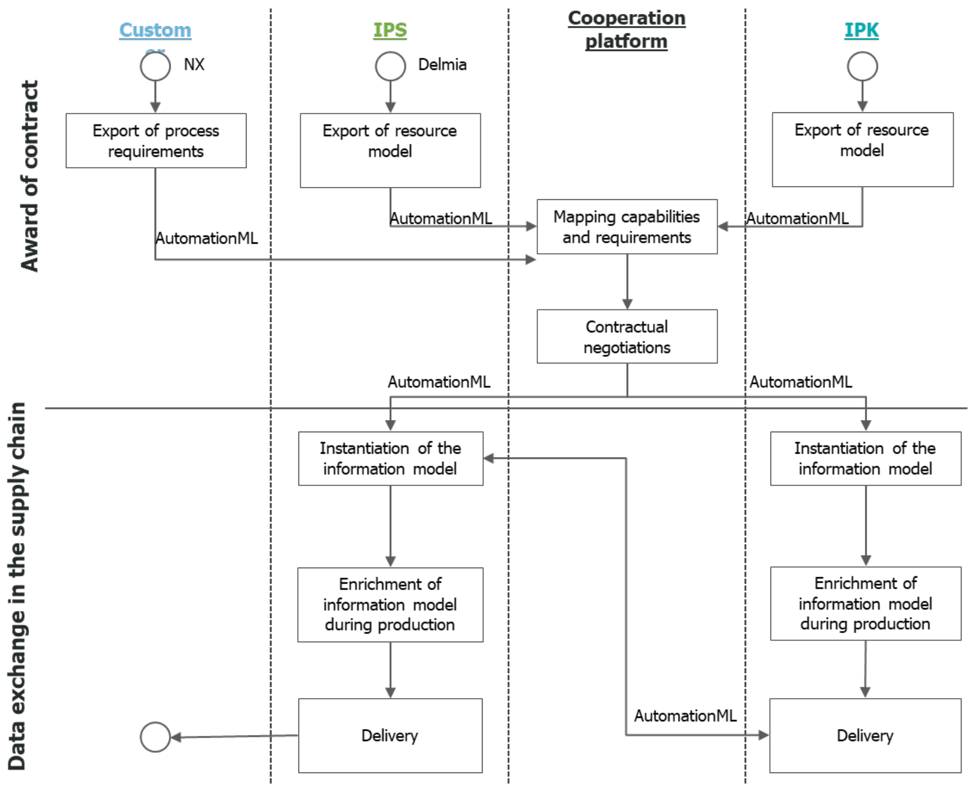



Figure 14: Data exchange within the production network

The customer defines the process steps required for the product that is to be manufactured and provides all the necessary product models in digital form. The information comprises, for example a bill of materials, production plan, product requirements and a product model. Companies can make their production capacities and capabilities (resources) available on the platform. The selection and networking of providers that make their equipment, employees and so on available for lower-level process steps results in a supply chain that leads to the creation of a product that meets the customer's requirements. During exchange via AML, the partners' context-specific development documents are added to, stored centrally and can be consulted by all the participating partners. Thanks to the high level of networking and the variability of this type of production system, small batch sizes can be manufactured efficiently as long as the platform contains a sufficient number of providers. Thanks to the ability to call on available resources and make efficient use of them, companies can enhance capacity utilization and customers can commission small series at economical conditions. In this context, automation measures (e.g. for order control) are only possible based on the technical-level networking of the model in order to get to grips with the complexity of various domain-specific engineering activities within the model.

## 6.3 Process chain

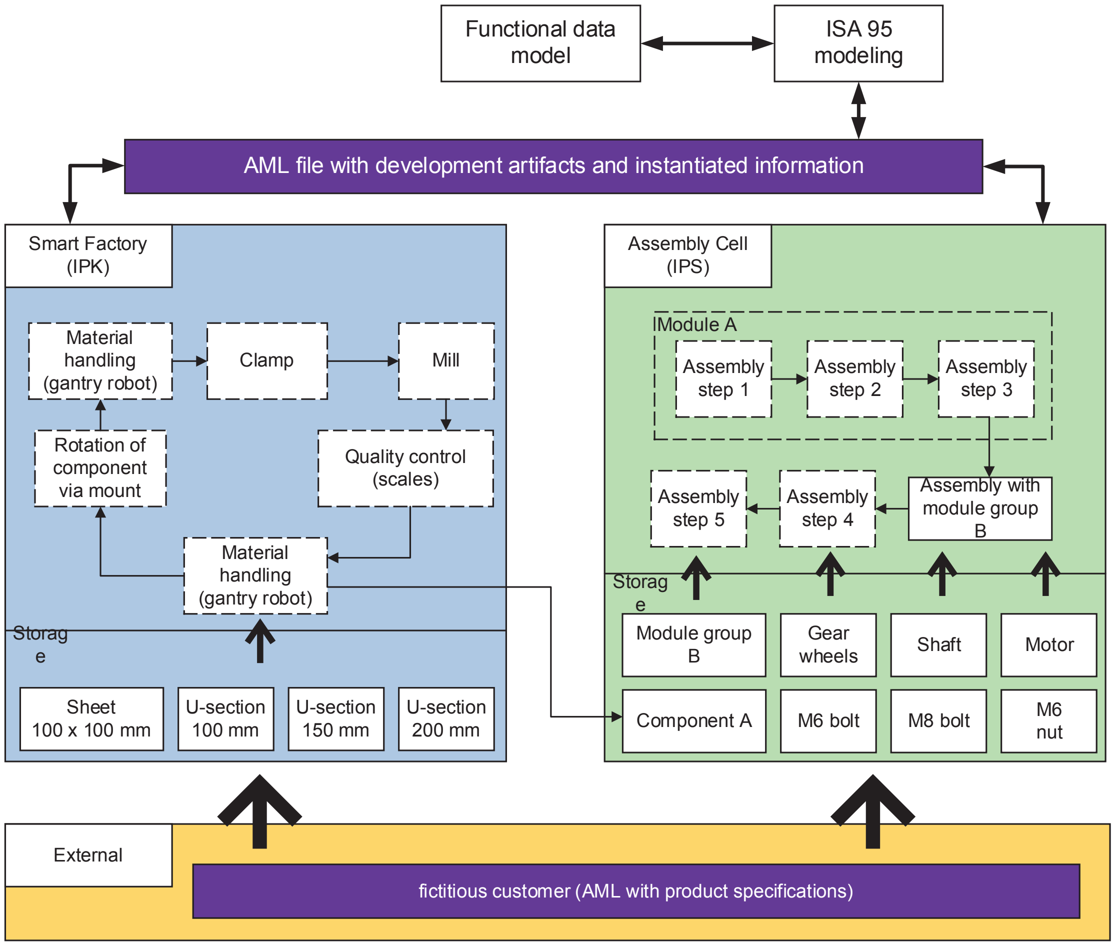



Figure 15: Depiction of the process chain in the production network

IPK produces and machines a component for the Mars Rover and makes available an example manufacturing system – the Smart Factory Industry 4.0 Demonstrator. Subsequent assembly is performed by IPS, which makes an assembly system available for this purpose. A customer makes product data, such as BOMs, production plans, geometric models and information that is relevant for production (e.g. quality requirements) and assembly (e.g. assembly sequence) available for the Rover, including requirements relating to order handling.

All the customer's requirements are entered on the platform as an order. At the start of the order handling process, the resource capabilities of the Fraunhofer IPK production system and the Dortmund IPS assembly system are exported from the planning tools as a resource information model. This information is also imported into the collaboration platform, on which a wide variety of production systems are in competition. The customer's process requirements are enriched by information from the resource models by assigning the corresponding capabilities from the resource models to the requirements. This makes it possible to choose suitable suppliers based on an evaluation of their potential and simulations. After this, the orders are passed on from the platform to the two participating production systems in the form of an integrated PPR model, the associated contracts are negotiated and a supply chain is created.

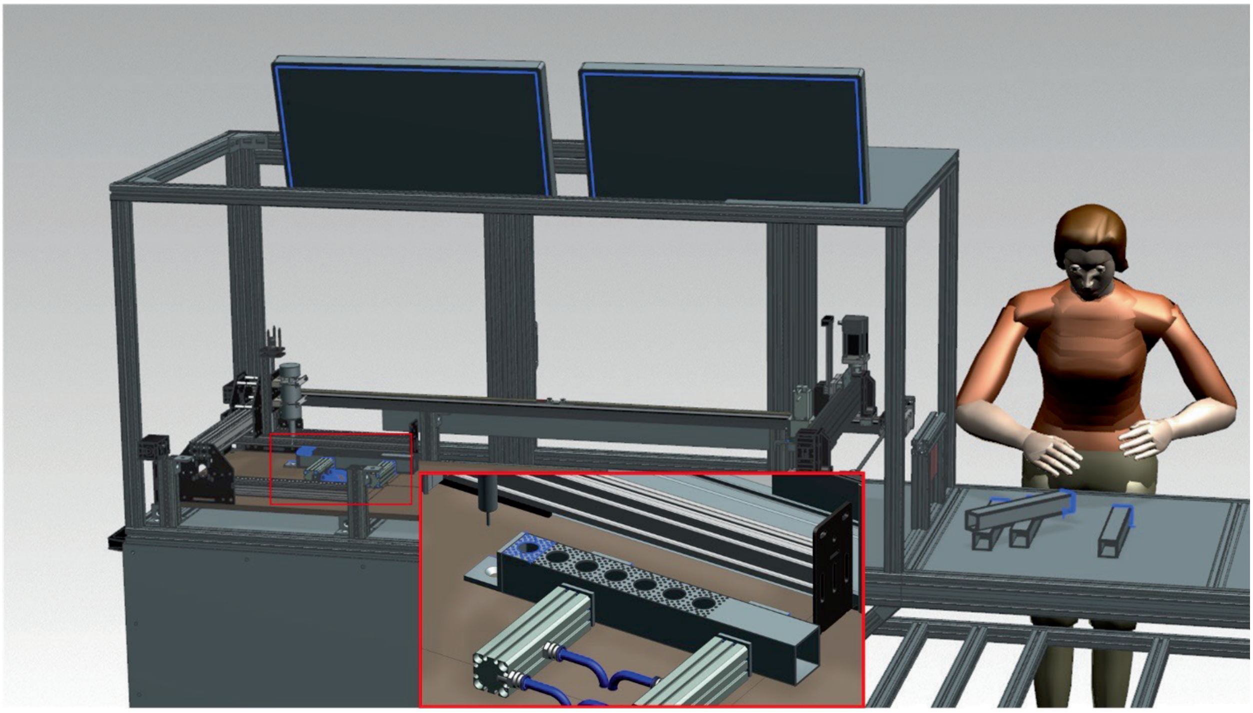


Figure 16: Design and process simulation in Siemens Mechatronics Concept Designer

At Fraunhofer IPK, the necessary engineering activities are then performed at the Smart Factory in order to make the required process possible. Integrating the Smart Factory's digital twin with simulation software permits the, in some cases, fully automatic adaptation of control code. Alternatively, manual programming can be performed, supported by the immersive integration of persons via VR (virtual reality). Control is performed live (Beckhoff TwinCAT) using a physical simulation (Mechatronics Concept Designer) in order to derive code for systems control on the basis of digital tools and to configure the process correctly. Robot trajectories for material handling are adapted in a robot simulation operation (Siemens Process Simulate). The development documents that are generated are stored, linked via AML and exchanged so that the domain-specific engineering activities performed at Fraunhofer IPK can be traced from beginning to end. Finally, following production release, it is possible to perform instantiation at the product in order to pass on further batch-specific information, which is linked to a product identification. This information includes quality data (weight of blank and finished component and 3D-scan point cloud of the finish component) as well as identifiers (serial number, timestamp, etc.). If required, it would, for example, be possible to incorporate additional data such as the gripping forces at a robot end effector in order to document any deviations during the process. All the relevant information and product data is passed to the assembly system by means of an exported AML file together with the physical components.

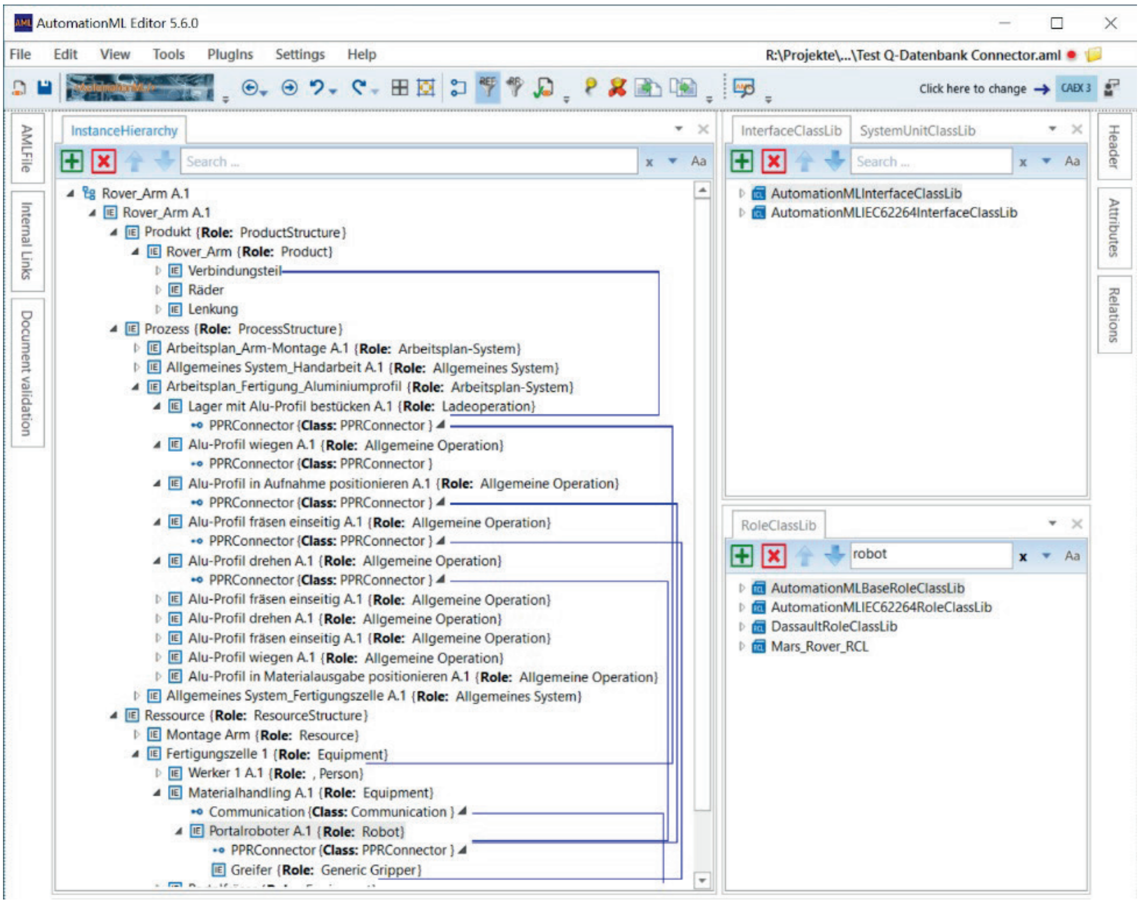



Figure 17: Mapping of the Mars Rovers as a PPR model in AutomationML [1] (View: AutomationML Editor)

At the IPS assembly system in Dortmund, the AML file is imported and complemented by the addition of further planning and process information in order, ultimately, to make it possible to assemble various modules sourced from external suppliers. When deviations from tolerances occur that are relevant for assembly, it is possible to check whether these are attributable to Fraunhofer IPK and whether process adaptations are necessary there. Shipment to the customer is then performed, accompanied by the corresponding documentation (such as quality defects, for example).

The fact of working at a single dataset now permits cross-enterprise, simultaneous virtual commissioning prior to the commencement of actual production. To this end, the assembly process is simulated with various configurations of the assembly system at IPS, where the Rover is actually assembled, in order to generate an optimum scenario based on ergonomic (MTM EAWS) and temporal (MTM UAS) analyses. Production-relevant information resulting from the knowledge gained during the assembly simulation is then passed on to IPK via AML file in order to permit production in accordance with the assembly requirements. Following assembly, the Mars Rover is shipped to the customer together with the corresponding documentation, which contains all the collected information from the first two product lifecycle phases, the product engineering phase and the product manufacturing phase.

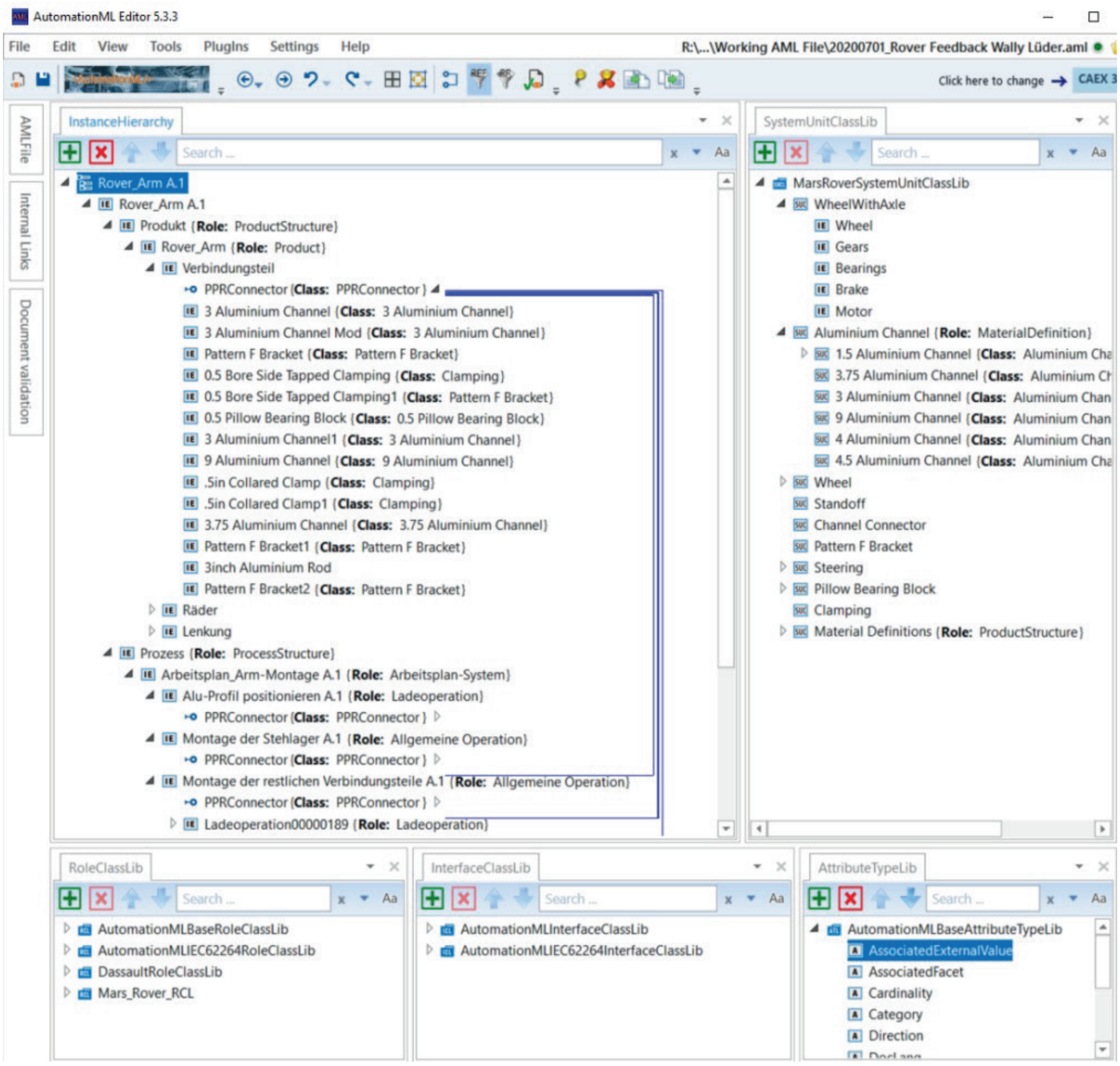



Figure 18: Mapping of the Mars Rovers as a PPR model in AutomationML [2] (View: AutomationML Editor)

In this way, the information model is used throughout the entire supply chain and permits comprehensive feedback-to-design for both product and production system development and quality management. The networked digital twin grows beyond enterprise boundaries and permits optimized planning, design and traceability as well as new, networked production chains. Thanks to the up-to-date, complete knowledge of the development data, it is possible to integrate the (local) production systems and reconfigure them when processing larger volumes.

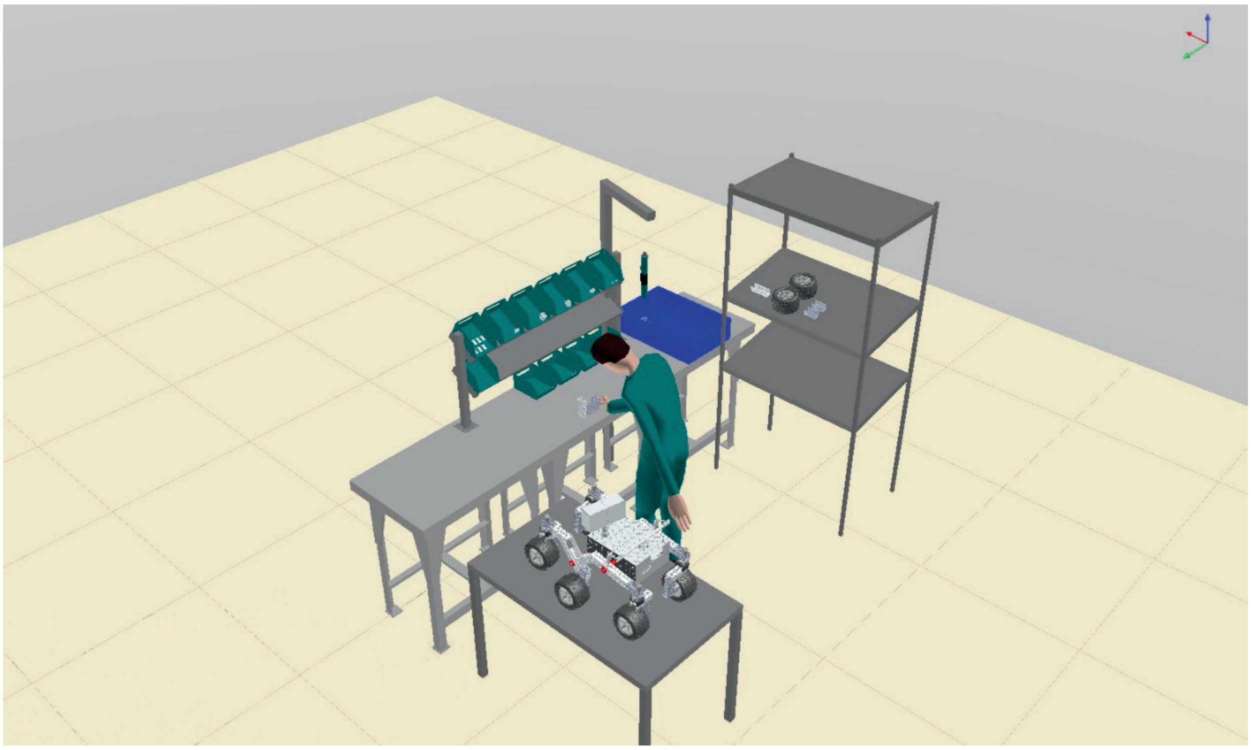


Figure 19: PPR model for the virtual planning of the assembly process

## 7 Summary and avenues for development

The use case examined here therefore shows that the functional data concept described here and the use of the AutomationML generator for transforming differing data formats into the uniform AutomationML format are very well suited for creating a uniform, cross-department and cross-enterprise data storage and management approach for asynchronous processes. Given the current state-of-the-art, today's AML tools do not yet provide the functionality necessary for synchronous use. At the same time, the results of the survey highlight the relevance of the problem of media discontinuities in industry and the approach presented here represents a possible solution to this. Independently of the tools employed locally, e.g. Delmia and NX, a standardized data exchange between the various stakeholders is made possible across the entire product lifecycle. During this process, the flexible transformation architecture of the AutomationML generator permits the efficient adaptation of the model to the product- and process-specific requirements, as shown in the example of the Mars Rover presented here. This now has to be validated in further practically-oriented use cases.

What is more, internal enterprise and/or department workflows underwent only minor adaptations when selecting the export from the familiar system and established internal processes were therefore not changed. This model makes it possible to solve the problem of creating homogeneous, consistent cross-department and cross-enterprise data storage and management as revealed by the survey by establishing an industrial standard for data homogenization without creating another isolated solution. Unlike existing approaches, this makes it possible to integrate existing data formats rather than converting them to a standard format, thus making implementation in real industrial scenarios more realistic since there is no requirement for additional migration effort. The solution also brings with it the advantage that the responsibility for data recency and its suitability for integration during the local adaptation of data storage and maintenance lies with the generator of the data and is therefore unambiguously defined. Because the model is derived from concrete use cases and due to the flexible granularity it offers, usability is guaranteed even after the brief instantiation process.

For the future, this means that media discontinuities can be reduced and improved collaboration centered around agile methods and simultaneous engineering can be achieved because standardized data exchange forms the basis for efficient, agile production system development. To ensure broad-based usability, further testing in realistic industrial environments in a variety of different industries should be conducted in order to reveal any weaknesses and help identify further challenges in order to further improve the model and ensure industry-wide applicability. The aim is to create a scalable, adaptable industrial standard that should also be incorporated into ISO 16400-2 and taken into account during collaboration with the Digital Twin Association. In this latter area, the use of the information model can provide critical support for the structuring and generation of cross-process digital twins thanks to the improved end-to-end consistency of the data models. Further avenues for future development can be found in European initiatives such as GAIA-X or Catena-X.

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ISBN 978-3-948988-17-3
PSI 26
2021-12/Version 1.0