Optimized planning of the integration of a Reference Plant into existing brownfield environments based on an entity model

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Abstract

In plant engineering, due to the very individual brownfield environments, there is an enormous mass and heterogeneity of requirements that arise when a plant that was initially developed independently of the customer is to be integrated. This leads to the fact that specifications and requirements for the integration of a plant are often in the form of prose text, not standardized and not automatically processable further. The developed method describes a way to uniformly record the circumstances of the customer's brownfield environment and to automatically derive which requirements or conflicts arise during the integration of a pre-developed plant.

Keywords

requirements elicitation, plant engineering, object detection, reference plant, customer brownfield

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1. Motivation

Increasing competitive pressure in the market and shorter product development cycles are forcing companies to increase their productivity and produce higher quality, more customised products faster than ever. The digitalisation of many different economic sectors has also led to a significant productivity boost in many industries [1].
However, for a company to remain stable and still meet the requirements of its customers and authorities, it must reconcile cost pressure with flexibility, minimum planning time with high planning reliability and minimum planning effort with maximum planning quality. This is equally important for plant engineering as for companies in product development. [2]
In contrast to this, there is an enormous mass and heterogeneity of requirements in plant engineering, due to the highly individualised brownfield environments. Within the specifications, the customer tries to describe all his requirements for the plant to be built. The effort in the subsequent engineering work depends strongly on the quality of the information in the specifications and should therefore be as detailed and comprehensive as possible. In the further course of developing and planning the plant, the technical and financial feasibility of the requirements is checked. The more detailed the planning is in the early phases of a project, the higher the probability that the project will exceed the budget in later phases. The diagram (see Figure 1), shows the individual phases of a plant project. [3]
In the project's initial phase, the ability to influence the project costs is very high. 80% of the total costs of a plant project are determined in this planning phase [4].
The motivation is therefore to identify the customer's requirements as efficiently as possible and to process them automatically. For this purpose, a library with relevant geometric entities of the customer's brownfield environment needs to be developed. These entities are provided with labels so that the characteristics of the objects can be derived automatically. These characteristics are then related to integrating the plant using SysML [5] to derive integration requirements.

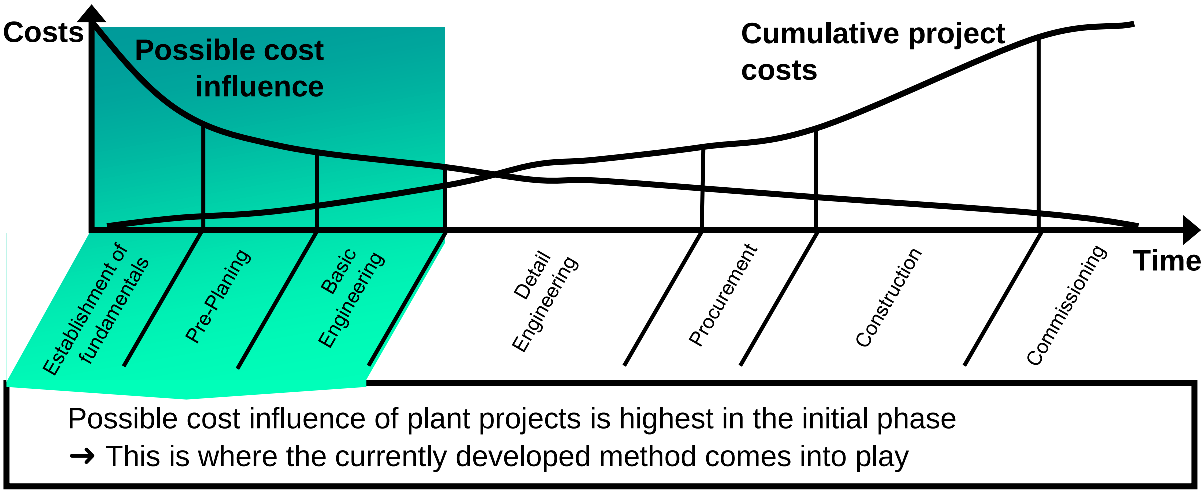

Figure 1: Possible cost influence during the runtime of a plant project and starting point of the developed methods following Weber [3]

2. State of the art

In many areas of plant engineering, a process plant is first pre-developed independently of the customer. In the literature, the word "Reference Plant" is used in this context [6]. In the following, this customer-independent developed process plant is called a "Reference Plant".
The Reference Plant can then be integrated with different customers. However, most projects in plant construction are not greenfield but brownfield projects, where construction takes place in existing buildings and existing infrastructure must be considered. [7]

The individual customer adaptations must be kept as low as possible when adapting the Reference Plant for cost reasons. This is a complex undertaking because usually no two environments into which a Reference Plant is to be integrated are identical. Especially those parts of the plant that have a direct interface to the customer's brownfield environment must be adapted cost-intensively and individually for each customer. However, it is the same entities within the integration environment and the Reference Plant, independent of the customer, that play a role in the plant planning process and whose characteristics influence the customer-specific plant development and planning. There are standards (ISO, IEC, and others), classification systems and initiatives relevant to the planning of plant integration. This paper describes how entity libraries are developed to describe a Reference Plant and the customer brownfield. The following sources serve as a basis for analysis and industrial input:

- The international “Data Exchange in the Process Industry” (DEXPI) initiative has set itself the goal of enabling interoperability between different partners involved in a plant project. The focus here is on developing uniform standards for various data exchange processes throughout the life cycle of a plant. The core of the research activities within DEXPI so far is the development of an Extensible Markup Language (XML) standard. This enables the import and export of Piping and Instrumentation Diagrams (P&ID) created in Plant-LM systems (such as COMOS or Intergraph Smart). [8]
  The name of this XML standard is "Proteus". Within Proteus, interfaces and important entities of a process plant are described. [9]
- DIN EN ISO 10628-2 deals with schemas for the chemical and petrochemical industry and is also analysed to identify relevant entities for the Reference Plant as well as the customer's brownfield. [10]
- The VDI 2776 “Process engineering plants - Modular plants - Fundamentals and planning modular plants” is in use to describe which functions, must be fulfilled by a Reference Plant. [11]

The entities of a Reference Plant and the brownfield environment must be described and managed. A flexible approach is provided by the concept of the Asset Administration Shell (AAS). It is a data management structure based on the eXtensible Markup Language (XML) investigated within the Plattform Industrie 4.0 initiative. Plattform Industrie 4.0 is an initiative launched by the Federal Republic of Germany that pursues the goal of realising the future project of the comprehensive digitalisation of the entire industry by 2030. [12]
The concept of asset management anchored in the “Reference Architecture Model Industry 4.0” (RAMI 4.0) is being taken up. The detailed specification of the AAS is developed by Plattform Industrie 4.0. [13]
This document is divided into three parts that can be directly applied to the requirements of asset description, search and accessibility. The division of an asset into AssedKind for a type and AssetKind for an instance follows the division scheme according to RAMI 4.0. The AAS consists of a body and a header, which describe the asset, also referred to as a resource in this context, uniquely identifies and makes it accessible to other Internet of Things (IoT) participants (see Figure 2). The identification of the AAS takes place via a unique identification method contained in the header, whereby the resource-specific data is in the body. [14]
AAS can be further subdivided and created specifically by submodel elements [15]. In this paper, the AAS is used to define entities of the brownfield environment and the Reference Plant first as types and then to derive customer-specific entities as instances.

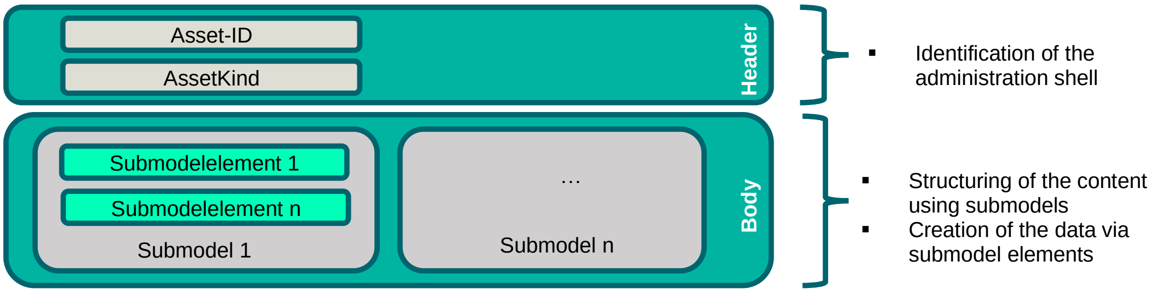

Figure 2: Simplified representation of the structure of an Asset Administration Shell

Submodel templates exist for specific fields of application. A submodel contains information about certain properties of an asset and offers the possibility of assets to subdivide the digital representation of an asset including its functionality. Each submodel is tailored to a specific subject area and, if standardised, it is a submodel template. [14]

Plattform Industrie 4.0 explicitly calls for developing as many such templates for submodels as possible for different areas of application within the industry [16]. In this paper, the AAS is used to define entities of the brownfield environment as well as the Reference Plant first as a type and then to derive customised entity instances.

The Systems Modelling Language (SysML) is suitable to describe the dependencies of different characteristics of entities of the brownfield and entities of the Reference Plant and make them usable in an automated way. SysML is a graphical language for visualising systems engineering. It makes it possible to specify, analyse, design, verify and validate systems. These possibilities can be applied to hardware, software, information, processes, personnel, and plants. SysML is also an extension of the Unified Modeling Language (UML). However, it does not simply add extensions from UML to SysML, but also removes features that are not necessary for a system view. [17]

To relate the dependencies of characteristics of the brownfield environment to the characteristics of the Reference Plant, the “Parametric diagram” in SysML is in use. Within this diagram, the relationship of the characteristics can be described with the help of an assurance block. Individual parameters required for the assurance are recorded in the "parameters" area and the individual conditions themselves in the "constraints" area. The individual parameters can be divided into input and output parameters, with input parameters flowing in from other system blocks. [5]

3. Research problem and research objective

There are many current problems in plant development and engineering that need to be addressed (see figure 3). Determining the customer-specific integration requirements of a plant using prose texts is time-consuming. Therefore, reducing the time for requirements elicitation by eliciting the requirements in a predefined and reusable form is a development goal. Requirements that can be derived from other requirements have so far been elicited manually. The new method developed is intended to counteract this by deriving requirements directly from known requirements or information (e.g., 3D model of the integration environment). Another goal of the development is to lay the foundation so that the documents created during requirements elicitation do not end up in an information silo but can be used seamlessly in the subsequent processes. The basis should be created to minimise many unique designs during the integration of the Reference Plant.

To achieve these goals, a method needs to be developed to identify entities within the geometry of the brownfield environment that are relevant for plant integration. By identifying the relevant entities, parts of their characteristics can be determined and requirements for the entities of the Reference Plant can be derived on this basis. Furthermore, a long-term goal of the research is to semantically segment the 3D model of the integration environment, which is

the basis for optimised, virtual integration of the plant. Special plant engineering is not considered here, where an utterly individual plant is built based on customer requirements. Two fundamental research questions are defined.
It must be determined which entities and associated features in the customer's brownfield environment influence the plant’s integration. This leads to the first research question: Which entities in the brownfield and in the Reference Plant are relevant for plant integration and how will their integration relationships be described and used? **(RQ1)**
How can the requirements and adjustments during the integration of a Reference Plant into a customer brownfield be determined from the customer's geometric integration environment? **(RQ2)**

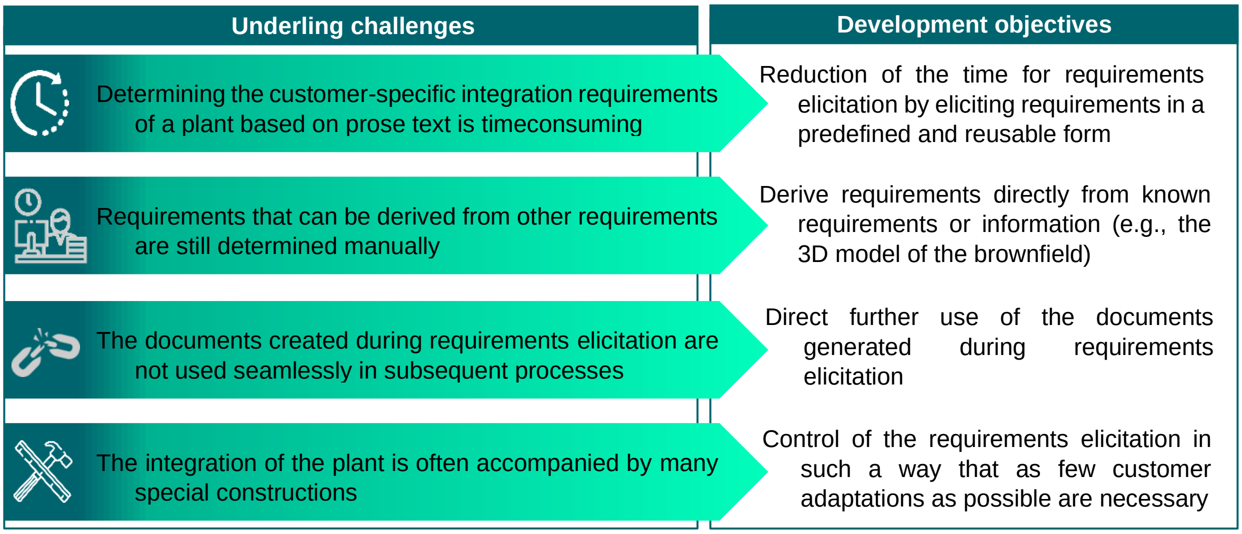

Figure 3: Problems during the planning of a plant integration and development objectives based on them

4. Methods and procedures used

A systematic literature review was conducted to answer RQ 1. Various sources exist in the literature that provides an overview of the components of a process plant. These include the standard DIN EN ISO 10628-2 [10], the standard VDI 2776 [11], the public standard ECLASS [18] and the Asset Management System COMOS [19]. These sources overlap mostly in the objects they contain, but they also contain differences. Therefore, a summary list must first be compiled, considering the entries of the different sources.
First, all named entities were extracted from each source. In the next step, these were compared with each other and evaluated in how far they are relevant for the integration process of a plant. The aim here is not to include all theoretically occurring entities down to the smallest screw but to give an overview of the most important entities of the brownfield environment. Table 1 shows the identified entities of the brownfield. The linguistic variable after the respective entity indicates the geometric recognition level (see chapter 5).

Table 1: Entities of the brownfield that have an impact on the integration of a Reference Plant

Entities in the brownfield							
Beams	o	Flange	+	Power machine	o	Stirrer	o
Blower, fan	o	Floor	o	Pump	+	Traffic routes	o
Compensator	-	Fluid Connection	+	Rails	o	Ventilation shafts	+
Compressor	o	Frame construction	o	Roof	o	Vessels and tanks	+
Cooling tower	o	Gate	o	Separator	-	Wall	+
Damper	-	Heat exchanger	-	Sewer (cover)	+	Windows	+
Door	+	Mixer/Kneader	-	Stage / Scaffolding	o		
Filter	-	Valve	o	Stairs	+		
Fitting	o	Pipe	+	Steam generator	-		

The next step is to determine the relevant entities within the Reference Plant. Since the method claims to be domain-independent, the essential functions of a Reference Plant are examined. For this purpose, VDI 2776 and the standard components of a P&ID described in DEXPI were analysed. Entities that realise the function are assigned to these functions (see Table 2). The relevant associated characteristics are also listed in Table 2.

Table 2: Assignment of basic components to basic process engineering functions [9, 11]

Basic function	Assigned entities in the Reference Plant	Assigned characterisitics
Condensation	furnaces / heat exchangers / steam generators / cooling towers	max. cooling capacity, Tmin cooling medium
Conveying	pumps / compressors / blowers / fans	max. volume flow
Cooling	vessels and tanks / heat exchangers / steam generators / re-cooling units / cooling towers	Tmin/Tmax Cooling medium, target temperature, cooling capacity
Dosing	Pumps / compressors	min./max. volumetric flow, metering accuracy
Evaporation	heat exchangers / steam generators, furnaces, re-cooling units	max. heating capacity, Tmax heating medium
Heating	vessels and tanks/heat exchangers / steam generators, furnaces, re-cooling appliances	Max. heating capacity, Tmax heating medium
Mixing	vessels and tanks / mixers / stirrers	active energy input, max. energy input, max. tangential speed of mixing elements
Pressure increase	pumps / compressors	pmin/pmax suction side, pmin/pmax discharge side
Pressure reduction	pumps / compressors	pmin/pmax high pressure side, max. pressure difference
Separating	columns with internals / filters / separators / centrifuges	particle size distribution, separation efficiency
Storage	vessel and tanks / cooling towers	volume

Based on this the entities of a brownfield environment and a Reference Plant are determined. The description of relationships of the most important entities of the environment to the entities within the Reference Plant is described in SysML by a parametric diagram. This is advantageous for various applications. For example, it could be (automatically) checked which components of the Reference Plant or the integration environment must be adapted to set up the plant at the customer's site. In case of conflicting goals between the integration environment and the Reference Plant, it can be decided on this basis which adaptations must be made. Figure 4 shows a straightforward example of the issue just described. In the Reference Plant, there is the entity liquid connection with defined characteristics. From this entity, it can be deduced that the plant needs a water supply. Now it can be derived from the integration environment whether this requirement can be fulfilled. The required fluid can be provided by the integration environment because there is also an entity that provides water. However, there is an integration conflict with the nominal width. This leads to the requirement that must either adapt the integration environment or the Reference Plant in this aspect. In addition, the height difference and thus the pressure difference can be derived. In our example, this is a 5100mm height difference and thus a 0.51 bar pressure difference (see Figure 4). The next step in the causal chain is that if the connections are connected directly, the pressure equipment directive [20] must be considered, as there is a pressure delta of over 0.5 bar. From this information, further requirements can be derived, either the safety factor of the component concerned must be adjusted or the pressure difference must be compensated in some way.

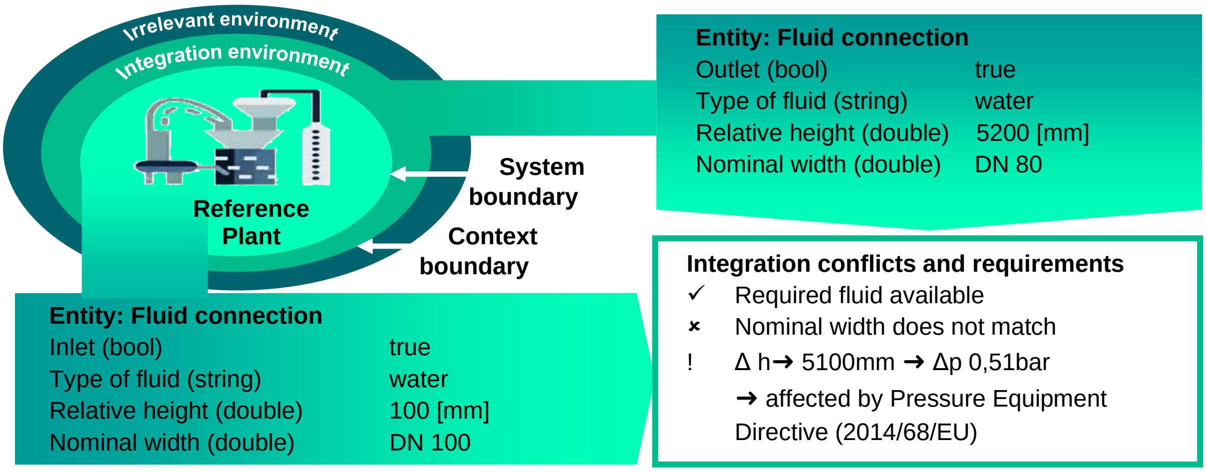

Figure 4: Example of the matching process from an entity of the Reference Plant with an entity of the brownfield

The identified entities in the brownfield environment and the Reference Plant form the basis for building AAS for the entities of the brownfield environment and the Reference Plant. The entities are described in AAS with AssetKind: Type. Within the properties submodel, the identified characteristics and the associated data types, as well as entities, can be described in general terms. It is important to understand that these AAS do not contain concrete values for the individual properties, as they have no real counterpart. They are used to describe the entity in general terms. However, they form the basis for deriving ASS of the AssetKind: Instance, i.e., ASS with a real counterpart.

In the next step, it is necessary to check which of these entities are identifiable in the pure geometry of the brownfield. Labels in the form of 3D point clouds are assigned to the components recognisable in the pure geometry of the brownfield environment within a sub-model of the AAS. Using these labels, the entities can be recognised in 3D scans of the geometry of the brownfield environment.

An evaluation method has been developed for this purpose. Each entity is assigned with a geometric recognition level. This is documented as a property within the AAS (AssetKind = Type). This feature can be used to decide which entities to assign geometric labels to or how many labels to assign. The geometric recognition level can have three possible characteristics, which are differentiated from each other as follows:

- High geometric recognition level (**+**)
  - Characterised by entities that have a very low variance in their geometric characteristics (standardised components or entities whose characteristics only differ in size, e.g., pipes).
- Medium geometric recognition level (**o**)
  - Characterised by entities whose features differ geometrically but have the same features (e.g., valve).
- Low degree of recognition (**-**)
  - The characteristics of the entity are very different and there are hardly any or no characteristic shapes (e.g., steam generator).

The entities of the brownfield environment (see Table 1) were evaluated according to this principle. Recognisable in the form of the linguistic variable behind the entity designation. One entity that is evaluated with a high geometric recognition value is the fluid connection. This entity is primarily used to validate an assignment of labels and to realise an object recognition based on it using a supervised learning method.

Since the goal is to recognise the entities within 3D scans of the brownfield environment, labels in the form of point clouds are needed. The basis for creating labels is created using the Intel® RealSense™ D435 depth camera and a script implemented in Python for recording 3D point clouds. For this purpose, the camera is mounted on a tripod and the validation entity "fluid connection" is recorded in various forms from different views. The recorded point clouds are available in the point cloud data format (.pcd) and are processed into labels using the OpenCV CVAT label tool. These labels are then available in the polygon file format (.ply). They are inserted into a newly developed submodel "Labels". If a customised brownfield environment is to be layered in the form of a point cloud, the object recognition algorithm "You only look once" (YOLO) [21] accesses the "Labels" submodel and delivers results directly in the point cloud of the customised brownfield environment. If an entity is recognised, it is framed with a so-called bounding box and characteristics of the entity, such as distance to a defined plane (e.g., floor) can be derived [22]. With the recognition of the entity in the brownfield environment, a concrete AAS (AssedKind = Type) is derived based on the abstract form of the AAS (AssedKind = Instance), which contains the values (e.g., distance to ground) of the recognised entity.

With the principle "Occlusion sensitivity" the labels are checked and indicated which geometric features are particularly important for the recognition of the object. Thus, labels can be created in a more targeted manner. [23]

Figure 5 describes the instantiation process of the AAS and the request derivation process based on it, using the example of a "fluid connection" (representative for an entity of the brownfield environment) and a pump (representative for an entity of the Reference Plant). The fluid connection is created as an abstract AAS (AssedKind: Type). In the submodel property, three characteristics are listed that describe the entity "fluid connection" (see Figure 5). The various labels of the entity are in the "Labels" submodel.

The pump is also created as an abstract AAS (AssedKind: Type) and has the characteristics max. Operating pressure and max. volumetric flow. In the next step the brownfield environment is searched for the fluid connection entity in the form of a scan. The object recognition algorithm (e.g., YOLO) recognises the fluid connection entity in the brownfield geometry and can recognise the characteristics of relative height and a nominal width of the connection directly from the geometry. The fluid type "water" is added manually. These values are entered into the predefined SysML Parametric Diagram, in which the requirements for the pump are derived. The requirements for the pump can now be found in the submodel "Requirments". The static pressure difference and thus, with the inclusion of a safety factor, the minimum requirement for the pump's operating pressure can be set via the height difference.

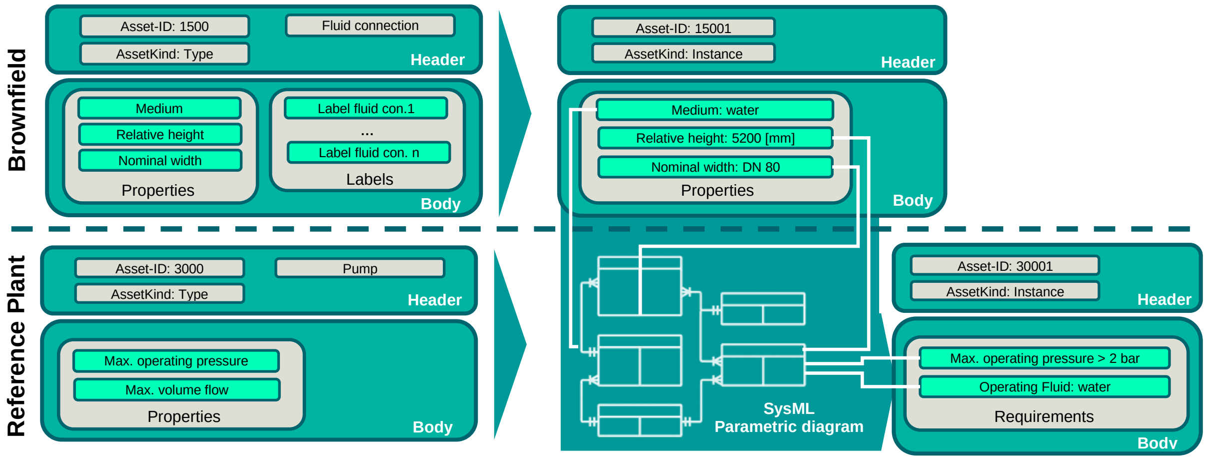

Figure 5: Simplified representation of the instantiation process of the Asset Administration Shell and the process of deriving requirements through SysML based on it, using the example of a "Fluid connection"

5. Results and discussion

The result of the context analysis described in this paper defines the most important entities for integrating a Reference Plant into a customer's brownfield environment. The description of the relationships of the most important entities of the integration environment and the Reference Plant is also a result. Proposals are elaborated on which form the AAS can be used in this context. The submodel "Labels" is introduced.

Labels are assigned for the first entities of the integration environment. These entities can be identified automatically by using a supervised learning method [21, 22] within the integration environment, e.g., in the form of a 3D scan. Furthermore, properties could thus also be extracted directly from the geometry. Based on SysML, requirements can be derived from the identified properties of the entities. So far, only a few entities are equipped with labels and their relationships are described in SysML (see Figure 6).

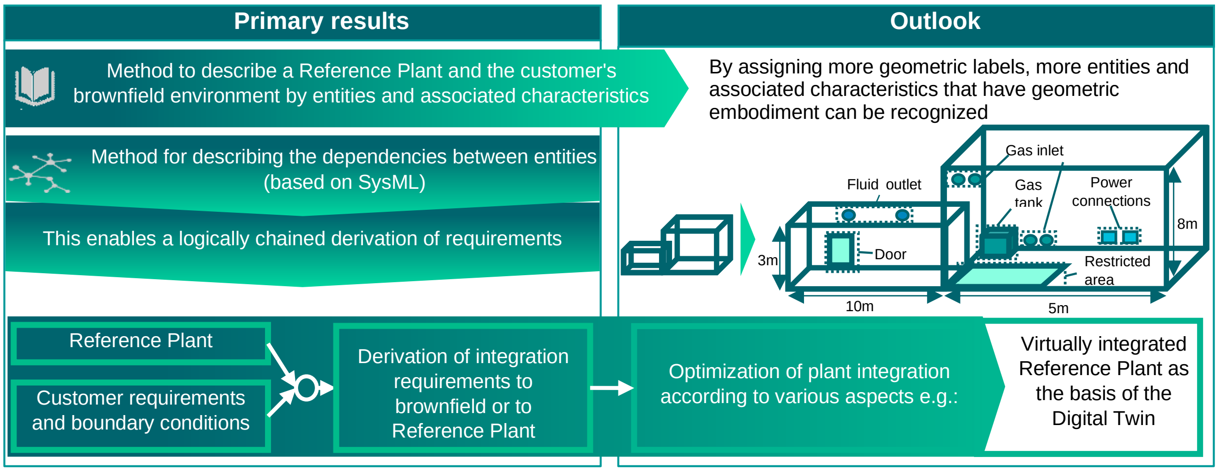

Figure 6: The entity library defined in this paper provides the basis for planning a process for the virtual integration of the Reference Plant into the customer's integration environment

6. Summary and outlook

The developed method as a kind of digital-twin-method forms the basis for accelerating the requirements elicitation in plant engineering. The focus is on the automated derivation of requirements for the integration of an initially customer-independent Reference Plant into a customer-specific brownfield environment (in a kind of a “Requirments-Twin”). Generic entities of the brownfield environment and the Reference Plant are described in the form of AAS. The identified characteristics and labels of the entities are managed in the AAS. A SysML parametric diagram accesses concrete characteristics and thus derives integration requirements.

The method must be further developed in the future to provide all identified objects with labels. The long-term goal of the research is to semantically enrich the initially "naked" 3D Scan of the brownfield environment and thus provide the basis for optimised, virtual plant integration. Optimisation aspects can include minimising pipe lengths or maximising the use of standard components. The potential optimisation possibilities must be considered, during the further specification of the individual entities. One feature that might be required, for example, for entities with increased explosion protection is the minimum distance to hot components. In this way, the boundary conditions for optimising plant integration can be ensured.

In the future, the planning of plant integration should take place on the semantically enriched model of the integration environment and thus a seamless use of the data from the requirements elicitation to the integration planning of the plant is used and information silos in the individual project phases are counteracted.

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