IDENTIFICATION AND RETRIEVAL OF RELEVANT INFORMATION FOR INSTANTIATING DIGITAL TWINS DURING THE CONSTRUCTION OF PROCESS PLANTS

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ABSTRACT

While volume-driven industries such as automotive are characterized by a high degree of data backflow across all production cycles, there is still a certain residue in the planning and construction of process plants. This is firstly due to the high proportion of customer-specific requirements and secondly to the significant amount of value added on site during construction. To handle recurring project-specific process plants as time- and cost-efficiently as possible, optimal information exchange among contractors of various disciplines and the plant developer is a prerequisite. For this purpose, a holistic digital representation of the plant is created, which consolidates all relevant information in one place serving as a foundation of multiple digital twins. An approach to identify and define relevant information depending on their subsequent use is developed. On this basis, a framework is proposed to enable a multipliable BOM-based automatic definition of information backflow to instantiate digital representations in parallel to the planning and construction process. Furthermore, project-specific contextual information will be captured and referenced in a structured form preventing their loss for subsequent similar projects.

Keywords: Information management, Contextual Information, Instantiation, Digital / Digitised engineering value chains, Knowledge management

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1 INTRODUCTION

1.1 Motivation

Compared to other industries, the planning and construction of process plants involves a high proportion of project-specific engineering effort (Watermeyer 2002). Even though standardization at system level is already being successfully implemented in the process industry (Braaksma et al. 2011), plant-specific modularization and standardization only become worthwhile when a certain number of similar follow-up projects can be expected. For this use case, the concept of "**reference plants**" is already applied, as they can be modified for customer projects with less effort (Gepp et al. 2014).
Furthermore, the challenge of efficient cooperation between different disciplines within and outside company borders remains when conducting customer projects. Typically, the components of process plants are prefabricated in an assembly shop or factory, but the plant is assembled and erected on site (Elfving 2003), creating additional barriers to information backflow. Short-term design changes or holistic coverage of all installed components for different cooperating contractors on-site pose a recurring challenge (Son et al. 2015). Especially those companies that are confronted with the demand for increasingly powerful plants in ever larger quantities, as it is currently the case in the hydrogen-producing industry (see Figure 1 as an example), require solutions for comprehensive information and data management in the plant engineering and construction process.

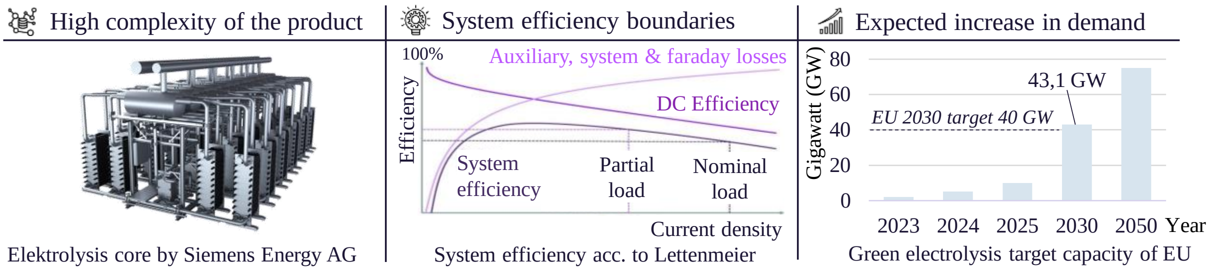

Figure 1: Factors requiring higher efficiency in H2-plant construction based on (Siemens Energy AG 2022) left, (Lettenmeier 2020) middle, (THEMA Consulting Group 2021) right

1.2 Research objective

Both the generic reference plant and the project-specific plant exist and evolve as a digital version in a variety of native engineering tools depending on the respective discipline (Figure 2 "as-is"). While there are norms and company guidelines to set up review processes to ensure that the latest version of this digital plant is manufactured, **additional information** is created during production, construction and commissioning. Site and supplier integration and data backflow of this additional information are insufficient. For this purpose, the development of a holistic **digital representation** (Figure 2 "to-be") as foundation and therefore part of future **digital twins** of a project-specific process plant is proposed, in which all relevant information is stored or referenced.

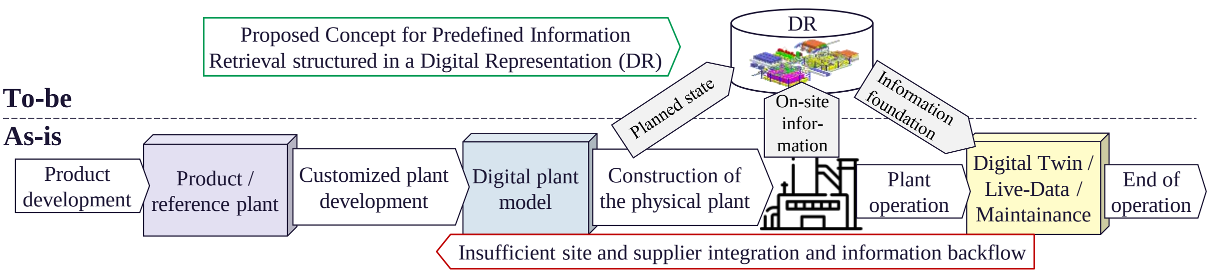

Figure 2: Aspired project lifecycle of process plants based on Saske et al. (2022)

A method is developed within the DIAA-H_2 project (Saske et al. 2022) that creates a central access point for all plant data for various parties involved, enables an interface between plant development and as-built documentation and allows in-depth data analysis for optimization of product and production. In context of this project, the research objective is to solve this insufficient information backflow through a method of predefined information retrieval during the so-called **instantiation** process (see section 4). As

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a foundation, an **analysis and categorization** of information representing a physical plant and its required capture depending on their subsequent use is given in section 3.

2 STATE OF THE ART

2.1 Information retrieval during planning and construction of process plants

The process plant life cycle can be summarized into design, construction, commissioning, operation and decommissioning (Nouri and Lucke 2022). Following IEC 62337 (Figure 3), there are several milestones especially during commissioning.

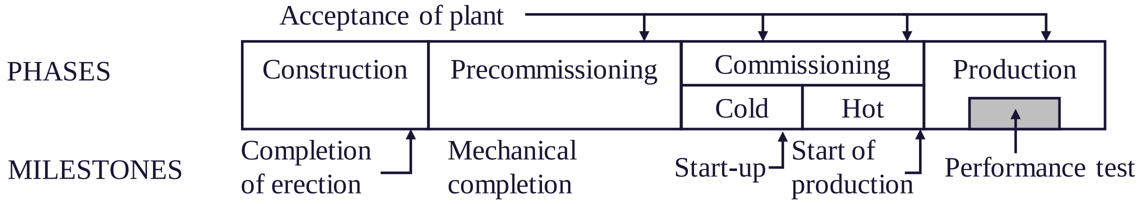

Figure 3: Phases and milestones in the in the commissioning of electrical, instrumentation and control systems from process industry according to (IEC 62337:2012)

These milestones can be documented according to IEC 62381 in form of the Factory Acceptance Test (FAT), the Site Acceptance Test (SAT), and Site Integration Test (IEC 62381:2012) There are concepts in Building Information Modelling (BIM) to enable scanning technology for as-built capturing, shown by Bosché et al. (2015); Esfahani et al. (2021) framed by the name "Scan-to-BIM".
An approach to define information to be captured in a structured manner is the Quality Information Framework (QIF). The QIF architecture consists of a reusable library which contains definitions and components, thereby ensuring interoperability and extensibility. The QIF focuses mainly on machine readable quality instructions for measuring machines. (ISO 23952:2020). Even though there are defined project phases and assessment methods based on guidelines and standards, a holistic and systematic approach to automatically define **information retrieval** is missing. Furthermore, the authors identify that the requirements for information backflow at system and component level need to be linked in a structured way based on their specific characteristics and relevance.

2.2 Information management and knowledge-based engineering

Data is defined by ISO 2382-1 as a reinterpretable representation of information in a formalized manner suitable for communication, interpretation, or processing (ISO 2382-1:1993). Information consists of processed data, the processing directed at increasing its usefulness (Ackoff 1989). Knowledge is the cognition or recognition, capacity to act, and understanding that resides or is contained within the mind or in the brain (Liew 2007). Focus is set on how to extract information and how to store and use this as generated knowledge. Li et al. (2008) explore possibilities of semantics-based engineering document analysis and retrieval by using an engineering ontology (EO) representing the established design and manufacturing knowledge in- and outside a company. The design of a novel context-aware user interface is based on a new computational framework for the EO-based search system that aims at effectively retrieving unstructured engineering content. Shafiee et al. (2017) propose a framework for creating an IT system of previously completed products and compare against new projects. This approach allows efficient comparisons to be made while using the available methods and tools. While various publications investigate information extraction and knowledge-based engineering in general (Udeaja et al. 2008), there is limited literature on the **reuse of context** which was generated during specific project adaptions. Existing approaches to create a simulation-based digital twin of an industrial process plant are investigated by Martinez et al. (2018). In order to perform data analytics in the process industry, Ge et al. (2017) state the need for a historical database, the operating regions of the process and any changes of operating condition in combination with real-time information.

2.3 Instantiation in context of the process industry

The concept of instantiation originates from object-oriented programming, where an object is created by “instantiating" a class (McAllester and Zabih 1986). This notion is abstracted and applied to other areas such as the instantiation of a geologic database schema from a generic meta-model by

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Ballesteros (2004), the instantiation of a new production module from a modular process component design by Gorecky et al. (2016) or the instantiation of mathematical models by filling a generic one with specific parameters (Mallier et al. 2021). Furthermore, instantiation processes are used to assist in the product lifecycle development by reusing general models that can be tailored to particular scenarios (Ramírez and Molina 2021). In the context of production systems and process plants there is literature about the instantiation of plant control simulation models based on templates (Tang and Clarke 1993) and the instantiation of digital twins (Figure 4) from a digital master, which can launch several digital twins instances (May et al. 2021; Stark et al. 2017).

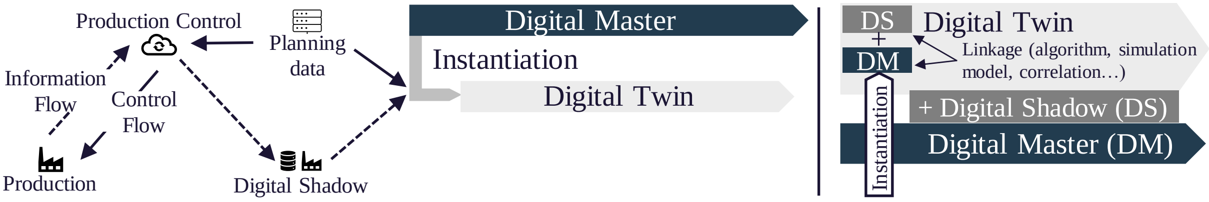

Figure 4: Instantiation of a digital twin from a digital master acc. to May et al. (2021) left and Stark et al. (2017) right

Definitions of instantiation given by Lechler et al. (2017) and Kim et al. (2020) align with the context and understanding of the present publication. Focus is set on the assignment of specific physical systems to information objects during the instantiation process. This object should reflect the state and the behaviour of the real system as ideally as possible. If the physical system already exists, the instantiation can be carried out by the identification of real data of the physical system. As a result, a digital twin is created. Kim et al. (2020) **instantiate information objects** at each state of their lifecycle with persistent identifiers thus linking detailed data generated from commercial engineering systems.

3 ANALYSIS AND CATEGORIZATION OF INFORMATION

For the development of an instantiation method, a detailed analysis of the different information of interest was carried out. The information is first broken down according to Figure 5 depending on its later use in the project-specific plant. Apart from **functional information**, which is required to operate the plant in general, the **documentation** includes all required technical information describing the project-specific plant and its later operation (such as maintenance, repair and operation) and is oriented on conventional customer documentation. As an addition, the **internal analysis** includes information that is relevant for optimizing the core product of the plant developer and represent information, which is e.g. relevant for comparison with simulation models.

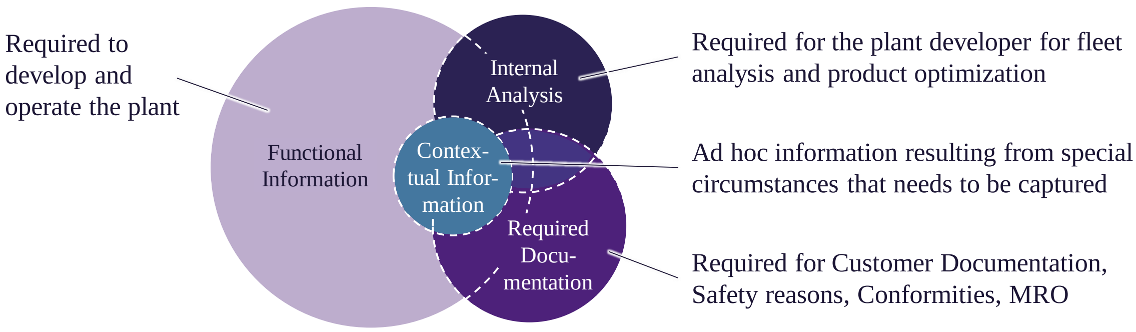

Figure 5: Analysis and categorization of information of project-specific process plants

Contextual information represents ad hoc decisions and their context that were considered during the planning and construction of the specific plant and are potentially reusable for future projects and thus need to be captured in a structured manner. In the following, above proposed categories of information are further elaborated and analyzed. While possible storage of the identified relevant information in a database is not focus of this publication and initial testing one the basis of a tabular storage, most literature approaches use graph databases (Pinquié et al. 2019; Zhao et al. 2020; Ismail et al. 2018). In any case, a close connection to the hierarchical bill of material (BOM) of the overall system is required, while components need to have categorical attributes such as "sensor" to enable general applicability.

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3.1 Documentation

For all documentation, a method is developed in parallel that defines specific information as relevant based on standards, guidelines, past projects or customer requirements. A first aspect is the analysis of already existing norms such as DIN 28000, DIN 61355 or DIN 77005 as well as existing protocols as they represent information retrieval guidance. Observed requirements on documentation e.g. which components require as-built documentation, need to be stored in a structured knowledge database. In addition, information for the field of maintenance, repair and operations (MRO) can be extracted from DIN 13460 or existing spare and wear parts lists.

To automate this process, there is already research in extracting knowledge from standards (Luttmer et al. 2021) supported by recent developments of the American National Information Standards Organization (NISO) for establishing a XML tag set defined as NISO-STS which is based on the ISO Standard Tag Set (Wheeler et al. 2016). Additional opportunities are provided by "technical language processing" where the emerging technology of natural language processing is applied to technical documents (Brundage et al. 2021) or their classification (Jiang et al. 2022).

3.2 Internal analysis information

In parallel to required documentation for customer and operator, the authors identify an increasing interest in an optimized information backflow from the point of view of the plant designer. This interest is driven by the fact that much of the construction and commissioning is carried out by contractors, and only the final values of the test phase are usually captured in the setting and parameterisation processes. For both commissioning optimization and internal analysis, the comparison of simulation models and the real behaviour of the physical plant provide important insights for the improvement of the product. The monitoring of fleet data already takes place in practice and is prepared accordingly. However, it is possible that additional monitoring in the form of digital twins may be created after the system has been handed over to the operator. This requires an extensive information backflow beyond the documentation of the as-built status.

3.3 Contextual information

A resulting output is based on raw information as input and context. Figure 6 left introduces the general origin of a proposed **contextual information** while their location (Figure 6 right) can vary, thus affecting the transparency.

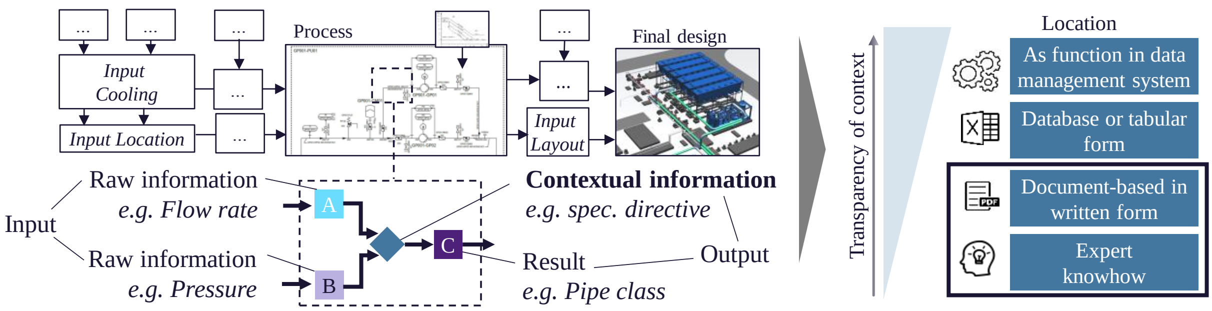

Figure 6: Origin and location of project-specific contextual information

While context located in databases, functions and tools used in design phases can and will be reused, a challenge arises in the identification of context stored in written form and expert knowhow as their collection requires an additional effort. Especially context, which arises during the project-specific planning phase or ad hoc on-site during construction and commissioning due to special requirements, should be captured. Focus here is not only on the resulting change but on the decision itself and its underlying basis. Hicks et al. (2002) define a similar category as one of four classes of reuse as "decision making". In practice, this contextual information is currently passed on through expert discussions and the exchange of acquired knowledge after project completion. However, these practices are time delayed and prone to error in larger organizations with multiple disciplines involved.

Within the proposed method, this contextual information can be linked with the components of the system and the requirements during the instantiation of the digital representation thus storing it in a structured and consistent manner. The integration of contextual information in the proposed instantiation method will be subject of section 4.3.

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4 INSTANTIATION OF PROCESS PLANTS

Identified, relevant plant-specific information (derived in section 3) needs to be linked with their physical counterpart. This process of linking is called instantiation, following section 2.3, as this link is subsequently considered as final. The following sections propose a framework for definition, preparation and instantiating components represented by different kinds of information.

4.1 Information backflow

Since the instantiation process involves linking and associating **physical** components, represented by specific information, with their **digital** counterparts, focus is laid on the production, construction and commissioning phase. After reviewing typical information to be gathered during these phases, in the form of protocols, checklists and testing processes, the authors derive six main categories of information backflow from pre-production or on-site construction and commissioning which need to be captured:

- **Component information** such as delivery date, serial numbers
- **Certificates**, arriving with the delivery of subsystems premanufactured by suppliers
- **As-built** confirmation and, if necessary, redlining of design
- **Parametrization values** of components and control units
- **Confirmations** of testing and inspection procedures generated during FAT or SAT
- **Context information** generated during planning or on-site as described in

Each of these categories require their own specific information retrieval, which can be predefined based on a general architecture to be developed in section 4.2. The confirmation of as-built design for example requires the availability of the as-planned document for comparison and the possibility to integrate changes into this document if changes arise. In contrast, the category of parametrization will only specify values to be captured and their data format.

4.2 Proposed architecture

The identified categories of information backflow show the potential to derive a framework generically and reuse this independently from the specific component. The overall architecture (Figure 7) propose the introduction of so-called **instantiation blocks (IB)**, which contain the requirement of a specific information to be instantiated and will be linked to a system or component.

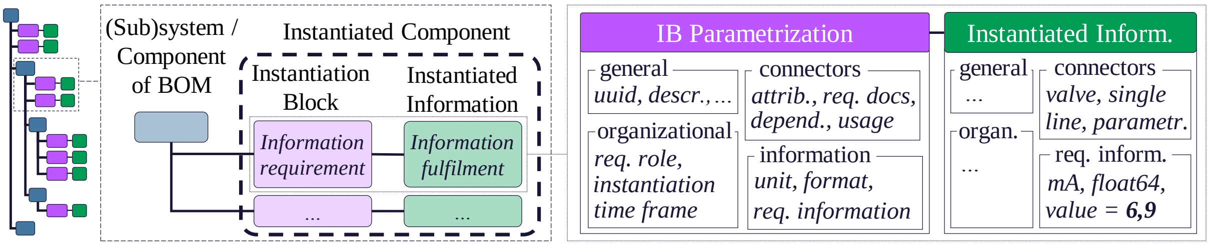

Figure 7: Schematic of (Sub)System/Component, IB and instantiated information

For each category of information, these instantiation blocks can be prepared and individually optimized based on their usage. The instantiation of a component or system will be completed once all instantiated information are filled accordingly. While there will be always a 1:1 relationship between instantiation blocks and instantiated information, single instantiation blocks need to be connectable to several components (n:1) for information referring to more than one component such as a welder certification.

For every information to be instantiated specified in the instantiation block **general** metadata such as a universally unique identifier (uuid), description, instantiating time and date as well as name, role and position of the person instantiating should be saved. This is to be distinguished from the **organizational** section, defining a required role of the instantiating person and the time frame in which this is to be provided. Furthermore, a **connector** section enables the linkage to attributes, required documents, the later usage of the information and instantiation gates defining compulsory preceding instantiation blocks. Finally, the **information** section details the required information, their format and units.

The overall instantiation process of a component begins with the first information instantiated and ends with the last respectively. A (sub)system is instantiated once all connected information is instantiated. If traditional form such as PDF or print is required, the project documentation can be generated from the existing information structure, reusing connectors and further structured information for clustering.

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4.3 Usage of instantiation blocks for contextual information

As introduced in section 3.3, contextual information needs to be captured and documented. This can be due to general documentation requirements or to understand the causes of these changes for future and ongoing parallel projects. This is integrated into the existing architecture by considering the contextual information as a standalone instantiated information (Figure 8 left) without an instantiation block as counterpart.

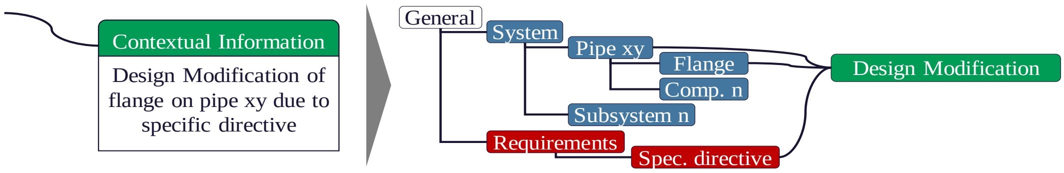

Figure 8: Standalone contextual information (left) and concept for integration (right)

In the absence of a preceding instantiation block, the authors propose to connect the contextual information both on component/subsystem level and on requirements level (Figure 8 right) ensuring traceability and reusability for future projects. Classical change management approaches (Eigner and Stelzer 2009) organized in committees still need to decide on overall design changes, but are enabled with structured information on the connected context for faster decisions. If the design change is sustained, a preceding instantiation block can be derived efficiently.

4.4 Resulting framework of instantiation

Figure 9 gives a generic overview of the proposed concept, which results in a method to initially define information to be captured generically on a component and system level based on the knowledge generated and stored according to section 3.

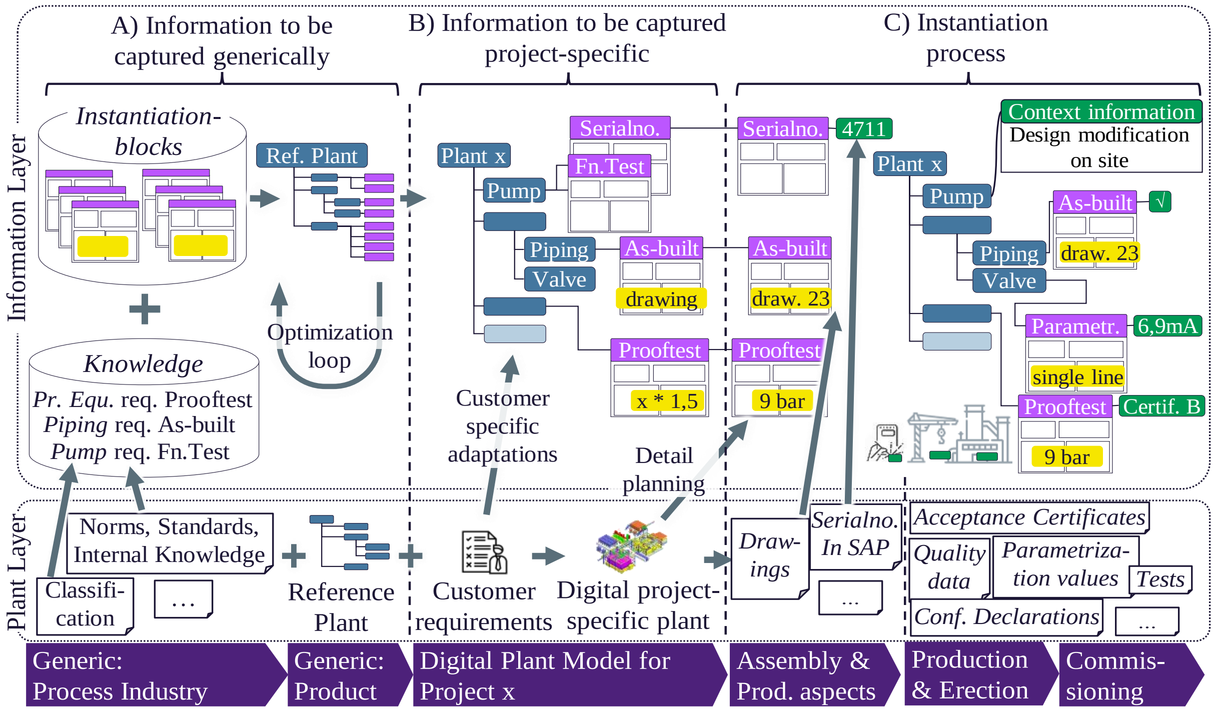

Figure 9: Framework for semi-automatic definition and retrieval of relevant information

Predefined IBs and this structured knowledge in combination with the BOM of the reference plant enable the derivation of a generic list of required information which can be optimized (Figure 9 A). This represents a multipliable master structure, which, based on project-specific requirements and design, can **automatically** generate a list of all required instantiation blocks for a customer plant (Figure 9 B). Specific design values or generated drawings are already predefined and will be filled during the detail planning of the digital plant. The instantiation process (Figure 9 C) will be conducted in parallel to production, construction and commissioning. As a result, a digital representation of all relevant information of the plant is created, serving as a detailed foundation for different digital twin applications.

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4.4.1 Initial feasibility study

An initial validation of the first approach is given on the example of retrieving test data required by the pressure equipment directive (2014/68/EU). Partly visualized in Figure 9, a pressurized system such as a cooling system is required to undergo a proof test ("pressure strength test") with […] ~1,5 * maximum allowable pressure before accessing the market. This is stored as knowledge in a tabular form (see Table 1) and through the classification "pressure equipment" connected with the BOM of the reference plant. The instantiation block "Proof test" already holds the connection to the attribute of maximum pressure, within the respective PLM-system while containing connectors and required information. When initialising a customer project, this information requirement is kept and transferred while the project-specific information such as the design maximum pressure is detailed out. During instantiation of the system on site, the proof test is conducted and the information and resulting certificate stored in a structured manner. Analysis of pressure curves and comparison with simulation models will drive product optimization while retrieved metadata on upstream and downstream tests as well as duration will be used to optimize commissioning.

Table 1: Exemplary instantiation knowledge

ID	description	component class	source	connec-ted IB	required attribute	resulting certificate
1	Hydrostatic pressure test with 1,5 * maximum design pressure (proof test)	cooling system, …	2014/68/EU	Proof-test	max_ pressure	CE marking, declaration of conformity
2	Parametrization values of valve	control valve	Requirement by control system	Paramet rization	para_ range	none

4.4.2 Potentials

By consolidating all relevant information in one place, the framework optimizes the information retrieval process, allowing for efficient tracking and monitoring of the entire offsite and onsite production cycle. This, in turn, can reduce downtime and increase productivity. The automatic definition of information backflow through the framework enables the accelerated preparation of the planning and construction process. Additionally, the resulting structured backflow of information is incremental, ensuring that data is provided earlier, thus reducing data dependency latency. It also allows for the capture and referencing of project-specific contextual information in a structured form, preventing loss of information and optimizing future similar projects. This leads to better decision-making and design, ultimately improving efficiency of engineering and the plant itself. Moreover, by tracing every component from the appearance of the first instance-individual information the framework allows for the integration of all additional data such as testing procedures and parametrization values into root cause analysis or more accurate simulation models within Digital Twins. Lastly, the connection of instantiated information with the BOM and retrieval requirements prevents discontinuity and enables a consistent basis of data.

4.4.3 Challenges

One challenge is the integration of a large amount of data from different sources and systems. This process can be time-consuming and resource-intensive, particularly when dealing with complex native engineering systems or data stored in different formats. A prerequisite are standardized data formats and clear protocols for data exchange, which can streamline the integration process and minimize errors. Another challenge is the management of sensitive information, which can be overcome by clear data access policies and security protocols. Lastly, the risk of employees not accepting the methodology and resulting tool can be avoided by providing training and support, while communicating and highlighting the benefits and its potential to improve efficiency and reduce errors in the engineering process.

5 SUMMARY AND OUTLOOK

A methodological solution to several data backflow challenges in the process industry is proposed. Firstly, the availability to automatically define information to be fed back generally and customized project-specific is enabled through a structured connection with part lists and components. Secondly, through instantiation seen as a process, intercepting information based on predefined requirements can be used to accelerate and monitor information backflow in a multipliable way. The structured

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information can be clustered and delivered to the customer, internal development, or service teams through a digital representation in a simplified and accessible way. Lastly, by defining ad hoc changes and their causes as contextual information and integrating them in the overall architecture, a new way of capturing these is given. As an outlook, the extraction of general knowledge from standards, norms, guidelines, former projects or internal instructions needs to be automated by new techniques such as data mining or machine learning. Furthermore, a user interface for end devices is currently being developed to test real application scenarios to validate the feasibility of the method in field.

REFERENCES

2014/68/EU. Pressure Equipment Directive, 2014. (accessed 2/15/2023).

Ackoff, Russell L. (1989). From data to wisdom. Journal of applied systems analysis 16 (1), 3–9.

Ballesteros, John R. (Ed.) (2004). Meta-model instantiation for geoscientific data collection. ITC.

Bosché, Frédéric/Ahmed, Mahmoud/Turkan, Yelda/Haas, Carl T./Haas, Ralph (2015). The value of integrating Scan-to-BIM and Scan-vs-BIM techniques for construction monitoring using laser scanning and BIM: The case of cylindrical MEP components. Automation in Construction 49, 201–213. https://doi.org/10.1016/j.autcon.2014.05.014.

Braaksma, A.J.J./Klingenberg, W./van Exel, P.W.H.M. (2011). A review of the use of asset information standards for collaboration in the process industry. Computers in industry 62 (3), 337–350. https://doi.org/10.1016/j.compind.2010.10.003.

Brundage, Michael P./Sexton, Thurston/Hodkiewicz, Melinda/Dima, Alden/Lukens, Sarah (2021). Technical language processing: Unlocking maintenance knowledge. Manufacturing Letters 27, 42–46. https://doi.org/10.1016/j.mfglet.2020.11.001.

Eigner, Martin/Stelzer, Ralph (2009). Product lifecycle management: Ein Leitfaden für product development und life cycle management. Springer Science & Business Media.

Elfving, Jan Alarik (2003). Exploration of opportunities to reduce lead times for engineered-to-order products. Berkeley, University of California.

Esfahani, Mansour Esnaashary/Rausch, Christopher/Sharif, Mohammad Mahdi/Chen, Qian/Haas, Carl/Adey, Bryan T. (2021). Quantitative investigation on the accuracy and precision of Scan-to-BIM under different modelling scenarios. Automation in Construction 126, 103686. https://doi.org/10.1016/j.autcon.2021.103686.

Ge, Zhiqiang/Song, Zhihuan/Ding, Steven X./Huang, Biao (2017). Data Mining and Analytics in the Process Industry: The Role of Machine Learning. IEEE Access 5, 20590–20616. https://doi.org/10.1109/ACCESS.2017.2756872.

Gepp, M./Vollmar, J./Schaeffler, T. (2014). Standardization programs in the industrial plant business: Best practices and lessons learned. In: 2014 IEEE International Conference on Industrial Engineering and Engineering Management, 2014 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM), Selangor Darul Ehsan, Malaysia, 09.12.2014 - 12.12.2014. IEEE, 122–126.

Gorecky, Dominic/Weyer, Stephan/Hennecke, André/Zühlke, Detlef (2016). Design and Instantiation of a Modular System Architecture for Smart Factories. IFAC-PapersOnLine 49 (31), 79–84. https://doi.org/10.1016/j.ifacol.2016.12.165.

Hicks, B. J./Culley, S. J./Allen, R. D./Mullineux, G. (2002). A framework for the requirements of capturing, storing and reusing information and knowledge in engineering design. International Journal of Information Management 22 (4), 263–280. https://doi.org/10.1016/S0268-4012(02)00012-9.

IEC 62337:2012. Commissioning of electrical, instrumentation and control systems in the process industry, 2012. Geneva, Switzerland. (accessed 11/7/2022).

IEC 62381:2012. Automation systems in the process industry, 2012. Geneva, Switzerland. (accessed 11/2/2022).

Ismail, Ali/Strug, Barbara/Ślusarczyk, Grażyna (2018). Building Knowledge Extraction from BIM/IFC Data for Analysis in Graph Databases. In: Leszek Rutkowski/Rafał Scherer/Marcin Korytkowski et al. (Eds.). Artificial Intelligence and Soft Computing. Cham, Springer International Publishing, 652–664.

ISO 2382-1:1993. Information technology - Vocabulary - Part 1: Fundamental Terms, 1993. Switzerland. (accessed 11/21/2022).

ISO 23952:2020. Automation systems and integration — Quality information framework (QIF), 2020. Switzerland. (accessed 10/31/2022).

Jiang, Shuo/Hu, Jie/Magee, Christopher L./Luo, Jianxi (2022). Deep Learning for Technical Document Classification. IEEE Transactions on Engineering Management, 1–17. https://doi.org/10.1109/TEM.2022.3152216.

Kim, Byung Chul/Kim, Bongcheol/Park, Sangjin/Teijgeler, Hans/Mun, Duhwan (2020). ISO 15926–based integration of process plant life-cycle information including maintenance activity. Concurrent Engineering 28 (1), 58–71. https://doi.org/10.1177/1063293X19894041.

Lechler, Armin/Riedel, Oliver/Coupek, Daniel (2017). VIRTUAL REPRESENTATION OF PHYSICAL OBJECTS FOR SOFTWARE DEFINED MANUFACTURING.

Lettenmeier, Philipp (2020). Efficiency – Electrolysis. White Paper. Available online at https://assets.siemens-energy.com/siemens/assets/api/uuid:a33a8c39-b694-4d91-a0b5-4d8c9464e96c/efficiency-white-paper.pdf.
Li, Zhanjun/Raskin, Victor/Ramani, Karthik (2008). Developing Engineering Ontology for Information Retrieval. Journal of Computing and Information Science in Engineering 8 (1). https://doi.org/10.1115/1.2830851.
Liew, Anthony (2007). Understanding data, information, knowledge and their inter-relationships. Journal of knowledge management practice 8 (2), 1–16.
Luttmer, Janosch/Ehring, Dominik/Pluhnau, Robin/Nagarajah, Arun (2021). REPRESENTATION AND APPLICATION OF DIGITAL STANDARDS USING KNOWLEDGE GRAPHS. Proceedings of the Design Society 1, 2551–2560. https://doi.org/10.1017/pds.2021.516.
Mallier, Lise/Hétreux, Gilles/Thery-Hétreux, Raphaele/Baudet, Philippe (2021). A modelling framework for energy system planning: Application to CHP plants participating in the electricity market. Energy 214, 118976.
Martinez, Gerardo Santillan/Sierla, Seppo/Karhela, Tommi/Vyatkin, Valeriy (2018). Automatic Generation of a Simulation-Based Digital Twin of an Industrial Process Plant. In: IECON 2018 - 44th Annual Conference of the IEEE Industrial Electronics Society, IECON 2018 - 44th Annual Conference of the IEEE Industrial Electronics Society, Washington, DC, 21.10.2018 - 23.10.2018. IEEE, 3084–3089.
May, Marvin Carl/Overbeck, Leonard/Wurster, Marco/Kuhnle, Andreas/Lanza, Gisela (2021). Foresighted digital twin for situational agent selection in production control. Procedia CIRP 99, 27–32. https://doi.org/10.1016/j.procir.2021.03.005.
McAllester, David/Zabih, Ramin (1986). Boolean classes. In: Conference proceedings on Object-oriented programming systems, languages and applications, 417–423.
Nouri, Mahdi/Lucke, Eberhard (2022). Life cycle of a process plant. Amsterdam, Netherlands, Elsevier.
Pinquié, Romain/Véron, Philippe/Segonds, Frédéric/Zynda, Thomas (2019). A Property Graph Data Model for a Context-Aware Design Assistant. In: Clement Fortin/Louis Rivest/Alain Bernard et al. (Eds.). Product Lifecycle Management in the Digital Twin Era. Cham, Springer International Publishing, 181–190.
Ramírez, José/Molina, Arturo (2021). Improving Manufacturing System Design by Instantiation of the Integrated Product, Process and Manufacturing System Development Reference Framework. In: Alexandre Dolgui/Alain Bernard/David Lemoine et al. (Eds.). Advances in Production Management Systems. Artificial Intelligence for Sustainable and Resilient Production Systems. Cham, Springer International Publishing, 99–107.
Saske, Bernhard/Schwoch, Sebastian/Paetzold, Kristin/Layer, Max/Neubert, Sebastian/Leidich, Jonathan/Robl, Peter (2022). Digitale Abbilder als Basis Digitaler Zwillinge im Anlagenbau: Besonderheiten, Herausforderungen und Lösungsansätze. Industrie 4.0 Management 2022 (5), 21–24. https://doi.org/10.30844/IM_22-5_21-24.
Shafiee, Sara/Kristjansdottir, Katrin/Hvam, Lars (2017). Automatic Identification of Similarities across Products to Improve the Configuration Process in ETO Companies. International Journal of Industrial Engineering and Management 8, 167–176.
Siemens Energy AG (2022). Silyzer 300 Datasheet. Available online at https://assets.siemens-energy.com/siemens/assets/api/uuid:a193b68f-7ab4-4536-abe2-c23e01d0b526/datasheet-silyzer300.pdf?ste_sid=18909f929d5f3bfcad922e9252ae5689 (accessed 11/7/2022).
Son, Hyojoo/Bosché, Frédéric/Kim, Changwan (2015). As-built data acquisition and its use in production monitoring and automated layout of civil infrastructure: A survey. Advanced Engineering Informatics 29 (2), 172–183. https://doi.org/10.1016/j.aei.2015.01.009.
Stark, Rainer/Kind, Simon/Neumeyer, Sebastian (2017). Innovations in digital modelling for next generation manufacturing system design. CIRP Annals 66 (1), 169–172. https://doi.org/10.1016/j.cirp.2017.04.045.
Tang, D./Clarke, J. A. (1993). Application of the object oriented programming paradigm to building plant system modelling. In: Proceedings of the Building Simulation, 317–323.
THEMA Consulting Group (2021). Hydrogen deployment accelerates, but a lot remains to reach 40 GW EU target by 2030. Available online at https://thema.no/en/nyheter/store-steg-naermere-men-langt-igjen-til-40-gw-elektrolyse-i-eu-i-2030/ (accessed 11/7/2022).
Udeaja, Chika E./Kamara, John M./Carrillo, Patricia M./Anumba, Chimay J./Bouchlaghem, Nasreddine/Tan, Hai Chen (2008). A web-based prototype for live capture and reuse of construction project knowledge. Automation in Construction 17 (7), 839–851. https://doi.org/10.1016/j.autcon.2008.02.009.
Watermeyer, Peter (2002). Handbook for process plant project engineers. John Wiley & Sons.
Wheeler, Robert/Rosenblum, Bruce/West, Lesley (Eds.) (2016). NISO STS Project Overview and Update. National Center for Biotechnology Information (US).
Zhao, Huaxuan/Pan, Yueling/Yang, Feng (2020). Research on Information Extraction of Technical Documents and Construction of Domain Knowledge Graph. IEEE Access 8, 168087–168098. https://doi.org/10.1109/ACCESS.2020.3024070.