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METHODOLOGY

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Towards a systematic and knowledge-based requirements and conceptual engineering for modular electrolysis plants

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Abstract

The production of green hydrogen and its scale-up require the enginering and installation of new electrolysis plants. Modular electrolysis plants ease the scale-up as they allow to add further modules with growing demand. While many engineering methods focus on the detailed planning of the plants and their automation systems, the early engineering phases are scarcely considered, supported or formalized. However, especially these phases are crucial in the current scale-up of modular electrolysis plants. In this paper, an intention-based engineering approach for the early engineering phases Requirements Engineering and Conceptual Engineering for modular electrolysis plants is presented and evaluated based on three different use cases. The approach is based on Goal-oriented Requirements Engineering from Software Engineering and relies on an early, systematic as well as formalized description and analysis of intentions of different engineering disciplines.

Keywords: Conceptual engineering, Hydrogen, Intention-based engineering, Modular electrolysis plant, Module type package, Requirements engineering, Ontologies

Introduction

Motivation and problem description

Production of green hydrogen (i.e., hydrogen production based on renewable energies) using electrolysis plants is one possibility to support the energy transition (Yue et al. 2021; Tashie-Lewis and Nnabuife 2021). In the future chemical production, gray hydrogen (based on fossil fuels) is planned to be gradually replaced by green hydrogen (Hermesmann and Müller 2022; Neuwirth 2020). The potential of hydrogen production via electrolysis is at the same time a challenge, as renewable energies can be volatile and thus intermittent (Tashie-Lewis and Nnabuife 2021). This potentially results in a temporal mismatch between energy supply and demand. Additionally, scale-up of hydrogen production (in demand and production capabilities) is a main challenge nowadays (Odenweller et al. 2022). This prevents a rapid ramp-up of hydrogen production to drive the energy transition.

Modular electrolysis plants in particular offer the possibility of reacting flexibly to fluctuating power supply and demand (Lange et al. 2023). Electrolysis modules can be added, removed or replaced by larger ones. However, this must also be accompanied by a higher flexibility of the plant's automation concept (Lange et al. 2023; Bittorf et al. 2022). In order to reduce engineering efforts regarding automation, modular automation concepts provide means for standardized integration of modules and their automation systems (Hoernicke et al. 2022a). The project *eModule* in the H_2*Giga* flagship project[1] aims at developing a manufacturer- and process-independent and — as far as possible — technology-independent modular automation concept for water electrolyzers. In this modular automation concept, various operating and utilization scenarios of electrolyzers are considered.

In order to produce green hydrogen, modular electrolysis plants need to be engineered and operated. Although a rapid ramp-up of production is planned, very few plants are in operation and thus limited experiences in engineering and operation of such plants are available so far. Odennweller et al. point out that uncertainty in initial capacity, growth rate and final market volume are crucial factors in scalability of such systems (Odenweller et al. 2022). Crucial factors need to be considered in the decisions regarding the design of electrolysis plants and their automation systems. Such decisions are usually made in early engineering phases and significantly influence the system to be developed later (Martín 2016; Helmus 2008). Putting oneself in the shoes of a (future) plant owner/operator who is thinking of planning and operating such a plant in these times, that person faces several challenges, right from the early phases of engineering. These challenges will be addressed in the following.

Electrolysis plants carry out an electrochemical process and can be classified as process plants. Such plants exhibit a high degree of interdisciplinarity due to many engineering disciplines (e.g., automation engineering, process engineering, electrical engineering, material science) working together. Especially in the early phases of process plant engineering, different engineering disciplines are involved in the numerous decisions to be made (Martín 2016; Helmus 2008). The issue is particularly relevant for electrolysis systems, as the systems are currently subject to rapid technological developments, high complexity due to the integration of different systems (e.g., various electrolyzer units, water purification system, gas management, cooling systems), and are subject to emerging regulations driven by the global energy transition. An example is the development of an adequate safety and environmental concept, as hydrogen is highly flammable and thus safe operation for personnel, facilities and environment has to be ensured. In the early engineering phases of designing a safety and environmental strategy, safety specialists and environmental engineers from process engineering must be incorporated. Decisions about specific safety equipment, such as fire suppression systems or ventilation protocols, must be determined. Similarly, the collaboration between electrical engineering and process engineering becomes pivotal in the early engineering phases. When deciding on the right electrolysis technologies, considerations like energy efficiency and durability of components can sometimes present contradictory requirements from both disciplines. The intricacies of these collaborations and decisions amplify the complexity

[1] https://www.wasserstoff-leitprojekte.de/projects/h2giga.

in the engineering of electrolysis plants. Here, a balanced approach considering efficiency, costs, and environmental impacts is essential.

The various electrolysis technologies[2] present distinct requirements and adress diverse stakeholder goals while offering similar functionalities with different characteristic properties. This results in a high level of technology and company dependencies, resulting in highly individual solutions. However, this stands in contrast to the fundamental concept of reusable, standardized modules and a scalable, manufacturer-independent solution.

Adding to the high level of complexity are the numerous decisions that need to be adressed during the design of an electrolysis plant. While current decision-making processes emphasize quantitative analysis (see for example (Demirhan et al. 2019; Liu et al. 2011)), challenges in decision-making emerge when the quantitative decision-making base is (partially) absent. Though quantitative decision-making can be difficult in early engineering phases, due to factors such as unpredictable market dynamics and evolving technology standards, qualitative decision-making remains feasible. For instance, when selecting materials or technologies, engineers often rely on qualitative assessments based on industry experience and forecasted trends. To make such qualitative decisions, the collaboration of multiple engineering disciplines is necessary and leads to pronounced interdisciplinary dependencies. An electrolysis plant has to satisfy diverse requirements, which must be considered in the design (see "Energy Systems & Automation Engineering" section for requirements-based approaches). These span from grid-side requirements to hydrogen storage requirements. For example, while a mechanical engineer may focus on the physical layout and materials, an electrical engineer would prioritize power distribution and efficiency. Navigating these multifaceted requirements poses a challenge in early design stages. Foremost, numerous requirements pertain to the plant's automation, such as enabling flexible production and adhering to safety regulations. For instance, a plant intended for peak-load hydrogen production may have different automation nuances compared to one designed for steady, round-the-clock operation. Safety, while universally paramount, could see varied implementations based on regional regulations and the specific production technology in use. Thus, the automation concept including the needed functionalities of such an electrolysis plant can differ based on the plant owner/operators' intentions.

Defining the required functionalities within the modular automation concept is crucial for subsequent operations. The majority of projects concerning the engineering of electrolysis plants are "greenfield"-projects (i.e., newly built projects), given that this industry is still emerging and certain electrolysis technologies (e.g., HTEL) still remain under development (Lange et al. 2023; Odenweller et al. 2022). As of 2023, around 1 GW capacity of electrolysis plants has been installed or is under development globally, with a predicted 3.600 GW capacity demand by 2050 (Odenweller et al. 2022). This creates a knowledge gap in developing such systems because insights from earlier projects can't be used extensively and thus reusability is limited.

In summary, the previously stated problems underscore the necessity for a systematic and knowledge-based approach during the early engineering and automation

[2] e.g., *Proton Exchange Membrane Electrolysis* (PEMEL), *Alkaline Electrolysis* (AEL), *High-Temperature Electrolysis* (HTEL), *Anion Exchange Membrane Electrolysis* (AEM)

phases of electrolysis plants. Such an approach can mitigate the error risks, reduce engineering effort and minimize frequent iteration cycles. This paper aims to introduce a systematic and knowledge-based engineering method to support qualitative decision-making in early engineering phases. Consequently, we propose to use an intention-based engineering approach in the early phases of engineering and automation of electrolysis plants. This will facilitate the deriviation of an initial model consisting of owner/operator goals, abstract solutions and requirements. This acts as a basis for the derivation of a suitable automation concept. Here, emphasis will be placed on determining needed functionalities inside modular electrolysis plants. This ensures early recognition of goals being pursued with a modular plant and any potential conflicts. Utilizing this approach, intentions of individual engineering disciplines as well as their interdependencies concerning later operation of such a plant are outlined. Finally, functionalities of the plant are determined, grounded on the previously established intentions.

As previously noted, engineering and automation of electrolysis plants is a lengthy, complex and time-consuming process that requires the collaboration of multiple engineering disciplines. The early engineering phases in particular are often characterized by unstructured information and many decisions that have great influence on the plant's subsequent design. Intention-based engineering seeks to systematically support these early engineering phases. The core premise of this approach is to use the engineerâ€™s intentions as the basis for the system design and development of an automation concept. Thus, by assigning meaning to decisions and system elements, the various disciplines involved in the engineering process can better understand the decisions made and adjust their own decisions based on the previous ones. Although nascent in its application to electrolysis plants, preliminary findings from process plants indicate the potential of intention-based engineering. Markaj et al. (2022)

Research questions

To achieve the objective of the paper, the following five research questions are addressed in this contribution:

RQ1 How do current engineering approaches for energy systems (especially electrolysis plants) support the early phases?

RQ2 How can the early engineering and automation phases of modular electrolysis plants be supported systematically using an intention-based engineering approach?

RQ3 How can different engineering disciplines work interdisciplinary using a joint model in early engineering phases?

RQ4 Can reusable domain models for electrolysis technologies and operation strategies be determined to support qualitative decision-making in early engineering phases?

RQ5 Given the diverse intentions stemming from various stakeholders, which specific functionalities can be derived for a modular electrolysis plant?

Paper structure

The remainder of this contribution starts with a description of an exemplary use case and scenarios for modular electrolysis plants as well as a general overview of modular automation and engineering approaches in Fundamentals and Use Cases" section. "Related Work" section deals with the related work regarding current engineering and automation approaches for modular process plant and energy systems. Thus, "Related Work" section provides an answer to RQ1. The description and adoption of the intention-based engineering methodology is presented in "Methodology" section and contributes to the answer of RQ2. "Evaluation" section illustrates a detailed evaluation of the intention-based engineering approach using three use cases for modular electrolysis plants. Hence, this section focuses on RQ3, RQ4 and RQ5. Ultimately, the interpretations, implications and limitations of the approach are discussed in "Discussion" section and the contribution summarized and an outlook given in "Summary and outlook" section.

Fundamentals and use cases

Engineering spans diverse sectors of industry of industry, encompassing domains like manufacturing engineering, process systems engineering or energy systems engineering. Specifically, electrolysis plants for the production of hydrogen from water and electricity are hereby situated at the interface between process systems engineering and energy systems engineering. In the course of globalization and the resulting intense competition, companies in process industries are trying to launch their products on the market at an ever faster pace. In order to fulfill individual customer requirements at the same time, flexible plant concepts are needed. The introduction of modular plants is envisioned as a strategy to infuse this requisite flexibility. Mothes (2015); Bieringer et al. (2013); Eilermann et al. (2018)

The engineering of modular plants is divided into two phases: module engineering and plant engineering. In module engineering, the module manufacturer designs a versatile module aiming for broad applicability and automates it using the *Module Type Package* (MTP). In plant engineering, the plant owner/operator integrates various modules physically into a modular plant and in terms of information technology into the control system (Holm et al. 2015; Obst et al. 2015). Here, the MTP is key because it provides a standardized automation interface that is consistent regardless of the manufacturer. An MTP describes a standardized, manufacturer-independent interface between a module and a control system. Within an MTP, capabilities of a module are encapsulated in automation services and made available to a control system. With the aid of uniform semantics, these services can be orchestrated into a production recipe (Bloch et al. 2018).

Figure 1 provides an overview of the engineering workflow for modular process plants, including the distinct roles and documents exchanged between them. Plant engineering consists of several engineering phases, executed by various engineering disciplines of a plant owner/operator. These disciplines communicate and share ideas, documents, and models, both within and across different engineering phases. A plant owner/operator exchanges requirements and functional specifications with several module manufacturers. Within each manufacturer's workflow, different engineering disciplines similarly

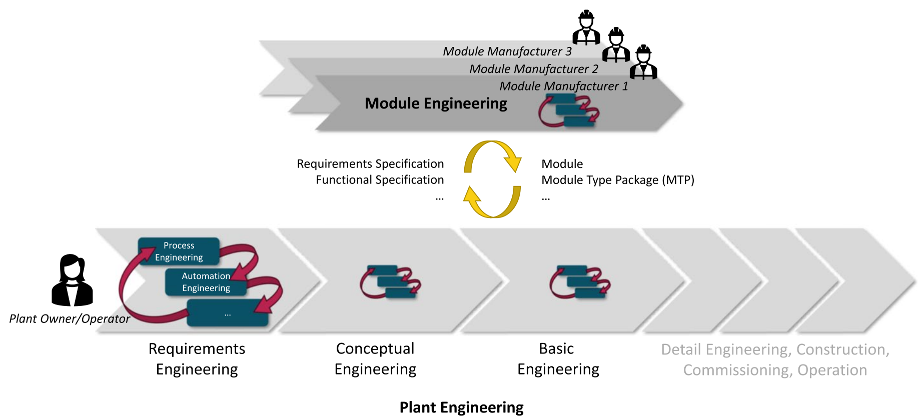

Fig. 1 Generalized engineering workflow for modular process plants consisting of various iteration cycles between roles, engineering disciplines and engineering phases

share ideas, documents and models. In return, the constructed module as well as the automation (i.e., MTP) are handed over. It is worth noting that this workflow is generic and can be tailored to fit modular electrolysis plants specifically. In summary, it can be concluded that there are iteration cycles of communication between various roles (e.g., plant owner/operator, module manufacturers), engineering disciplines (e.g., process engineering, automation engineering) and engineering phases (e.g., Conceptual Engineering, basic engineering).

In this contribution, modular electrolysis plants are focused and conceptually planned according to VDI/VDE/NAMUR 2658 (MTP guideline) and VDI 2776. A plant owner/operator intends to operate a modular electrolysis plant. When a plant owner/operator decides to operate a modular electrolysis plant, they outline the desired system, detailing the necessary functionalities and automation. This requirement specification is shared with multiple module manufacturers, who either use pre-exisiting modules or newly manufacture or design them to suit the specific needs. At its core, a modular electrolysis plant consists of different modules with a variety of offered services. Central to the modular structure are electrolysis modules, which provide the main functionality (eletrolysis) to a plant. Different technologies like PEMEL or HTEL might be used simultaneously in the plant. Upstream modules for pre-treatment (e.g., water purification) and downstream modules for post-treatement (e.g., hydrogen purification) can be connected to electrolysis modules. Depending on the specific electrolysis technology chosen, other additional modules, like heat recovery or air supply, might also be integrated. All modules come with the an electrolysis-specific MTP, which is imported by a higher-level process control system. A modular electrolysis plant can be used in various industrial applications. However, each plant owner/operator's requirements differ, leading to varying plant and automation concepts. In this contribution, we want to demonstrate how different intentions of plant owners/operators can be modeled in early engineering phases and how these intentions shape diverse concepts. Our manuscript delves into three use cases, each chosen for its distinct challenges and relevance in today's energy landscape:

1. *Hydrogen Bus Refueling Station* (HBRS) (highlighting urban energy needs)

2. *Green Steel Production* (showcasing industrial application)
3. *Flexible Hydrogen-based Ammonia Production* (representing large-scale energy storage)

For each of these applications, a modular electrolysis plant can be used. An in-depth discussion of each use case is described in "Evaluation" section, where the presented approach is critically assessed.

Related work

To understand how engineering of modular electrolysis plants is systematically supported, a foundational understanding of the methodologies used in the engineering and automation (modular) process plants and energy systems is crucial. For this purpose, it is relevant that approaches for engineering and automation of modular plants are outlined first ("Modular Process Plant & Automation Engineering" section). Given that electrolysis plants also embody energy systems, it's equally important to consider approaches specific to energy systems engineering ("Energy Systems & Automation Engineering" section).

Modular process plant & automation engineering

As this contribution focuses on the early engineering phases, various approaches supporting these engineering phases of modular plants and their automation are analyzed in this section. A categorization of approaches can be conducted beforehand into type-based approaches, mapping-based approaches, and intention-based approaches.

Type-based approaches, such as (Klose et al. 2022; Hoernicke et al. 2022b), separate between a more abstract modular automation concept using MTPs as types and as specific instances of it. These approaches facilitate the separation of a specific implementation of automation (in later engineering phases) from the automation concepts (in early engineering phases), which enhances reusability. These approaches are profound regarding their methodological foundations and support collaboration between various engineering disciplines. However, the transfer of information is not specified in detail and currently relies on different manual transformations, which hinders traceability in early engineering.

By using mappings between various engineering documents and file formats, mapping-based approaches try to counter the drawbacks of type-based approaches. In Rahm et al. (2021) a bi-directional transformation approach for exchange formats is presented. The authors in Rahm et al. (2021) enrich modular automation concepts (MTPs) by means of other digital engineering artifacts (e.g., P &IDs) and use *Triple Graph Grammars* (TGGs) to map information between engineering artifacts and MTPs. This approach is supposed to be used in basic and detail engineering, while the authors in Rahm et al. (2021) point out that formalized approaches for earlier engineering phases (e.g., Requirements Engineering) are missing for modular plants.

Lastly, intention-based approaches focus on these early engineering phases and formalize them. In Markaj et al. (2022) a method for an intention-based engineering of modular plants is introduced. By demonstrating how intentions can be modeled in a systematic way and the resulting MTP created based on these intentions, traceability is remained between various engineering disciplines. The authors leverage the potential of ontologies to semantically formalize knowledge as early as possible in engineering Markaj et al. (2022).

Energy Systems & Automation Engineering

Engineering and automation of energy systems may follow in some aspects conventional engineering of process plants if the energy carrier is a chemical energy carrier (e.g., gas). Since the development of electrolysis plants consists of a combination of electrical and process engineering steps, it is essential to consider methods for developing energy systems as well. Especially for electrical engineering, specific requirements are imposed on electrolysis plants: precise voltage and current control, electrical energy conversion as well as heat management. The approaches can be categorized into three categories: mathematical-based approaches, model-based approaches, and requirements-based approaches.

Energy systems engineering defines a methodological foundation for developing energy systems in a systematic way (Kikkinides et al. 2008). Liu et al. describe that *Superstructure Modeling* is a key methodology for energy systems engineering, which is adopted and adapted from process systems engineering (Liu et al. 2011). The approach focuses on mathematically finding an optimal conceptual design of the energy system. This can be extended by mixed linear or nonlinear problem optimization and/or multicriteria optimization (Liu et al. 2011). However, in order to follow up with this kind of optimization techniques, the criteria need to be known beforehand. Additionally, quantitative information (e.g., specific capacity values of equipment or flow rates) is needed to fuel such optimization approaches, which is usually not available in early engineering phases. Demirhan et al. argue that using heuristics in times of rising complexity in systems are less useful for decision-making than mathematical optimization-based approaches (Demirhan et al. 2019). Modeling, design, operation, multi-objective and robust optimization are key methodologies for energy systems engineering. Furthermore, Demirhan et al. point out that information technologies, AI, interdisciplinary work between engineering disciplines and to know the *Why* in engineering are essential new trends in energy systems engineering (Demirhan et al. 2019).

In contrast to mathematical-based approaches, model-based approaches foster interdisciplinary work between engineering disciplines by considering mutual, multi-view models. Berjawai et al. use a multi-system perspective approach in a system-of-systems setting to support energy systems integration. The conceptual framework considers system requirements as well as structure and behavior (Berjawi et al. 2021). Furthermore, an evaluation framework considering various evaluation criteria was introduced (Berjawi et al. 2021). However, their approach remains on a high abstraction level and is missing a more detailed model as well as guidance using a modeling workflow. Pröstl Andrén et al. point out that information is redefined in later engineering phases, because machine-readable formats and seamless informations flows are missing in earlier phases (Pröstl Andrén et al. 2019). The authors list several model-driven engineering approaches tackling this problem and provide a possible framework, which starts with a definition of use cases and specifying needs, which go directly into an automatic engineering phases to automatically generate target configurations. The used *Power*

System Automation Language (PSAL) can further support the proposed framework (Pröstl Andrén et al. 2019). The approach seems beneficial as it supports automatic generation. However, collection, analysis and description of requirements before use case design remains an open topic. Further, Strasser and Pröstl Andrén point out that an integration of the before mentioned approach into traditional engineering approaches is necessary in the future (Strasser and Pröstl Andrén 2019). Linnenberg and Fay propose a model-based approach for developing agent-based energy systems, called 2DECS (Linnenberg and Fay 2018). The authors consider both, technical and organizational aspects, and support their method with different models (e.g., role models or artifact models) (Linnenberg and Fay 2018). This approach considers early phases such as requirements analysis, however focuses on the development of agent-based energy systems, which only reflect a specific area of energy system control.

While the aforementioned model-based approaches try to cover all engineering phases, requirements-based approaches focus on early phases and thus specialize on supporting them. Martin et al. carried out a study in order to understand how users are viewed and incorporated in hydrogen energy systems and their design (Martin et al. 2020). They propose to switch from a more technical-focused design to a human-driven design to design desirable technology (Martin et al. 2020). Azzouzi et al. introduce a new methodology to put stakeholders of multienergy cyber-physical systems into the centre of system design (Azzouzi et al. 2022). They develop a multi-layered methodology, where stakeholder goals and requirements are modeled on different hierarchical layers (from intentional level to formal requirements level). The goals (as the highest elements) are modeled using the goal modeling language i* (i-Star) (Azzouzi et al. 2022). Svetinovic develops a strategic Requirements Engineering model focusing on the engineering of complex sustainable energy systems (Svetinovic 2013). While the approach offers a meta model for linking requirements and sustainability, it lacks a methodogological foundation. The authors in Lehnhoff et al. (2014) argue that self-organization properties should be addressed in Requirements Engineering of smart grids. Especially, their influence on design decisions is emphasized (Lehnhoff et al. 2014). Heussen et al. use *Multilevel Flow Modeling* (MFM) for the early detection of conflicts in requirements, especially in control structures (Heussen et al. 2015). Using a graphical modeling language such as MFM provides a beneficial interdisciplinary approach, but lacks in interoperability as well as formulation of natural-language requirements. It is strongly linked to the functional representation of a plant. Orellana et al. use a combination of the IEC 61850, the goal modeling language KAOS and petri nets to analyze requirements in smart grid systems (Orellana et al. 2021). Similar to Svetinovic, a methodological foundation is missing. Furthermore, the requirements stay in a requirements space, as their operationalization (e.g., into control code) is not explained.

Conclusion and research gap

In this section, related work was analyzed with respect to modular plant engineering and automation and energy systems engineering. It was shown that model-based and intention-based approaches are suitable for the early engineering phases of modular plants and could already be usefully applied there. Hence, this suggests potential applicability for the engineering and automation of modular electrolysis plants.

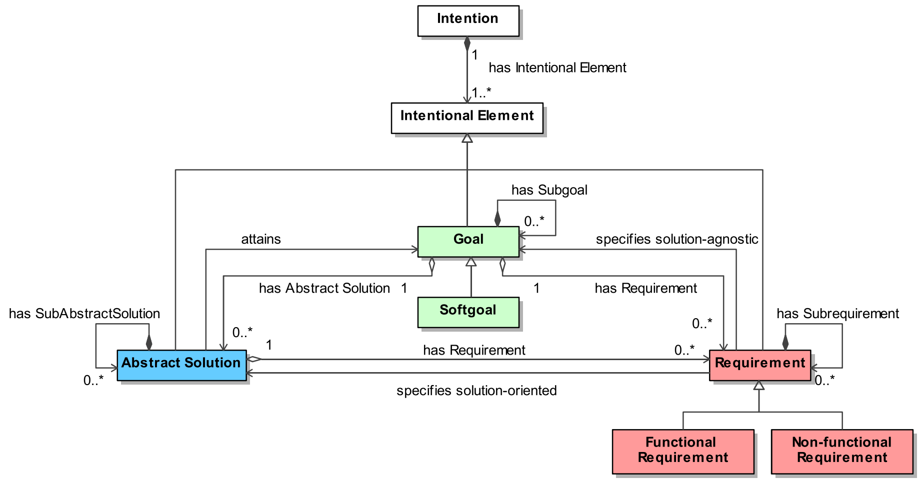

Fig. 2 Intention Ontology represented as an UML class diagram, displaying the main classes and relations (extended from (Markaj et al. 2022))

However, the research gap in energy systems engineering and automation also becomes apparent. In particular, the methodological and semantic foundation is missing in many approaches. Furthermore, elicitation and operationalization of intentions are rather poorly addressed. However, this is essential to create a consistent, seamless and interdisciplinary approach, which can then be integrated into existing engineering processes.

The intention-based engineering method, as outlined in Markaj et al. (2022), is chosen for its capability to address these challenges. By centering the engineering process around clear intentions, it promises a more directed and efficient design phase. Next, we will apply this method to the early engineering phases of modular electrolysis plants.

Methodology

In this section, a general overview of the methodology is given, highlighting specific enhancements made to individual steps. First, an overview of the *Intention Ontology* is given, the cornerstone of the intention-based engineering approach (Intention Ontology" section). This is followed by a detailed description of the intention-based engineering approach "Intention-based Engineering Methodology" section.

Intention Ontology

The Intention Ontology represents concepts for describing, modeling and analyzing intentions in engineering (Markaj et al. 2022). The ontology borrows concepts from different *Goal-oriented Requirements Engineering* (GORE) (van Lamsweerde 2001) approaches and unifies them into a single ontology.

Figure 2 illustrates class concepts inside the Intention Ontology. Above all, the concept of an *Intention* in a technical system development context is comprised of *Intentional Elements* goals, (alternative) abstract solutions to reach goals and requirements specifying goals and solutions. An intention can contain several intentional elements and hierarchies out of them. Thus, intentional elements can be decomposed into elements of the same type. *Goals* represent a specialization of intentional elements and

Table 1 Relations between intentional elements

Hierarchical contribution links[1]		Lateral contribution links[2]	
Link	**Description**	**Link**	**Description**
Optimize	Child intentional element must be achieved in the most optimal way in order for the parent element to be achieved	*Make*	Achievement of intentional element is dependent on achievement of linked intentional element
Achieve	Child intentional element must be achieved in order for the parent element to be achieved	*Help*	Achievement of intentional element positively affects achievement of linked intentional element
Maintain	Child intentional element must be kept in the current state in order for the parent element to be achieved	*Hurt*	Achievement of intentional element negatively affects achievement of linked intentional element
Prevent	Child intentional element should not be achieved in order for the parent element to be achieved	*Break*	Achievement of intentional element is dependent on prevention of achievement of linked intentional element

[1] Hierarchical contribution links represent parent–child contributions

[2] Lateral contribution links represent contributions between non-parent–child elements

are defined (in an abstract and discipline-independent way) as desired end states of a technical system. Goals are the main elements of intentions and therefore required for modeling abstract solutions or requirements. Furthermore, the concept of *Softgoal* as a non-functional desired state of a technical system is introduced. Softgoals represent desired system properties and quality attributes (e.g., high maintainability). Unlike goals, they lack specific satisfaction criteria. Despite their vagueness, softgoals can significantly shape the final design of a system and should not be overlooked in early engineering phases. *Abstract Solutions* provide means to reach (= attain) desired goals and thus contribute to their satisfaction. They represent a problem-solving mindset in the engineering process but remain high-level, since actual implementation details are typically undecided at this stage. *Requirements* are more detailed than goals and focus on system functionalities and system qualities/properties. While they can elaborate on goals in a solution-agnostic manner, they can also define abstract solutions with a solution-oriented approach. Additionally, requirements can be specified either as functional or non-functional requirements.

Next to the general concepts and links between them, two types of object properties are defined to relate intentional elements to each other. The first type describes hierarchical contribution links between intentional elements in the same "branch" (parent-offspring decomposition). More specifically, they describe how an offspring intentional element contributes to the achievement (and thus the satisfaction) of a parent intentional element. Lateral contribution links denote a dependency between two intentional elements, which are not from the same hierarchical lineage. In other words, they connect elements related from the 2nd degree and beyond. A comprehensive breakdown of these contribution links, both hierarchical and lateral, can be found in Table 1.

Next to contribution links, a data property representing a satisfaction level of individual intentional elements is needed. This concept is borrowed from i*/GRL goal modeling languages (Dalpiaz et al. 2016). It consists of five ordinally ordered values. The value *satisfied* describes that the intentional element is reachable, while *weakly satisfied* represents limited reachability. Thus, there are still potential conflicts to be resolved. The

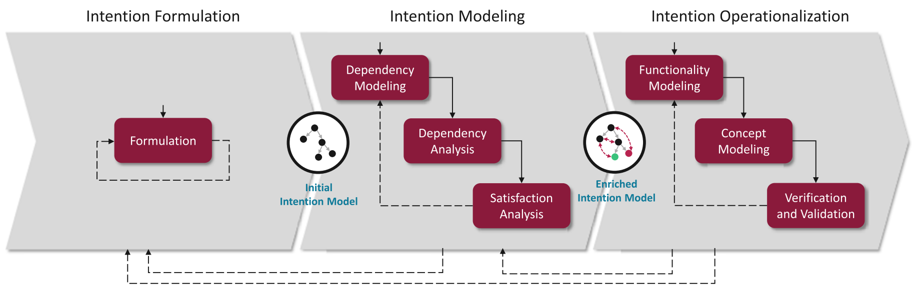

Fig. 3 Intention-based Engineering Methodology

value *weakly denied* mirrors the *weakly satisfied* level but in the opposite direction. The intention is mostly unmet, and conflicts might be present. The value *denied* clearly signifies that the intention has not been achieved.. The value *unknown* describes the state in which nothing can yet be said about the reachability. At this stage, a conclusive determination about the satisfaction level is not possible. This ambiguity could arise due to missing data, like other reachability values, or pending decisions, such as choosing between alternatives.

The Intenion Ontology provides concepts for describing intentions. Yet, ambiguities in content can still occur, so that domain ontologies (e.g., Open Energy Ontology (Booshehri et al. 2021)) need to be used in order describe the content of intentions in a semantically unambiguous way. This can be done by modeling individuals simultaneously as instances of a class in the Intention Ontology (e.g., a goal) and as instances of a class in a domain ontology.

Intention-based Engineering Methodology

Intention-based Engineering represents a systematic methodology for the early phases of technical system development, where intentions of engineers are used to guide conceptual design. The methodology consists of three main steps *Intention Formulation*, *Intention Modeling* and *Intention Operationalization*, which will be explained in more detail in upcoming sections. Figure 3 illustrates the three main steps and sub-steps. All steps can be iteratively performed within the same step or between steps.

Intention Formulation

Intentions are usually thought, expressed and communicated in natural language, from one human to another. In order to work with intentions and use them as guidance in engineering, they need to be systematically formulated. Furthermore, this provides a documentation and supports logical reasoning (Rolland and Salinesi 2005). Intention formulation represents the initial step, where intentions are formulated by using a *Controlled Natural Language* (CNL) (Kuhn 2014; Schwitter 2010), leveraging predefined templates known as boilerplates. In a first step, goals are formulated. According to the metamodel presented in Fig. 2, these form the basis of intentions. In addition to goals, softgoals can also be set up. In a next step, abstract solutions and requirements are assigned to goals. This general knowledge of abstract solutions can be sourced from earlier projects, enhancing their reusability. Requirements, which are assigned to goals, apply to all abstract solutions of the goal at the same time. Moreover, solution-specific requirements can be linked directly to abstract solutions. These requirements not only restrict the scope of abstract solutions but also represent specialized knowledge. They can originate from the same sources as the abstract solutions. For all intentional elements, further elements of the same type can be hierarchically appended.

The step of formulation can be iteratively performed. As a final result, an initial intention model including hierarchical contribution links is automatically generated from the formulations. Further dependencies, such as lateral contribution links, will be introduced in the next step.

Intention Modeling

Once intentions have been formulated by engineering disciplines, further aspects can be modeled. These include, for example, lateral contribution links. These indicate conflicts between intentional elements and affect the achievability (i.e., satisfaction) of intentional elements. Intention modeling is comprised of three consecutive steps: dependency modeling, dependency analysis and satisfaction analysis.

Dependency modeling focuses on the manual and automatic modeling of dependencies (e.g., lateral contribution links) between intentional elements. The intention model produced from intention formulation is used as input for dependency modeling. In particular, modeling of lateral contribution links is important, as they directly influence satisfaction of intentional elements. As multiple engineering disciplines collaboratively model intentions, certain conflicts, like the inability to simultaneously achieve all goals within given resources, inevitably emerge. Furthermore, not all stakeholders agree to all other intentions and thus conflicts arise and need to be resolved (Riechert et al. 2007). These conflicts need to be resolved, before developing concepts based on intentions. For further information on conflict resolving, we refer to (van Lamsweerde et al. 1998; Hu et al. 2015).

Dependency analysis infers, based on the combination of different modeled dependencies, if inconsistencies exist or if further dependencies need to be added automatically to make the intention model consistent. Taking the example of a conflict between intentional element I_x with another intentional element I_y, I_x is also in conflict with all offspring elements of I_y. In order to analyze dependencies automatically, *Semantic Web Rule Language* SWRL rules are implemented.

Lastly, satisfaction analysis determines if an intentional element can be reached (i.e., satisfied) based on satisfaction levels of connected intentional elements. Satisfaction analysis is a key method in goal modeling and can be used to guide early Requirements Engineering with qualitative decision analysis (Horkoff and Yu 2013). This analysis is also supported by SWRL rules where satisfaction levels can be determined automatically based on a variety of rules. An enriched intention model is the result of the second step.

Intention Operationalization

After modeling dependencies, resolving intention conflicts, and conducting an initial satisfaction analysis, the next phase is the operationalization of intentions. It is a crucial step in finding solutions to make intentions operational and thus satisfy them (Dalpiaz et al. 2014). In this contribution, operationalization entails the generation of engineering concepts based on intentions. Common to all concepts is the definition, identification and modeling of implementation-independent functionalities. This represents the first step in the operationalization of intentions. Based on the derived and modeled functionalities, the individual engineering disciplines can develop discipline-specific concepts (e.g., safety concept, process control concept). In the final stage, these concepts undergo verification and validation to ensure alignment with the initial intentions.

Functionalities describe the functional operationalization of intentions and represent purpose of system elements in a plant (Lind 1994). Thereby, it is important that this happens implementation- and discipline-independently. This guarantees that different implementation options can be used later and that functionalities are understandable across disciplines. For modeling functionalities, the *Fomalized Process Description* (FPD) according to VDI 3682 is used.

Using the identified functionalities, various engineering concepts can be developed. In this work, focus is placed on the automation concept for modular electrolysis plants. Once an engineering concept has been developed, it undergoes verirfication and validation (Pohl et al. 2012). Verification checks whether the developed engineering concept fulfills the required functionalities, while validation ensures whether the developed engineering concept fulfills the intentions. These evaluations are iterative, reflecting the ongoing refinements in the engineering process. In this context, the task of creating an automation concept is an aspect of intention operationalization, undertaken by the automation engineering discipline.

The focus of this paper is only on the functionality modeling, while the concept modeling as well as verification and validation will be addressed in an upcoming publication.

Evaluation

To evaluate the concept, three distinct use cases are considered for the modular electrolysis plant: (1) *Hydrogen Bus Refueling Station* (HBRS), (2) *Green Steel Production* and (3) *Flexible Hydrogen-based Ammonia Production*. For each use case an intention model is created, representing distinct perspectives of different plant operators in the three use cases. Each use case has a different focus in the intention modeling phases (see 4.2) on the evaluation, in order to highlight different facets of the methodology. These three use cases are intended to demonstrate how — depending on the context — a modular electrolysis plant can be systematically planned based on different intentions.

The first use case focuses on the intention model itself and demonstrates interoperability in modeling. It captures the intentions of various stakeholders, including plant owners/operators, safety engineers, and process engineers. Emphasis is put on the safety regulations. The second use case is concerned with the modeling and reasoning of dependencies between intentional elements. Given that a range of technologies can support electrolysis processes in green steel production, the intentions related to these technologies are modeled and reused in the form of domain models. The third use case primarily targets the operationalization of intentions and the subsequent development of a suitable automation concept. Thus, operation goals and requirements are modeled and operation strategies developed. Similar to the domain models for electrolysis technologies, these strategies can be reused from existing domain models. Lastly, functionalities are derived from operation intentions and modeled using FPDs.

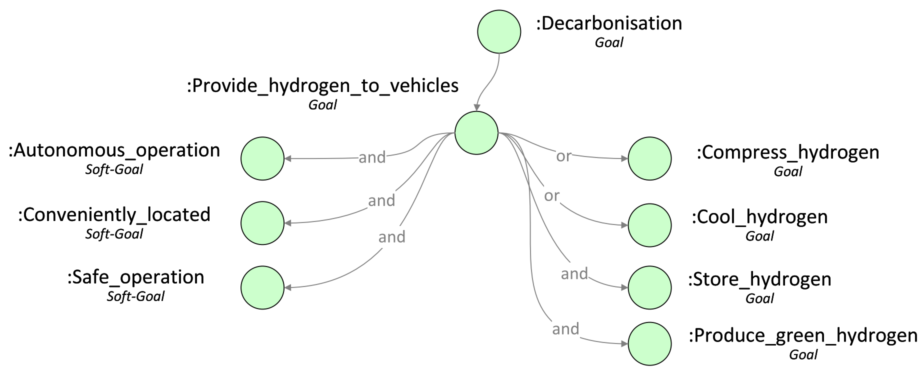

Fig. 4 Top Goals in use case 1—Hydrogen Bus Refueling Station

The implementation is realized by using different tools and description formats. The modeling of the intentions and functionalities as an ontology is performed in the Protégé[3] tool. For a graphical modeling of the functionalities, the tool FPBjs[4] is used.

For a better overview of the figures, not all relations between the intentional elements are shown.

Use case 1—Hydrogen Bus Refueling Station

In the first use case a modular electrolysis plant should designed and built for local hydrogen production, storage and usage in a bus refueling station. The development of the intention model is based on research conducted in the eModule project as well as information from literature (especially from Perna et al. (2022)). Intentions were formulated in a first step, in which perspectives of the different engineering disciplines were taken. This step is omitted here due to limited space.

From the formulations an initial intention model is automatically created. Figure 4 illustrates the "top" goals of the intention model. Supporting `:Decarbonisation` is the main goal of the plant operator. This has the subgoal `:Provide_hydrogen_to_vehicles`, which reflects the main mission of a HBRS. To provide hydrogen to vehicles, it needs to be produced (`:Produce_green_hydrogen`), stored (`:Store_hydrogen`), compressed (`:Compress_hydrogen`) or cooled (`:Cool_hydrogen`). These subgoals reflect functional goals which are later on achieved by specific functionalities. Furthermore, three softgoals are important to the plant operator: (1) the HBRS should be operated autonomously (`:Autonomous_operation`), (2) the HBRS should be conveniently located for vehicles (`:Conveniently_located`) and (3) the HBRS should be operated safely (`:Safe_operation`). This softgoal signifies the plant operator's intent to have the HBRS run with minimal human intervention and with minimum supervision. A conveniently located station can increase the utilization rate of the station, contribute to faster adoption rates of hydrogen-fueled vehicles, and ensure customer satisfaction due to reduced wait times and easier access. Especially, the safe operation of electrolysis plants is a major factor

[3] https://protege.stanford.edu/.

[4] https://github.com/HamiedNabizada/FPB.JS.

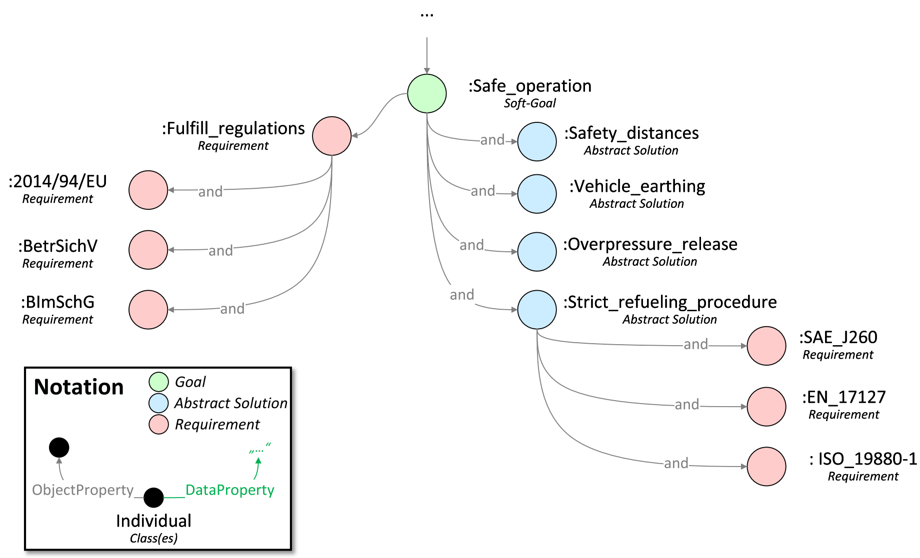

Fig. 5 Softgoal *Safe Operation* in use case 1—Hydrogen Bus Refueling Station

for acceptance throughout the population. Safe operations can lead to increased trust, smoother regulatory approvals, and potentially lower insurance costs, given the reduced risks.

Focusing on the safe operation softgoal, in Fig. 5 abstract solutions and requirements are listed. Concerning requirements, fulfillment of regulations is an important one. Depending on the country, there exist several regulations which need to be followed. These regulations define what a hydrogen refueling station is (`:2014/94/EU` for European hydrogen bus refueling stations) and how a safety concept for such a station has to be established and followed (`:BetrSichV`, `:BImSchG` for German hydrogen bus refueling stations). Four main abstract solutions should be implemented later on to reach the softgoal `:Safe_operation`. `:Safety_distances` between the hydrogen production system and the refueling system are crucial due to prevention of lethal accidents. Safety distances are crucial not just for the prevention of accidents like explosions or fires, but they also allow for easier containment and management should an accident occur. For context, the authors in Timmers and Stam (2017) calculated various maximum safety distances, carrying out a quantitative risk analysis based on general failure frequencies per year. Next to safety distances, `:Vehicle_earthing` is important to prevent sparks from causing explosive chain reactions. In case of compressed, gaseous hydrogen an `:Overpressure_release` is needed to prevent accidents from gas ignition. By following a `:Strict_refueling_procedure` according to the regulations `:SAE_J260`, `:EN_17127` and `:ISO_19880-1` a safe refueling can be achieved.

A safe operation of an HBRS can be supported by a safe storage of hydrogen (`:Store_hydrogen`). This is either possible in a `:Gaseous_phase`, which is needed for hydrogen compression (`:Compress_hydrogen`), or in a `:Liquid_phase`, which is needed for hydrogen cooling (`:Cool_hydrogen`). Without a safe operation, production of green hydrogen is not possible, as it is

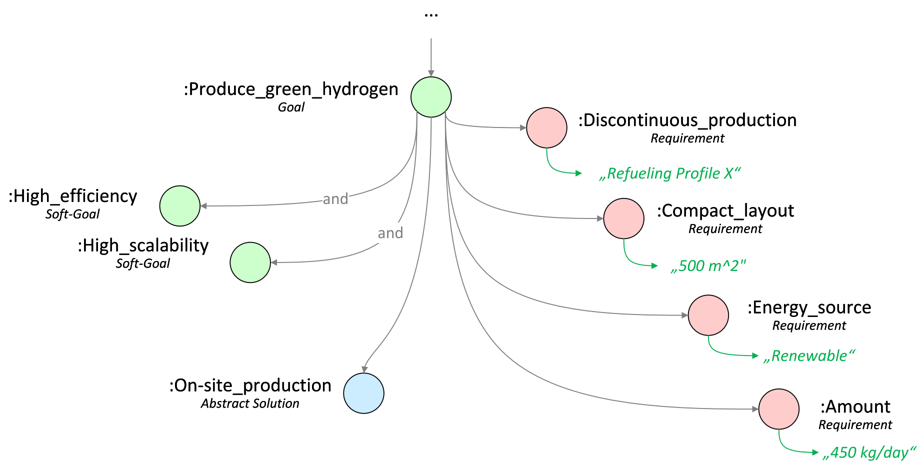

Fig. 6 Goal *Produce Green Hydrogen* including Softgoals, Abstract Solutions and Requirements in use case 1—Hydrogen Bus Refueling Station

prohibited by regulations. Therefore, the softgoal `:Safe_operation` is connected to `:Produce_green_hydrogen` by means of a make link. In other words, an achievement of `:Safe_operation` is required for an achievement of `:Produce_green_hydrogen`.

`:Produce_green_hydrogen` represents a functional goal and can be further decomposed into the softgoals `:High_efficiency` and `:High_scalability`. A high efficiency is mandatory for smaller HBRS to provide a profitable economic strategy. How this efficiency is achieved is not yet determined (no abstract solutions). A high scalability is important due to current ramp-up of electrolysis plants. Additionally, several requirements are imposed on the production of green hydrogen. These include a `:Discontinuous_production` of hydrogen based on a representative, forecasted refueling profile throughout the day. This means that hydrogen isn't produced continuously around the clock. Instead, its production is based on a representative refueling profile that's forecasted for the day. In simpler terms, the production of hydrogen aligns with the expected refueling needs throughout the day, ensuring that hydrogen is available when needed, without overproducing or wasting resources. In addition, due to the selected location, the layout should be very compact (`:Compact_layout`) and no larger than 500 m^2. The `:Energy_source` used shall be renewable and 450 kg (`:Amount`) of hydrogen shall be produced per day. Figure 6 represents these intentional elements.

Finally, it is specified that the production should take place on-site, i.e. the hydrogen is produced directly at the HBRS (`:On-site_production`). This abstract solution can again be decomposed into its four parts `:Hydrogen_source`, `:Hydrogen_production`, `:Power_production` and `:Hydrogen_separation`. As can be seen from the figure, the individual abstract solutions depend on each other. Thus, the choice of a particular abstract solution can influence the choice of other abstract solutions. Various possibilities are indicated here. Since modular electrolysis plants were considered before, the choice here is `:Electrolysis`. This results in the abstract solution for `:Power_production`, where `:PV_grid` is selected (power production via wind power is excluded due to limited space). Figure 7 illustrates these intentional elements.

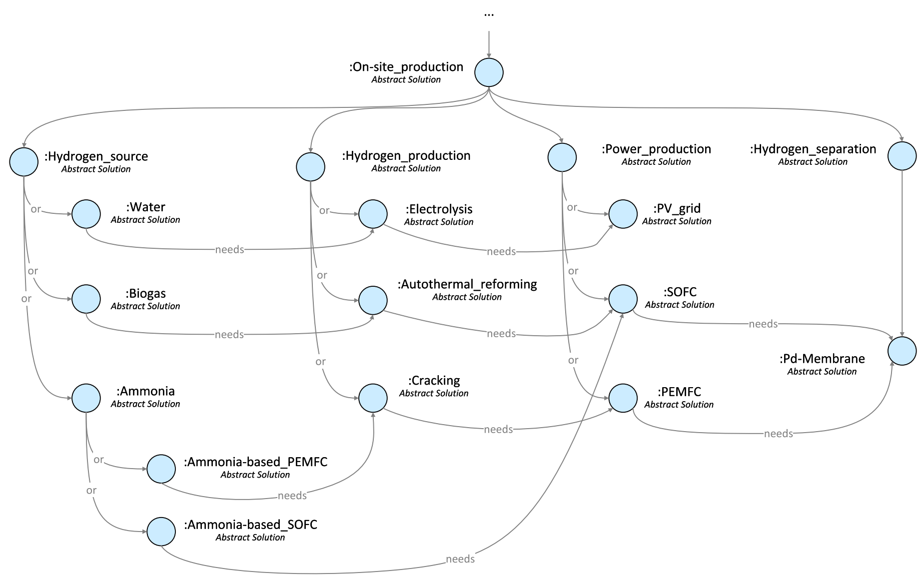

Fig. 7 Abstract Solution *On-site Production* decomposed into Sub-Abstract Solutions in use case 1—Hydrogen Bus Refueling Station

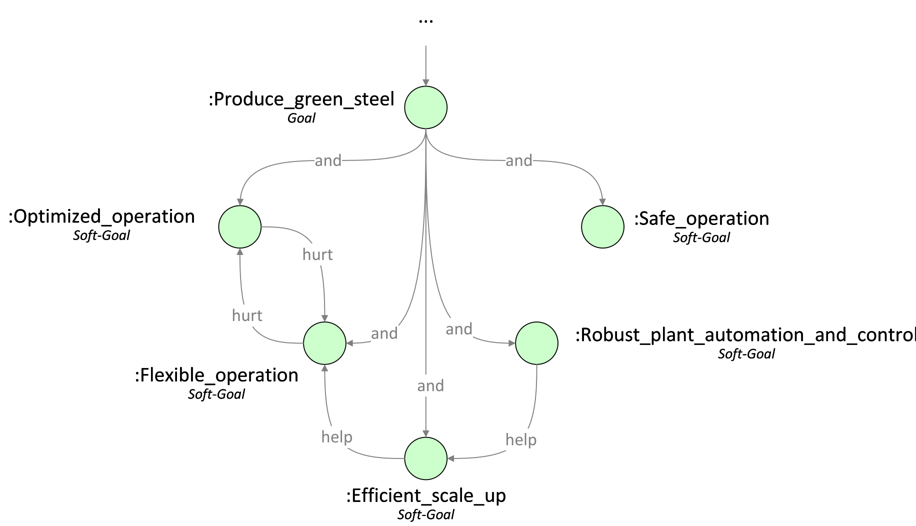

Fig. 8 Softgoals to the Goal *Produce Green Steel* for use case 2—Green Steel Production

Use case 2—Green Steel Production

In the second use case a modular electrolysis plant is to be designed and built for a green steel production. The development of the intention model is based on research conducted in the eModule project as well as information from literature (especially from Bhaskar et al. (2020); Richardson et al. (2023); Guidi (2022)).

Intention Modeling

Plant operators who are contemplating the implementation of a modular electrolysis plant, specifically for green steel production, begin by formulating their intentions in a first step. The main intention is the `:Decarbonization` of the steel industry. This

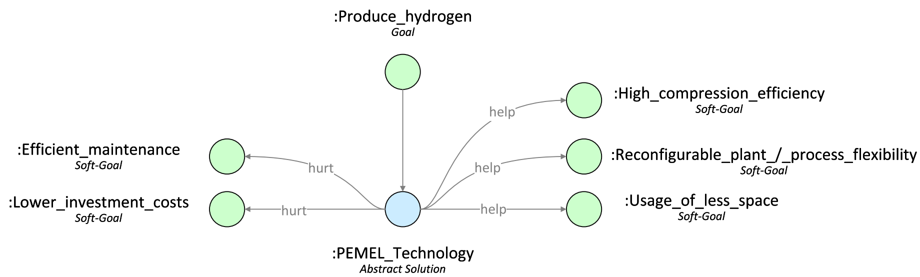

Fig. 9 Domain model for Abstract Solution *PEMEL Technology* in use case 2—Green Steel Production

is possible through the production of green steel by using green hydrogen (`:Produce_green_steel`). This goal can be further decomposed into several functional goals `:Produce_green_hydrogen`, `:Use_hydrogen`, `:Use_oxygen` as well as `:Store_hydrogen`. Production goals of the steel itself are omitted here due to the focus on the hydrogen production.

When considering the production of green steel, there are several softgoals that need to be taken into account, which can be in conflicting relations (see Fig. 8). On the one hand, as with the HBRS use case, `:Safe_operation` should be made possible. Importantly, this softgoal doesn't conflict with any other softgoal. Furthermore, robust plant automation and control should be enabled (`:Robust_plant_automation_and_control`). The achievement of this softgoal contributes to the achievement of another softgoal: the `:Efficient_scale_up`). This can be justified by the fact that when scaling up, the automation does not need to be rebuilt, maintained or modified. It is therefore also robust in the face of adaptations. Achieving efficient scaling supports the `:Flexible_operation`, as it allows electrolysis modules to be added or removed to meet a flexible electricity supply or hydrogen demand. However, `:Flexible_operation` and `:Optimized_operation` can be opposed to each other. The broad adaptability called for by flexible operation can sometimes be at odds with the narrowed, peak efficiency sought by optimized operation. This is not necessarily always the case, but the modules should be designed for as many different use cases as possible, that is at the expense of optimized operation, where a small operation window (with less flexibility) is targeted.

In the following, we will focus in particular on the softgoals, the goal `:Produce_green_hydrogen` and their dependencies. Looking at the `:Produce_green_hydrogen` goal in more detail, four different technologies (as abstract solutions) can be considered for electrolysis (`:PEMEL_Technology`, `:AEL_Technology`, `:HTEL_Technology` and `:AEMEL_Technology`). These technologies contribute differently to the achievement of the softgoals. For example, PEMEL technology is notable for the most flexible operation (e.g., regarding ramp-up times) in contrast to AEL. On the other hand, when HTEL is used, high temperatures for the operation can be used in later process steps for heating the hydrogen stream. This ensures efficient energy usage.

The various electrolysis technologies can be represented by reusable domain models. As a representative example, we present a domain model for PEMEL. Figure 9 illustrates an intention model for `:PEMEL_Technology`.

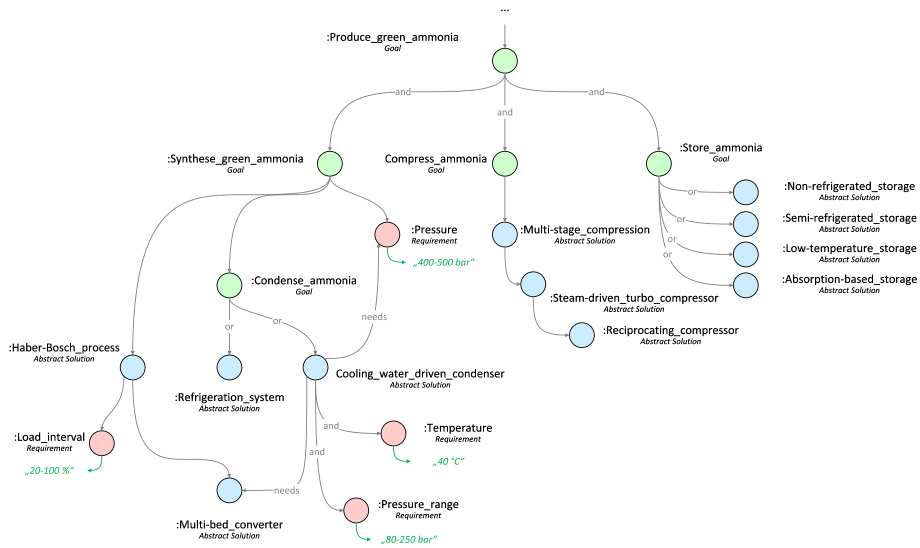

Fig. 10 Intentional Elemenets for Goal *Produce Green Ammonia* in use case 3—Flexible Hydrogen-based Ammonia Production

Domain Model—PEMEL

In Fig. 9 various intentional elements are modeled inside a domain model for PEMEL. The information is taken from Lange et al. (2023) where a literature review was conducted and profiles for different electrolysis technologies regarding specific requirements were given. Depending on these values, characteristics for PEMEL were derived.

An important consideration, in addition to the requirements, is the softgoal that are positively or negatively affected by the choice of PEMEL technology. Due to higher CAPEX, PEMEL technology can hardly guarantee `:Efficient_maintenance` (see for example Buttler and Spliethoff (2018)). Furthermore, the investment costs are higher than for other technologies, which is why there is a *hurt* relationship to the softgoal `:Lower_investment_costs`. On the other hand, the choice of PEMEL technology contributes to a lower space requirement (`:Usage_of_less_space`), a `:High_compression_efficiency` and higher process flexibility (`:Reconfigurable_plant_/_process_flexbility`).

Use case 3—Flexible Hydrogen-based Ammonia Production

The third use case focuses on the production of ammonia using hydrogen from a modular electrolysis plant. The development of the intention model is based on the results in Schulte Beerbühl et al. (2015); Chehade and Dincer (2021); Rouwenhorst et al. (2019).

Intention Modeling

Similar to the intention models of the previous use cases, the plant operator (i.e., individual engineering disciplines) first formulates intentions and generates an initial intention model. The main intention is also `:Decarbonization` with the production of green ammonia (`:Produce_green_ammonia`). The functional goals can be divided into the production of nitrogen, production of ammonia and production

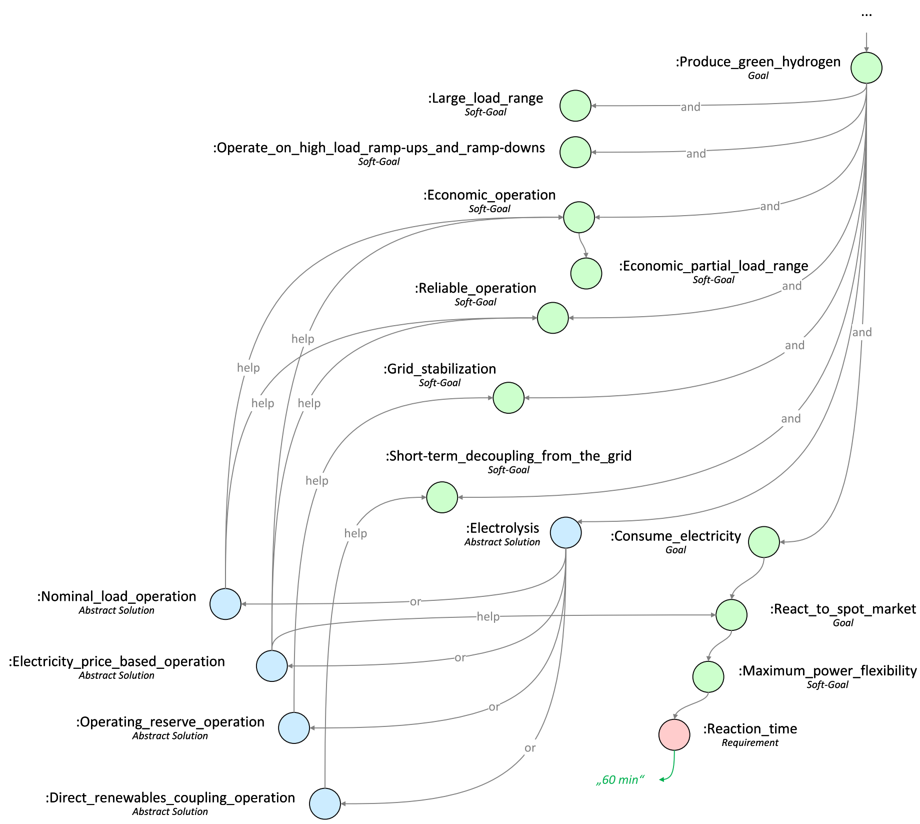

Fig. 11 Intentional Elemenets for Goal *Produce Green Hydrogen* in use case 3—Flexible Hydrogen-based Ammonia Production

of hydrogen. For the production of nitrogen the goals `:Produce_nitrogen`, `:Purify_nitrogen` and `:Store_nitrogen` are modeled as sub-goals with possible abstract solutions. The production of ammonia is modeled by means of the goals `:Synthese_green_ammonia`, `:Compress_ammonia` and `:Store_ammonia` and respective abstract solutions and requirements for each goal as depicted in Fig. 10.

The production of green hydrogen can be modeled similar to the other two use cases. In this use case, however, the focus is on electrolysis operating strategies. Figure 11 depicts the goal `:Produce_green_hydrogen` and all of its sub-goals etc.

The main abstract solution is (as before) `:Electrolysis`. This can be further decomposed into four different operation strategies. A `:Nominal_load_operation` is characterized by full load operation of the electrolyzers without flexible adjustment. The modules are either operated at full load or not at all. An `:Electricity_price_based_operation` takes advantage of fluctuating prices to flexibly operate the electrolyzers. Here, electricity is purchased at favorable times and electrolyzers are then operated as needed. The `:Operating_reserve_operation` is an operation strategy where load deviations are compensated by electrolyzers. Lastly, a `:Direct_renewables_coupling_operation` is considered, when the modular electrolysis plant is directly coupled to a photovoltaic system or wind farm. At least, one of the strategies is to be selected, but a combination is also possible.

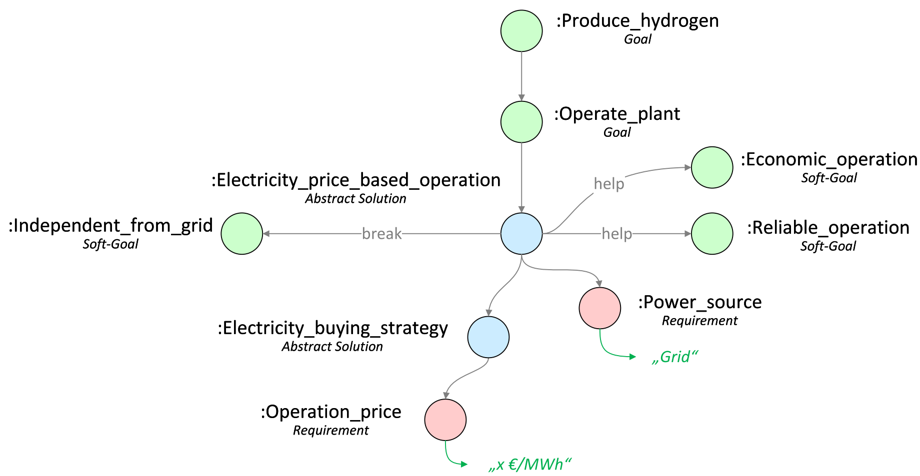

Fig. 12 Domain model for Abstract Solution *Electricity Price-based Operation* in use case 3—Flexible Hydrogen-based Ammonia Production

The various operation strategies are useful in different conditions. Similar to the electrolysis technologies softgoals are formulated by the plant operator. A `:Large_load_range` is desired as well to `:Operate_on_high_load_ramp-ups_and_ramp-downs`. This shows the significance of the absolute required mode of operation as well as the adaptation to faster changes of the load. Additionally, a requirement for `:Adding_and_removing_large_consumers` is placed on the latter softgoal. For the operation strategies especially four softgoals are important. On the one hand, a `:Economic_operation` is required with a `:Economic_partial_load_range`, while on the other hand a `:Reliable_operation` is needed. Furthermore, a plant operator can envisage `:Grid_stabilization` to be a main concern. A `:Short_term_decoupling_from_grid` should also be possible. The various softgoals are satisfied by different operation strategies, depending on their characteristic strengths.

Further softgoals for the production of green ammonia are to `:Minimize_process_feedback_loops` as well as to `:Increase_overall_flexibility`. This is decomposed into the softgoal `:Separate_hydrogen_and_ammonia_production`, whereas it's satisfaction is being influenced by the satisfaction of the goals `:Produce_green_hydrogen`, `:Store_green_hydrogen` and `:Synthese_green_ammonia`. A hydrogen storage between the process steps decouples production of hydrogen and ammonia.

Domain Model—Electricity Price-based Operation Strategy

Similar to the domain models for electrolysis technologies, domain models for operation strategies are set up. In this contribution, a closer analysis of the electricity price-based operation strategy is performed.

Figure 12 depicts the domain model for an operation strategy based on electricity prices. Such strategies aid in achieving the softgoal `:Economic_operation` as electricity can be bought at lower rates and thus cost optimization can be leveraged. The underlying premise here is that an electricity price-based operation with a appropriate `:Electricity_buying_strategy` results in more economical operation due

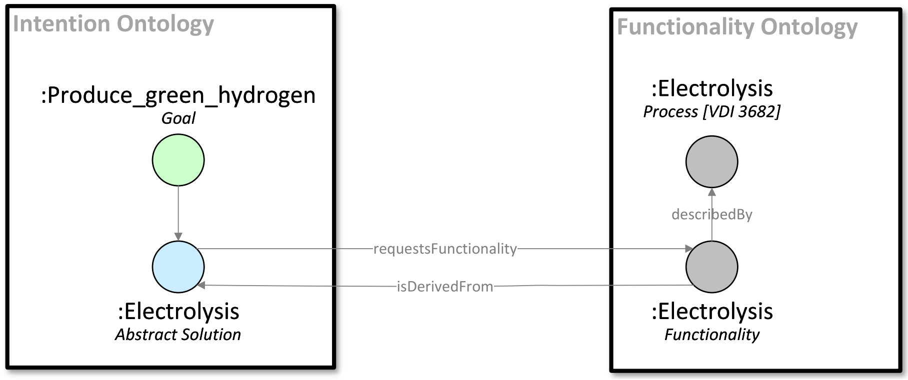

Fig. 13 Exemplary relation between intentions and functionalities

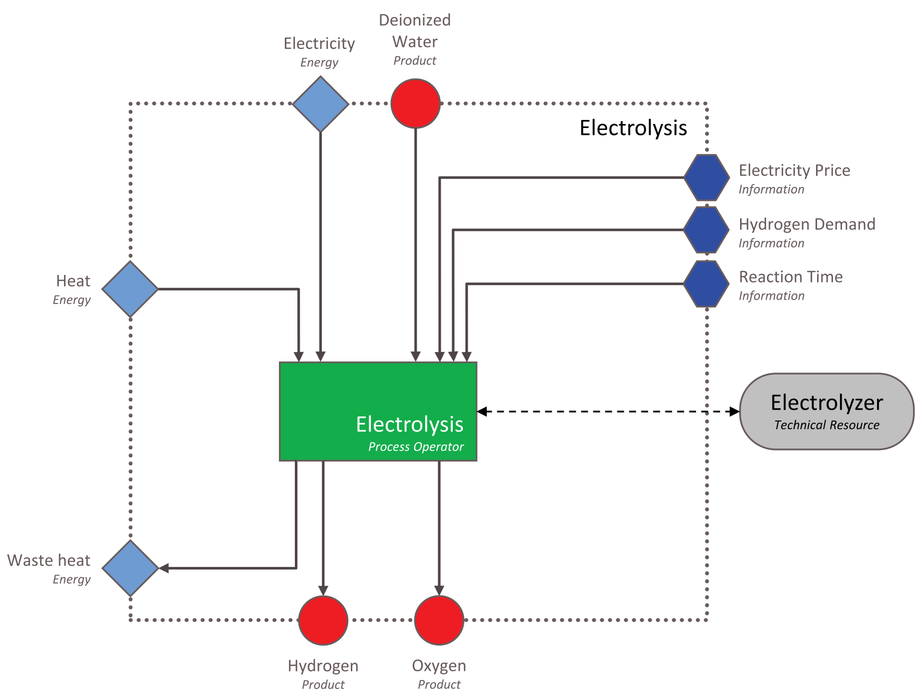

Fig. 14 Exemplary process describing a needed electrolysis functionality for use case 3—Flexible Hydrogen-based Ammonia Production

to energy prices compared to alternative operation strategies. Furthermore, a `:Reliable_operation` is possible, if electricity is bought early enough (as a safety buffer) and prices can be forecasted with a high accuracy. Independence from the electrical grid (`:Independent_from_grid`) is not possible, as this operation strategy requires active participation in the market and thus a connection to the grid.

Intention Operationalization

Once an intention model has been set up, possible abstract solutions have been added to all goals, and, given alternative solutions, a decision has been made in favor of a solution so that the reachability of all intentions in the intention model is ensured, functionalities can be set up that operationalize these intentions.

Focusing on the `:Electrolysis` abstract solutions, this can be further decomposed into individual abstract solutions tailored for various parts (i.e., modules) of a modular electrolysis plants. From these abstract solutions, functionalities can be derived. In order to model functionalities the *Functionality Ontology* based on the VDI 3682 guideline is used. Figure 13 illustrates an exemplary relation between goals, abstract solutions in the Intention Ontology and functionalities in the Functionality Ontology. The element `Electrolysis` can be described by a *Process* according to VDI 3682. In Fig. 14 the needed *Electrolysis* functionality as a process is depicted using a graphical model of the VDI 3682 elements. The elements can be related to intentional elements in the intention ontology.

In the last step of the operationalization of intentions, purposeful concepts are derived. A derivation of an automation concept depends on possible use cases as well as on the decisions regarding technologies and operations taken by plant operators. As mentioned before, the required functionalities of the modular electrolysis plant are central to the automation concept. A standard integration profile (as developed in the eModule project) should be able to cover a large part of these functionalities. It can be deduced that the previously mentioned intentions of plant operators as well as technologies and operating strategies should also be enabled by the standard integration profile. Yet a single electrolyzer will not cover all the required functionalities. For example, upstream and downstream process steps are also needed. In addition, the electrolyzers may come from different manufacturers with different hardware but comparable functionality. The automation concept to be derived must therefore be designed independently of the implementation.

The aforementioned functionalities need to be detailed out into more refined procedures, which serve as a basis for the development of automation services. The refined functionalities and services for electrolysis modules are out of scope of this paper and will be part of a future contribution.

Briefly, this section has demonstrated how an intention-based approach can be used to support the early engineering phases of modular electrolysis plants in various use cases. In the first use case (*Hydrogen Bus Refueling Station*), the focus was on interoperability in the collaboration between different engineering disciplines. The second use case (*Green Steel Production*) focused on modeling dependencies between intentional elements, as well as developing reusable domain models for different electrolysis technologies. The last use case (*Flexible Hydrogen-based Ammonia Production*) focused on the different operating strategies for a modular electrolysis plant. Furthermore, intentions are operationalized by functionalities and described by means of the formalized process description.

Discussion

The results of the evaluation are discussed regarding their interpretations, implications, and limitations.

The results of the evaluations on the three use cases show how a systematic support of the early engineering phases can be achieved. The existing and forecasted hydrogen demand underscores the urgency to quickly develop these electrolysis plants for the ramp-up of the hydrogen economy to succeed. Use case 1 (Hydrogen Bus Refueling Station) shows how different engineering disciplines can collectively define and relate their intentions within a shared model. This reveals conflicts and interrelationships which previously became apparent through mostly bilateral discussions in multiple iteration loops between engineering disciplines. This consolidated intention model supports *Model-based Systems Engineering* (MBSE) and also ontology-based systems engineering. In use case 2 (Green Steel Production), the potential of reusing domain models for electrolysis technologies in the early engineering phases was shown. These reusable domain models can thus be applied to other use cases as well. Lastly, use case 3 (Flexible Hydrogen-based Ammonia Production) revealed how functionalities can be derived as the first stage of operationalization based on the intentions. Such a derivation serves as a foundational step, paving the way for the conceptualization and implementation of a tailored automation concept.

The evaluation results yield several implications. One standout observation is the potential of early qualitative decisions that can be facilitated across multiple disciplines. The decisions to be made in these early engineering phases greatly influence the later design of a modular electrolysis plant. By basing decisions on semantically clear intentions and ensuring they are transparently traceable (rationale is apparent), potential pitfalls can be addressed more quickly, reducing unnecessary iterations. Despite the reusable domain models, the early engineering phases exhibit less standardization compared to the later phases. Thus, intentions for operating a modular electrolysis plant can be vary and differ depending on plant owners/operators. In contrast, subsequent implementation and integration steps can be more standardized. This underlines that varying goals can lead to different abstract solutions. The intention model serves as a tool to explicitly outline these variations. The approach presented here aligns with the effort to make the engineering of complex technical systems more systematic with the help of models. In this way, the early engineering phases can also be systematically supported.

While the approach presented here results in supporting the systematic development of modular electrolysis systems, it also exhibits some limitations. The generalizability of the approach still needs to be evaluated in detail. We need to ascertain if the domain models are versatile enough for diverse use cases and if they cover all necessary elements. Furthermore, several closely related use cases (e.g., bus refueling station 1 vs. bus refueling station 2) should be compared with each other. Another limitation was the methodological constraints imposed by the eModule project. Its primary aim is to offer a standard integration profile for the straightforward information technology integration of heterogeneous electrolyzers. The used approach leans heavily on ontologies and these are not yet widely used in industrial applications. As a result, a foundational understanding of ontologies is essential to harness the full potential of this approach. The situation is similar for tooling. Currently, some of the steps still have to be performed manually. The authors are currently developing a suitable tool to perform the steps of formulation, modeling and operationalization. If modular electrolysis plants are planned in the early engineering phases using the intention-based engineering approach, functional intentions can be modeled very well and also described semantically by domain ontologies, but non-functional intentions (such as softgoals) rather poorly. It is unclear how such non-functional intentions for modularity can be set up, how they are interdependent, and how they influence the subsequent modularity of the system. For this purpose, the authors explore an early description and analysis of modularity to bridge this gap.

By addressing these limitations, we believe our intention-based engineering approach can be further optimized and adapted to suit engineering of modular electrolysis plants.

Summary and outlook

Even though modular electrolysis plants are built using standardized electrolyzer modules, the specific use case for each plant varies, influencing its design and operation. Understanding these intentions requires a systematic, knowledge-driven approach. In this paper, we presented a systematic and knowledge-based approach for the early engineering phases focusing on Requirements Engineering and Conceptual Engineering of modular electrolysis plants. Here, an intention-based approach was used, in which intentions were formulated, modeled, and operationalized for three distinct use cases of modular electrolysis plants. Each evaluation had a unique aim: the first illustrated interdisciplinary intention modeling; the second showcased the reusability of electrolysis technology domain models; and the third linked intention modeling to functionality development.

Future, ongoing research will address the following three topics: First, building upon the functionalities discussed in "Evaluation" section, we aim to derive services for a standard integration profile tailored for modular electrolysis plants.. This will streamline the integration of diverse electrolysis modules into the plant, cutting down on the integration effort. Furthermore, the domain models will be further specified and evaluated in additional use cases. Herewith, a set of semantic domain models can be provided, supporting engineering of electrolysis plants. Lastly, a dedicated tool to support these early engineering phases will be developed to reduced manual input.

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