*Chemie Ingenieur Technik*

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# Accelerating the Roll-Out of Modular Plants: From Engineering and Approval to Operation of Energy-Efficient Modular Plants

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## ABSTRACT

Modular production concepts enable flexible process plants composed of standardized process equipment assemblies (PEAs). However, the practical implementation of modular plants across the entire engineering lifecycle, including planning, approval and operation, remains challenging. Within the ENPRO REUNION project, semantic PEA datasheets (SPEADs) were developed to enable manufacturer-independent and machine-readable module descriptions. The approach was validated through the commissioning of a modular pilot plant integrating modules from different manufacturers and through the development of a modular crystallization unit. In addition, energy monitoring via digital twins and a knowledge-graph-based hazard and operability study (HAZOP) analysis were implemented. The results demonstrate key technological building blocks for modular production while highlighting remaining challenges regarding semantic integration and regulatory approval.

## 1 | Introduction

The process industry is currently experiencing a fundamental paradigm shift towards more flexible and adaptable production systems. Modular production concepts enable process plants to be composed of standardized process equipment assemblies (PEAs) that can be rapidly deployed, replaced or reconfigured according to changing production demands [1]. Defined in guidelines such as VDI 2776-1 and VDI/VDE/NAMUR 2658, modular process plants promise significant advantages in terms of flexibility, scalability, and reduced time-to-market [2, 3]. Although these VDI guidelines provide an important framework for the design, automation, safety and approval of modular plants, further international initiatives are emerging with the shared objective of promoting modular production systems and the development of relevant standards and guidelines. In the United Kingdom, the Medicines and Healthcare products Regulatory Agency established a regulatory framework in 2025 for point-of-care and modular manufacturing to enable the production of highly personalized or short-lived medicinal products closer to the patient. This approach facilitates decentralized manufacturing at multiple sites, representing a shift from the traditionally

**Abbreviations:** AMPD, accelerated modular process development; COMPs, component-level indicators; DTBC, draft tube baffle crystallizer; eKPIs, energy key performance indicators; ELN, electronic lab notebook; EnMS, energy management systems; FAIR, findable, accessible, interoperable, reusable; FEAs, functional equipment assemblies; FGD, fine grain dissolution; HAZOP, hazard and operability study; HMIs, human–machine interfaces; MTP, module type package; PAT, process analytical technology; PEAs, process equipment assemblies; POL, process orchestration layer; RAPID, Rapid Advancement in Process Intensification Deployment; SEC, specific energy consumption; SPEAD, semantic PEA datasheet.

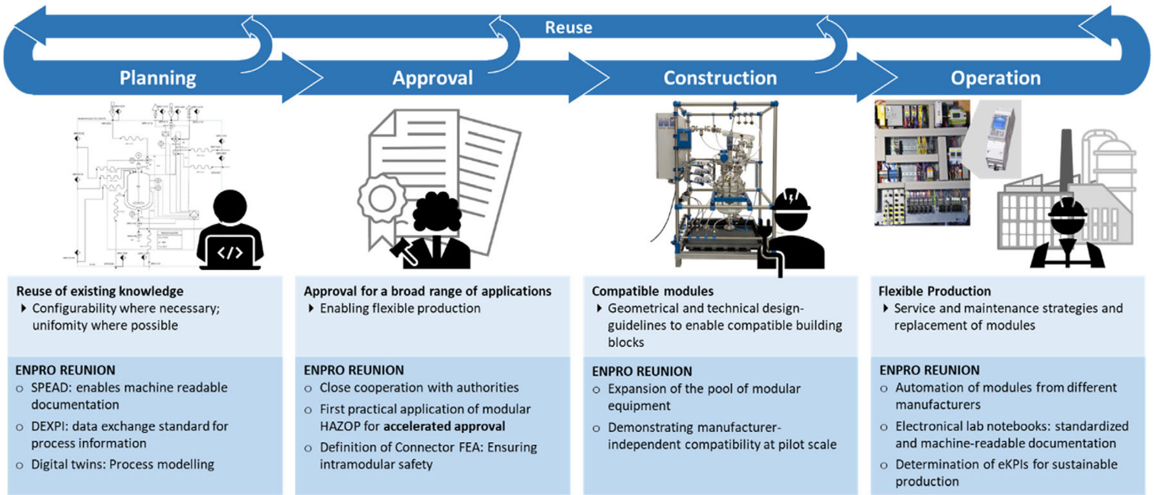


**FIGURE 1** | Procedural layers of modularization with approaches introduced in ENPRO REUNION, adapted from Dechema FG Modular Plants [11]. eKPIs, energy key performance indicators; HAZOP, hazard and operability study; SPEAD, semantic PEA datasheet.

centralized pharmaceutical production model [4]. In the United States, the RAPID Institute (Rapid Advancement in Process Intensification Deployment), established by the Department of Energy in 2016, promotes the development of modular and process-intensified systems for the chemical and pharmaceutical industries. In addition to research projects such as accelerated modular process development (AMPD), RAPID has produced publications addressing cost and risk assessment for modular plants, aiming to reduce uncertainties associated with their industrial implementation [5–7]. Due to climate change, the demand for hydrogen is increasing, which is why more efficient electrolyzer systems are being developed. This includes numbering-up using prefabricated modules [8, 9]. Although the module type package (MTP) was developed for the process industry, it is not necessarily limited to this domain. Bittorf et al. discuss this for the fields of maritime industry, biopharma industry and logistics as well as for hydrogen production [10].

Despite these advances, the implementation of modular plants across its entire engineering workflow, from planning and design through to approval and operation, has not yet been comprehensively demonstrated in practice. In particular, challenges remain regarding the availability of standardized and energy-efficient hardware modules, the provision of comprehensive and machine-readable module documentation, and the regulatory approval of modular systems. Figure 1 illustrates the steps leading to the realization of a modular plant.

The ENPRO REUNION project addresses the challenges involved in implementing modular plants by introducing semantically described modules that enable seamless data exchange throughout the lifecycle of modular plants. Structuring module information in a machine-readable form facilitates interoperability between engineering tools, approval processes and operational systems. Beyond the acceleration of planning and approval processes for modular plants, particular attention is given to the monitoring of energy key performance indicators (eKPIs). This enables improved transparency of energy performance and supports systematic process optimization. At the same time, the structured and interoperable data basis provides an important foundation for the development of digital twins of modular production systems.

## 2 | Demonstrators and Providing Process Data

The practical implementation of modular process steps can be illustrated and evaluated using demonstrators that allow modular equipment and automation concepts to be tested under realistic operating conditions while generating structured process data for further analysis and modelling. As demonstrating manufacturer-independent compatibility represents an important step towards the practical realization of modular production systems, within the ENPRO REUNION project, several PEAs from different manufactures were implemented and interconnected in a common modular plant in the technical centre at Merck KGaA, Darmstadt, Germany.

The core of the modular plant is a reactor PEA consisting of a continuously stirred tank reactor with a temperature-controllable volume of 10 L. As a model reaction system, the saponification of sodium hydroxide with ethyl acetate to sodium acetate and ethanol is carried out. The main equipment components of the reactor PEA were manufactured by De Dietrich Process Systems GmbH, Mainz, Germany (De Dietrich). The instrumentation comprises level measurement sensors supplied by KROHNE Messtechnik GmbH, Duisburg, Germany (KROHNE), as well as a conductivity sensor, which is applied as a process analytical technology (PAT) tool to monitor the reaction conversion [12]. The reactor PEA is shown in Figure 2.

The reactor PEA is connected to three dosing PEAs. Each dosing PEA consists of a pump and controllable valves and is supplemented by a storage vessel. Two modules supply the individual educt streams to the reactor, whereas the third module transfers the product stream from the reactor to a storage tank. The individual dosing PEAs were developed by HNP Mikrosysteme GmbH, Schwerin, Germany; NETZSCH Pumpen und Systeme GmbH, Waldkraiburg, Germany; and PFAUDLER NORMAG systems GmbH, Hofheim am Taunus, Germany. Automation


**FIGURE 2** | Pilot scale reactor PEA. Joint development with De Dietrich, KROHNE and HiTec Zang.

and orchestration of the modules were enabled through MTP files, allowing their integration into a process orchestration layer (POL) with reduced engineering effort [2]. In accordance with the VDI guidelines, each PEA is decentralized automated. The control logic of the reactor PEA is implemented in three LabBoxes and a control cabinet supplied by HiTec Zang GmbH, Herzogenrath, Germany (HiTec Zang) together with a dedicated safety automation system (safety PLC). The functionalities of the PEAs are defined as services. For the reactor module, a storage service was developed that enables filling of the reactor for batch operation or start-up of continuous processes, as well as maintaining a constant liquid level during continuous operation. In addition, a pressure swing inertization service is implemented using controllable valves at the reactor head and a pressure sensor, in combination with utilities such as vacuum and inert gas supplied via the control cabinet. For the implementation of these services in the Zenon 15 POL, Copa-Data, Salzburg, and Austria, MTP files were developed for each PEA with support from Semodia GmbH, Radebeul, Germany. The resulting modular plant, developed within the ENPRO REUNION project, demonstrates how standardized module interfaces enable flexible combinations of PEAs and facilitate the rapid implementation of modular process configurations. For industrial applications, this demonstrates that interconnection across different manufacturers is feasible. The definition of MTP and their integration into the Zenon 15 POL shows that modules can be integrated into the process control system quickly and with reduced effort for operators. This supports the objective of achieving more flexible production. Within this context, the pool of available PEAs was further expanded by the development of scaled-down separation units, enabling modular downstream processing.

A key focus is on the implementation of cooling and evaporative crystallization in a modular draft tube baffle crystallizer (DTBC). The specific hydrodynamic behaviour in this crystallizer type, combined with the dissolution of smaller crystals in the fine grain dissolution (FGD), promotes the formation of a narrow particle size distribution in the product, which has led to a widespread industrial application of DTBC [13]. The modular crystallization setup is based on a lab-scale DTBC with an internal volume of 2.1 L. Depending on the targeted crystallization process, specific peripheral equipment is required, which can be realized through the exchange of functional equipment assemblies (FEAs). For the operation of evaporation crystallization, an extended FGD configuration equipped with heat exchangers positioned approximately 1.4 m below the DTBC is used in order to prevent evaporation of the suspension within the heat exchangers. In addition, a vacuum PEA is integrated, enabling the adjustment of reduced pressure conditions to lower the boiling temperature of the system. Due to the applied vacuum, a gate system is required for product removal, allowing semi-continuous product removal under reduced pressure conditions at laboratory scale [14]. Independent of the type of the crystallization process, thermostats are used for temperature control of the system. As these units typically contain their own control logic, they are defined as temperature PEAs. The feed of mother liquor is supplied via dosing modules. Both batch and continuous operation of cooling and evaporative crystallization are automated through dedicated services. In combination with the exchangeable FEAs, this enables the rapid realization of different crystallization processes within the same apparatus. For the monitoring of the crystallization process, an open-source AI–based image analysis system [15] and an inline impedance measurement, enabling the relative determination of the solid fraction in suspension as well as the solute concentration, are used.

Another unit operation, implemented as a modular system, is a Karr-type extraction column with a diameter of DN15. This small laboratory-scale column is only sparsely described in the literature for Karr-type columns and is therefore of particular interest for testing the applicability of liquid–liquid extraction as a separation process, for example, for newly developed chemicals. Compared to other extraction columns, such as Kühni-type columns, Karr-type columns offer the advantage of operating at higher loadings [16]. The setup consists of two dosing PEAs, an extraction PEA, and a temperature PEA. The extraction PEA contains the column, an eccentric drive for the movement of the internals, a temperature sensor, an outlet pump and a level sensor. Because the column is too small to accommodate conventional level sensors, an optical sensor in the form of a Raspberry Pi camera is used for the determination of the liquid level. The modular set-up of the lab-scale DTBC and the Karr-type extraction column are shown in Figure 3.

For the modularization of the lab-scale equipment, the functionalities of the modules were defined as services and integrated into the laboratory automation software LabVision from HiTec Zang. Communication between the modules and LabVision is realized via the OPC UA communication standard. For this purpose, predefined OPC UA function blocks were implemented in LabVision, where the corresponding data points to the decentralized logic of the modules are interconnected within a shared address space. Through this approach, the modules can be operated in the same manner as other device components within LabVision. Consequently, modularized functional units can be integrated

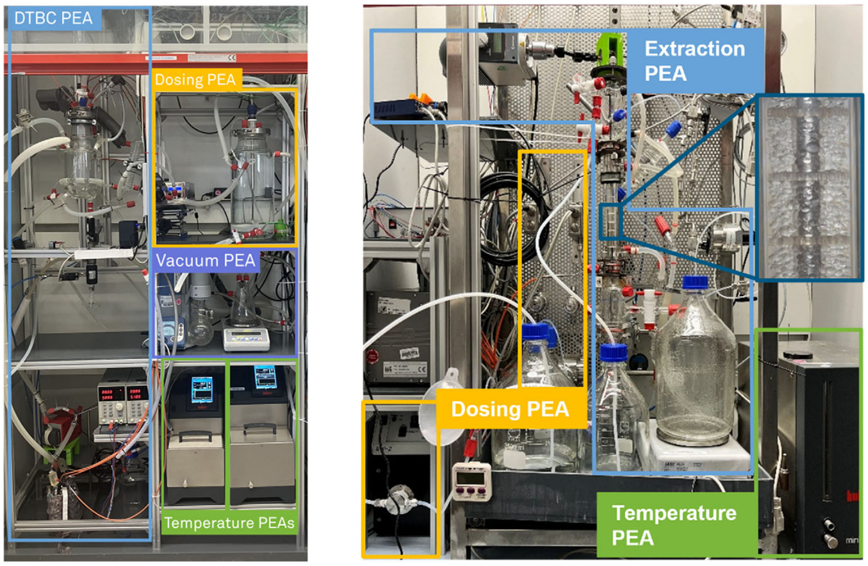


**FIGURE 3** | Left: modular DTBC with peripheral equipment for evaporative crystallization and highlighted PEAs; right: DN15 Karr-type extraction column set-up in the laboratory. The complete arrangement consists of two dosing PEAs, an extraction PEA, and a temperature PEA. DTBC, draft tube baffle crystallizer; PEAs, process equipment assemblies.

into existing laboratory infrastructures while maintaining compatibility with conventionally automated laboratory components. In this way, potential barriers to the implementation of modular systems are reduced, as the entire production line does not need to be immediately converted into a fully modular concept.

The generated process data are systematically recorded using electronic lab notebooks (ELNs) in order to ensure standardized and machine-readable documentation. The collected data are further utilized for modelling and simulation purposes. For the exchange of process information, DEXPI is used as a neutral data format. DEXPI provides a standardized XML–based representation of process flow diagrams and allows the visualization of modules via digital P&ID diagrams. The format enables interoperability across different CAD and CAE software tools, contains structured component information including design and operating parameters and supports modular plant engineering through a uniform description of equipment and interfaces [17]. This structured representation also facilitates compatibility and consistency checks between modules and process parameters and thereby supports the integration and analysis of modular process systems.

## 3 | Data Integration

The documentation of PEAs poses a significant information management challenge. Guidelines such as VDI 2776-2 specify minimum requirements for PEA documentation, including operational parameters, interface definitions and service descriptions, but neither prescribe a concrete representation format nor enforce terminological consistency [18]. The result is documentation that, while possibly complete in content, lacks the machine-readability and unambiguity required for automated processing across the PEA lifecycle. Furthermore, the wide variety of types and instances for each PEA class require documentation specific to the given PEA configuration while potentially sharing documentation for their class specification. This results in either large amounts of duplicated or disparate information, increasing the effort needed for extracting data when necessary.

To address this, the semantic PEA datasheet (SPEAD), developed as part of the ENPRO REUNION project, represents PEA documentation as a machine-readable knowledge graph, adhering to the FAIR principles (findable, accessible, interoperable, reusable) [19, 20]. SPEAD integrates established standards, particularly the DEXPI 2.0 data model for piping and instrumentation diagrams and the VDI 2776 guidelines, and enforces data quality through constraint-based validation. For example, physical properties are represented using standardized quantity and unit vocabularies, ensuring that every value is associated with an unambiguous quantity kind and a compatible unit, regardless of the internal naming conventions used by individual vendors or operators. Furthermore, it utilizes the metadata structure of the VDI 2770 guideline [21] to qualify tracked data with provenance, ensuring that the information is traceable to its source, allowing SPEAD to become a single point of truth. Figure 4 shows how different data sources are aggregated into an SPEAD.

The design of SPEAD is driven by competency questions derived from realistic engineering use cases. Consider the following scenario: A process engineer is tasked with selecting a replacement reactor module from a pool of available PEAs. To assess compatibility with the existing plant infrastructure, they need to know the maximum operating temperature each potential PEA can safely handle. In a conventional documentation landscape, answering this question may require manually consulting heterogeneous datasheets from different vendors, each using different terminology and formatting. In SPEAD, the operating temperature of a PEA is represented as a structured property with explicit minimum and maximum values, each linked to a standardized definition of temperature. This means that regardless of whether a vendor labels the property ‘maximum process temperature’ or ‘upper temperature limit’, both descriptions resolve to the

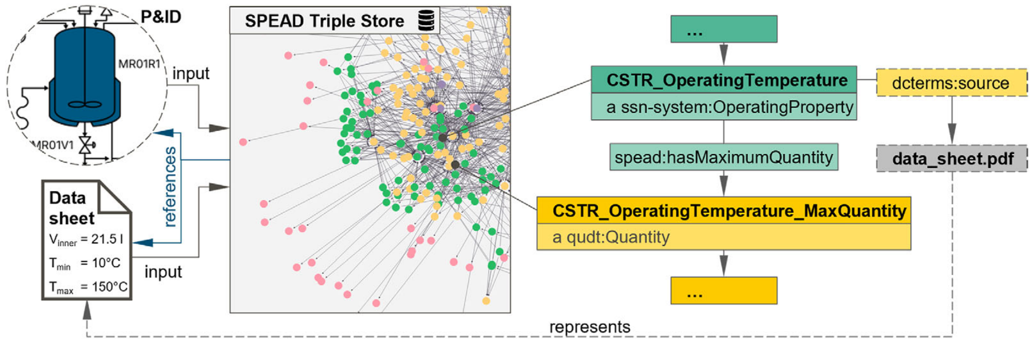


**FIGURE 4** | Data from P&IDs and data sheets are represented as semantic triples in an SPEAD, which are referenced back to their original source. SPEAD, semantic PEA datasheet.

same underlying concept, and the values can be retrieved and compared programmatically across the entire pool of candidate modules.

This design principle extends across the full scope of PEA documentation. The hierarchical structure of a PEA, comprising FEAs and individual components, is explicitly captured, allowing queries to span multiple levels of the module. This enables SPEAD to become a source for static information (e.g., vessel diameters, stirrer diameter, stirrer type, …), which are necessary for engineering tasks such as process simulations or eKPI calculation, which is described in the following section.

The machine-readable nature of SPEAD also positions it as a natural data source for AI-assisted engineering workflows. Large language models and retrieval-augmented generation (RAG) systems, for instance, require structured, unambiguous input to reliably answer domain-specific queries. Because SPEAD enforces terminological consistency and links every property to a standardized definition, it can serve as a well-formed knowledge base for such systems, reducing the risk of misinterpretation that arises when AI tools are applied to unstructured vendor documentation. A process engineer could, for example, query a conversational AI assistant about the compatibility of available PEAs with a given process specification, with the system drawing directly on SPEAD to provide traceable, verifiable answers rather than relying on brittle text extraction from heterogeneous documents. As AI tooling in engineering environments matures, the availability of FAIR-compliant, semantically rich documentation such as SPEAD will be a prerequisite for reliable and auditable AI integration.

## 4 | Energy Efficiency and Transparency

Energy efficiency is a critical objective in modular plants, requiring systematic acquisition, structuring and utilization of energy-related data that must also be collected and exchanged. The measurement data from smart meters and process sensors (e.g., flow, temperature and power measurements) are collected and systematically structured within ELNs. These data streams are linked to the energy management systems (EnMS), where eKPIs are calculated and aggregated. These eKPIs are orchestrated to the POL via a communication protocol.

Within the EnMS, eKPIs are calculated with respect to defined functional units, such as product output, recipe execution or specific services. A key indicator is the specific energy consumption (SEC) [22], which quantifies the total energy demand per functional unit. Electrical energy consumption is directly measured using energy meters (e.g., power consumption of mixers or pumps), whereas thermal energy demand is estimated using model-based approaches that incorporate process conditions and system configurations. Both contributions are combined to obtain a comprehensive representation of energy usage.

Following calculation, eKPIs are aggregated hierarchically across different levels of the modular plant. At the lowest level, component-level indicators (COMPs) are consolidated to derive eKPIs at the PEA level, providing detailed and actionable insights into localized performance. These indicators enable the identification of deviations and support targeted optimization measures. Subsequently, PEA-level eKPIs are aggregated at the POL, yielding a plant-wide perspective on energy performance. This hierarchical aggregation approach follows established resource efficiency indicator methodologies [23], ensuring both granularity and scalability in performance assessment.

The orchestration of eKPIs refers to their coordinated utilization within the system to enable monitoring. These aggregated indicators are then communicated to the POL via standardized communication protocols (e.g., OPC UA), where they are visualized and interpreted within process human–machine interfaces (HMIs). Figure 5 shows an EnMS architecture illustrating data acquisition, eKPI calculation, aggregation and orchestration across system layers.

Such integrated approach enhances energy transparency and enables continuous optimization of energy performance across the modular plant. In addition, equipment-specific information from systems such as SPEAD is incorporated to provide contextual understanding of energy data, enabling more accurate interpretation and improved decision support.

## 5 | Approval of Modules

In addition to cross-manufacturer compatibility and cost advantages, approval is essential for the commissioning of a modular plant. Conventional plants in the process industry are approved for a specified process which has to ensure safe operating of this

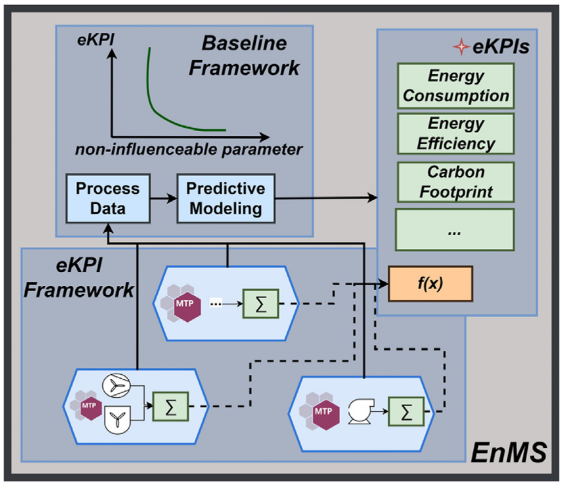


**FIGURE 5** | Architecture of an energy management system showing data acquisition, eKPI calculation, aggregation, and orchestration across system layers [24]. eKPIs, energy key performance indicators; EnMS, energy management systems; MTP, module type package.

process. Although a multipurpose plant is able to cover a range of products, it is still necessary to approve each possible process with its corresponding substances by the authorities. Modular plants are subjected to the same legal requirements for safe plant operation as those laid down by the German Federal Immission Control Act (BImSchG) [25]. However, the high variability of possible plant configurations in modular systems creates additional challenges for safety assessment within approval procedures, as different combinations of modules may lead to varying process interactions and risk scenarios.

To address these challenges, the concept of a modular hazard and operability study (HAZOP), according to Klose [26], was applied for systematic hazard identification and evaluation. The modular approach enables the reuse of HAZOP analyses across different plant configurations and can significantly reduce documentation efforts in approval procedures. For this purpose, modules and processes are analysed separately. The equipment-specific HAZOP is independent of the process and can therefore be reused for different processes. It focuses primarily on the intramodular safety of a module under varying process parameters. In contrast, the process-specific HAZOP evaluates both the intra- and intermodular safety of the modules for a specific process. A reference process is used that is intended to cover a broad range of potential hazards. This approach reduces the effort required for the approval of future processes, as processes with lower safety complexity that fall within the scope of this reference process do not require a separate, full safety analysis. For conducting the modular HAZOP, a standardized table template with predefined dropdown fields was used to ensure consistent documentation of deviations, causes and consequences as interconnected HAZOP elements (see Figure 6).

After the separate execution of the equipment-specific and process-specific HAZOP analyses, the results are merged into a single HAZOP corresponding to a conventional study. For this step, a Python script was developed that identifies matching HAZOP cases in the modular HAZOP datasets. During this process, module interfaces are automatically mapped, enabling the HAZOP analyses of separate modules to be merged into an integrated representation of the overall process. This approach allows interactions between modules to be transparently captured and supports a holistic analysis of process safety. In industrial application, this reduces the effort required for safety assessments, as existing HAZOP analyses can be automatically combined for a new process or a new configuration of the process.

For further analysis, the results were visualized in the form of a knowledge graph; see Figure 7. In this graph, the edges represent the individual HAZOP cases. The connected nodes of the edges depict either a deviation, a cause or a consequence.

This representation highlights causal relationships between modules that are difficult to identify in conventional tabular HAZOP documentation, for example, when deviations of a critical process parameter may originate from different causes while simultaneously leading to multiple consequences. The use of structured and semantic data in this context enables a more comprehensive understanding of complex system interactions and facilitates the identification of potential risk pathways, thereby enhancing the quality and explanatory power of safety assessments for modular plants.

## 6 | Conclusion

This work demonstrates significant progress toward the implementation of modular production concepts in the process industry within the REUNION project. A central outcome is the development of the SPEAD, which enables a manufacturer-independent and machine-readable description of PEAs. By representing module properties such as operating ranges, services and safety information in a semantic knowledge graph, SPEAD facilitates the automated matching and integration of modules from different manufacturers.

The practical feasibility of this approach was demonstrated through the commissioning of a modular pilot plant in which dosing modules from different manufacturers were successfully combined with a reactor module under industrial conditions. In addition, the development of a modular crystallizer capable of both cooling and evaporation crystallization highlights the potential of modular concepts for implementing flexible downstream processing steps. Complementary work addressed energy transparency and plant configuration, including the implementation of eKPIs via a digital twin for real-time monitoring. Moreover, a simulation of a modular approval procedure was conducted based on a simple substance system and subsequently validated using a more complex reference process. The implementation of a knowledge graph for the HAZOP analysis of this reference process further improved transparency regarding interconnected hazard scenarios within the system.

The results of the REUNION project demonstrate the technological maturity of several key building blocks required for modular production plants. However, transferring these developments into industrial practice still requires overcoming a number of technical and regulatory challenges. A major limitation is the lack of a consistent semantic information layer that both links all

| | Deviation | | | Cause | | | Consequence | | | | Risk classification (without safeguards) | | | | Safeguard | | Safeguard consequences | | | Risk classification (with safeguards) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| HAZOP-Case | HAZOP-Node | guideword | parameter | HAZOP-Node | guideword | parameter | HAZOP-Node | guideword | parameter | Description | Severity | Probability | Possibility of avoiding | Frequency of presence | HAZOP-Node | Description | HAZOP-Node | guidword | parameter | Severity | Probability | Possibility of avoiding | Frequency of presence |
| | Dosing-modul | no | flow | | | | | | | | | | | | | | | | | | | | |
| | | | temperature | | | | | | | | | | | | | | | | | | | | |
| | | | pressure | | | | | | | | | | | | | | | | | | | | |
| | | | flow | | | | | | | | | | | | | | | | | | | | |
| | | | level | | | | | | | | | | | | | | | | | | | | |

**FIGURE 6** | Standardized table template to list safety-relevant cases by predefined guidewords and parameters. HAZOP, hazard and operability study.

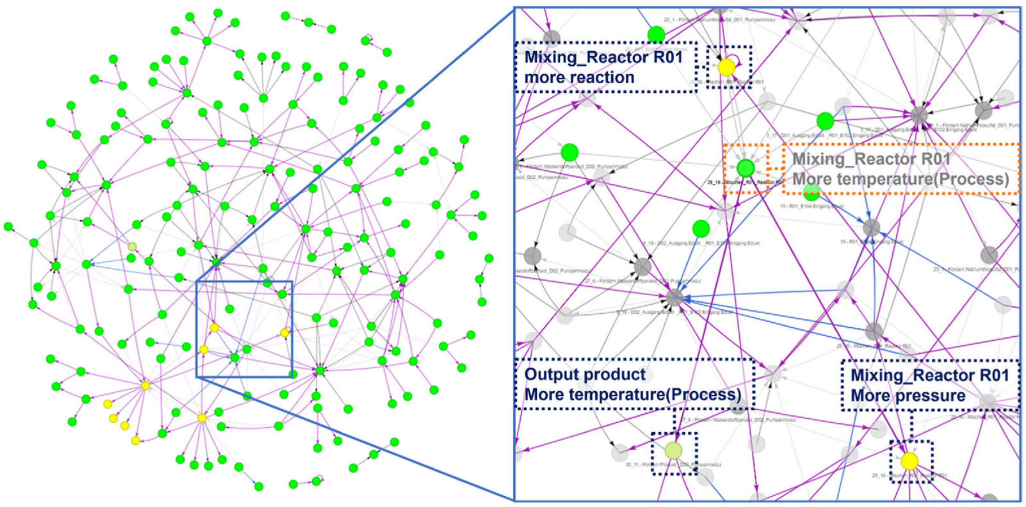


**FIGURE 7** | Modular HAZOP results showing interrelations between HAZOP elements. Edges and nodes are colour-coded according to security level, accessibility and their relationship to the safeguards. Green nodes: no instrumented safety function required. Yellow nodes: SIL 1. Purple arrows: reachable paths. Black: non-reachable. Grey: safeguarded cases. Blue: safeguard consequences.

phases of the plant lifecycle and enables the integration of multiple modules into coherent plant-wide representations, including their connection to P&IDs and infrastructure descriptions. In addition, user-friendly tools are required to reduce the complexity of semantic module descriptions and make them accessible to different stakeholders. Another important aspect concerns safety and regulatory integration. Intra- and intermodular safety concepts, in combination with plant infrastructure, have not yet been fully addressed within approval procedures. In particular, topics such as explosion protection and safety instrumented systems have so far mainly been explored conceptually and still require practical implementation and validation.


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### Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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