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Modules in process industry — A life cycle definition

Lukas Hohmann[b,1], Katrin Kössl[a,1], Norbert Kockmann[b], Gerhard Schembecker[a], Christian Bramsiepe[a,*]

[a] TU Dortmund University, Department of Biochemical and Chemical Engineering (BCI), Laboratory of Plant and Process Design, Emil-Figge Straße 70, D-44227 Dortmund, Germany
[b] TU Dortmund University, Department of Biochemical and Chemical Engineering (BCI), Laboratory of Equipment Design, Emil-Figge Straße 68, D-44227 Dortmund, Germany

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ABSTRACT

The chemical and biochemical industry has to face the challenges of globalization, short product cycle times and volatile markets. Therefore, the lead time of development projects has to be shortened. Modules and module-based plant design are widely discussed to enable shorter time-to-market by reuse of engineering effort and standardization. In this paper general requirements on modules in process engineering and modules for particular applications in the chemical and biochemical industry are reviewed. This includes the impact of modules on the planning process and examples of realized modular equipment concepts. Based on this, a general terminology definition of 'modules' and of specific module types for the process industry is presented, whereas modules on various 'aggregation levels' are accounted. A 'block representation frame' stores information and tracks information fluxes along the whole process and plant life cycle and on different 'realization levels' from laboratory studies over miniplant validation to production plant design and operation.

1. Introduction

As a consequence of globalization, shorter time-to-market and more flexible production concepts are required in the chemical and biochemical process industry, hereinafter referred to as 'process industry', to stay competitive [1,2]. Utilizing 'modules' for plant design in the process industry has been discussed in literature to decrease the planning time due to reduced engineering effort [3,4]. Lier et al., Seifert et al. and Bramsiepe et al. have shown economically advantageous scenarios for chemical production in modular plants [5–7]. With modular plants an adaption of the production capacity to changing and less predictable markets is possible [2,8–10].

Nevertheless, a generally accepted module definition for the process industry still does not exist. This work aims at setting such a definition for the process industry including planning, construction, and operation, as well as information handling. First, a review and classification is given for module definitions already being stated in literature. Afterwards, concepts for modularization, module-based plant design and information handling are presented with respect to all phases of the life cycle and to all contributing disciplines of a process and production plant in the process industry.

1.1. Modules in the field of engineering

Generally in technical literature and particular in engineering science several definitions for modules exist. Each of these definitions states important requirements that can be used for developing a module definition for the process industry.

Abbreviations: BD, Block diagram with additional information; CAPD, Computer-aided plant design; CIP, Cleaning in place; DIN, German norm; EN, European norm; HMI, Human machine interface; HPLC, High performance liquid chromatography; I&E, Instrumentation and control engineering; ISO, International norm; MCSP, Modular and continuously operated small-scale plant; MIT, Massachusetts Institute of Technology; MEAR, Modular engineering and automation research; MRO, Maintenance repair and operation; NAMUR, User Association of Automation Technology in Process Industries; NPV, Net present value; P, Plant; PAT, Process analytics technology; PEA, Process equipment assembly; PEC, Process equipment container; PFD, Process flow diagram; P&ID, Piping and instrumentation diagram; PS, Plant section; UO, Unit operation.

* Corresponding author.
E-mail addresses: lukas.hohmann@bci.tu-dortmund.de (L. Hohmann), katrin.koessl@bci.tu-dortmund.de (K. Kössl), norbert.kockmann@bci.tu-dortmund.de (N. Kockmann), gerhard.schembecker@bci.tu-dortmund.de (G. Schembecker), christian.bramsiepe@bci.tu-dortmund.de (C. Bramsiepe).

[1] These authors contributed equally to this work.

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A building block for construction such as a LEGO™ brick is often applied as an illustration for standardized interfaces, which are essential for the combination of multiple modules to a larger modular assembly. However, according to Wiendahl et al., a module combines the aspects of providing standardized interfaces with a self-contained technical function [11]. Therefore, the function of a modular assembly of multiple modules results from the combination of the modules' functions. A module definition for so-called 'factory modules' in the metal processing industry is given by Wiendahl et al. [11]: "A module is a technically and organizationally limited area of the plant that fulfills a defined task in terms of company-internal or −external saleable goods and services. It is a standardized and self-functioning unit. As an autonomous operating element it should be able to be tested beforehand. All necessary flows of information, communication, material, energy, and staff are connected to a module via defined interfaces. The module has a defined degree of adaptability. Within planning, a module is reusable."

Modules are common in further industrial branches. In the automotive industry a car's underbody is constructed using a front, floor and rear module [12]. In the electronic industry multiple modular concepts exist, such as a modular radio [13] or the design of various electronic products based on modules [14]. In the civil engineering sector the application of preassembled parts of houses, so-called building modules, are common to accelerate the construction [15].

1.2. Module terminology for the process industry

Based on the general considerations and examples from other industrial branches, a general module terminology for the process industry is proposed: 'Modularization' refers to a procedure, where a complex setup is defined by modules. A 'module' is regarded as an unmodifiable element during planning and realization of assemblies with modules. An assembly consisting of two or more modules is then regarded as 'modular'. A module represents or provides a dedicated function for the process and is reusable during planning or realization of modular plants in the process industry. Therefore, planning elements, such as a process flow diagram (PFD), a piping and instrumentation diagram (P&ID), a 3D layout, and realized equipment can be considered as modules. 'Module-based plant design' is regarded as the selection and arrangement of multiple modules to a process plant, which transforms raw materials to products.

1.3. Requirements on a concept for modularization, module-based plant design and information handling in the process industry

As pointed out in the introduction, the utilization of modules in the process industry aims at decreasing time-to-market by shortening project times. This can be achieved due to the reusability of modules [11,16], enabling the reduction of engineering effort. In contrast to this, conventional process engineering often results in individual solutions. The documentation of such solutions does not allow for predicting whether existing designs can be reused in another project with different requirements. Existing designs are characterized by type of equipment, piping, instrumentation, material, dimensions, simulation models, function descriptions and experience reports if those are available. The project requirements are characterized by process parameters such as capacity, temperature, pressure, physical/chemical properties, e.g. density, heat capacity, process kinetics, and further constraints, e.g. given by legal regulations, and the site location.

A plant design approach using modules which makes engineering knowledge available for reuse needs new concepts. Equipment modules for a certain functionality have to be characterized with mathematical models in order to describe the equipment performance under given process conditions and thus its capability. This allows for a comparison between process requirements and equipment capabilities, the so-called 'matching' and thus for a selection and configuration of suitable equipment. For proper matching, information on project requirements and equipment capabilities has to be structured and made available for comparison. Thus, modularization in the process industry has to cover both planning procedures and equipment design by means of suitable data models and information technologies [4].

First concepts have been developed e.g. at INVITE GmbH research center [4,17,18] for flow reactors to match existing designs with requirements of new projects. Similar approaches for heat exchangers [19] and coiled tubular devices for single and multiphase processes [20,21] are under current investigation. Due to the fact that these concepts are presently not available in full coverage for required applications in the process industry, reasonable reuse of engineering achievements is not possible, yet.

Modularization and utilization of modules in module-based plant design should not be limited to product classes, production capacities or to a process mode, e.g. batch or continuous. It requires applicability from first laboratory trials during product development up to construction, operation and optimization of a production plant. This does not necessarily mean that equipment modules being chosen for small-scale studies in process development have to be of the same equipment type being applied later in production. Instead, scale-up concepts are required to perform the transformation from small-scale to production scale.

To maximize the benefit of modularization, all knowledge generating steps throughout planning and project realization need be covered by a structured data and information handling, making engineering knowledge reusable and information fluxes traceable throughout the life cycle.

Information handling should cover the specific views of all parties being involved in the development process and production life cycle, see Fig. 1. Beside the chemical product development, technical development of the process, and plant design managerial aspects such as market analysis, business and product strategy, or regulatory affairs have to be considered, as these aspects set important presettings and requirements for a development and investment project.

2. State of the art – modularization approaches in the process industry

Modularization approaches in the process industry started at the end of the last century. In 1980 Stephanopoulos et al. designed modular heat exchanger networks [23]. Their concept was based on shell-and tube heat exchanger modules with discretely defined exchange areas, as tube number and diameter were fixed and the tube length and the number of passes was varied in optimization to identify suitable modules. Afterwards, parallel and series arrangements of the optimal modules were investigated to setup the heat exchanger network.

For plant construction, transportable parts of the plant have been defined as modules. In 1985 Mecklenburgh [24] pointed out the key advantage of these module types to be the opportunity to manufacture plant sections under controlled conditions. This is especially reasonable for plants that shall be erected in remote areas, e.g. with difficult climate, in locations with limited local construction work force or in countries with difficult labor conditions. In 1990 Hesler presented small skid-mounted modules, such as reactor modules and a saline water conversion plant as an example for large modules on a plant section level [25]. Further large-scale process section based plants are a refinery and a methane plant, which were presented by Glaser et al. and built by C-E Lummus [26].

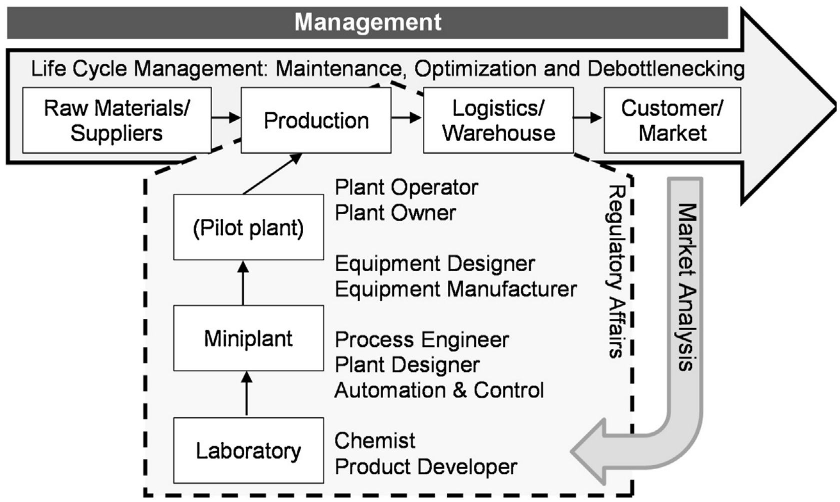

Fig. 1. Two value generation chains of process development and production for life cycle analysis of chemicals with involved professions in the chemical industry, adapted from [22].

Also, pilot plants have been built using modules such as a polypropylene unit built by Aristech Chemical Corporation that was introduced by Shelley [27] in 1990. These early examples of modular plants mainly aim at simplifying the plant construction in order to decrease project time and cost. As a result of the design process, detailed documentation of the engineering knowledge is required to build these plants. Reusing the modules and the related documentation in different projects seems not to be major goal, yet.

The first attempt to structure different modularization approaches in the process industry was done by Zeppenfeld and Kussi in 2009, who classified modules in process engineering into the following three general categories [28]:

1) Level of uncertainty: planning module, construction module, mounting module, transport module
2) Scale: laboratory module, miniplant module, pilot plant module, small production module, large production module
3) Function: piping assembly, equipment assembly, process assembly, package unit

Structuring modules into these three categories might be helpful, but most modules fit into two or three categories at the same time [3,29].

In the first category being introduced by Zeppenfeld and Kussi [28] the level of uncertainty is varied from planning to transport modules. This changes the focus of the module's information content from equipment performance to equipment dimensions. Thus a consistent module understanding throughout the whole life cycle cannot be guaranteed.

The second category being introduced by Zeppenfeld and Kussi [28] compares capacities provided by modules on different scales. Nevertheless, without limiting the operation mode or the field of application, mapping of scale and capacity is not possible, e.g. capacity of production plants differs a lot from bulk to fine chemicals and pharmaceuticals. Therefore, this category for module structuring is not applicable.

In the third category being introduced by Zeppenfeld and Kussi [28] modules are classified according to their function. A piping assembly executes the function of fluid transportation. However, this function is not adding value on the way from raw materials to products. In contrast to this, an equipment assembly adds value as a process step or unit operation. A process assembly represents the whole process or a process section and consists of multiple equipment assemblies. Adding piping or automation completes the process assembly to an operable part of the plan which can be regarded as a package unit. The classification by a value adding functionality does not violate any of the requirements stated in 1.3

Table 1
Plant and process hierarchical structures – 'aggregation level'.

DIN EN ISO 10628 [31]		Modular Process and Plant hierarchy by Hady [34] reflecting Rauch [32] and Lüneburg and Zahn [33]		Modular Process and Plant hierarchy according to Uzuner [35]	
Process Hierarchy	Plant Hierarchy	Process Hierarchy	Plant Hierarchy	Process Hierarchy	Plant Hierarchy
Process	Production Plant	Process	Plant	Process	Plant Module
Process Step	Plant Section	Process Step Unit Operation	Plant Section Module Group Plant Section Module	Unit Operation	Plant Section Module
Unit Operation	Plant Section Process Equipment	Unit Function Element of Unit Function	Building Group Module Equipment	Unit Function Element of Unit Function	Equipment-Module Building Group or Part Module
–	–	–	–	Sub-Element of Unit Function	Sub-Building Group or Building Group for Part Module

on modules in the process industry. Thus, function is a reasonable attribute to describe modules in the process industry.

To meet the requirements on modules outlined in 1.3, modules have to cover all phases of the life cycle. Such a definition has already been introduced in the position paper 'Die 50 %-Idee' ('The 50 %-Idea') [30]. There, a module is defined as a 'practical process function unit, which represents independent technical components'. Their function will be preserved starting from the process development in laboratory over the representation in a piping and instrumentation diagram (P&ID) to the constructive implementation in a 3D layout. For each module, simulation models, scale-up rules, and a reusable documentation are available and the modules can be produced in series. According to the 50 %-Idea three modules are required during the planning process:

1) Laboratory module: small-scale, represents functions and scales down the mass and heat transfer effects occurring in equipment that is used on production scale
2) Planning module: describes functions and tasks for all disciplines involved
3) Construction module: 3D, covers all disciplines, e.g. local piping, mechanical interfaces

The modules being defined according to the '50 %- Idea' can accommodate the entire process, a part of the process or a single unit operation. A similar approach is presented in [25] which correlates with DIN EN ISO 10628 [31], where the structures of processes and process schemes are standardized. In this norm the different hierarchical levels of the process scheme are defined, such as process, process step, and unit operation. According to the norm, the whole process is realized by a single production plant, a process step by a plant section and a unit operation by a plant section or process equipment. These hierarchical levels of structuring process schemes and plants are referred to as 'aggregation level' in the following. For the transfer of this top down approach to modularization, two different solutions can be found. One was given by Rauch [32] and Lüneburg and Zahn [33] which was further extended by Hady [34] and a second one was given by Uzuner [35]. Table 1 gives an overview of the different concepts for aggregation levels.

On the highest aggregation level, the plant level, only Uzuner defines a module, Hady defines an extra level between the plant level and the plant section level, where a plant section module group can be defined to realize e.g. a separation task. According to Hady and Uzuner a unit operation is realized in a plant section module, e.g. a distillation module consisting of the column part, reboiler, condenser, pumps, and tanks. Beneath the unit operation level, the unit function, e.g. the column part itself, is realized in different modules in the different approaches. According to Hady this is realized in a building group module. According to Uzuner modules with the same functional range are called equipment modules. The components of a distillation column, e.g. the column shell, which represent an element of the unit functions, are called equipment by Hady or part module by Uzuner, who also introduces part modules and building groups of part modules to describe e.g. a condenser system including a condensate collecting vessel belonging to a column system.

The different aggregation levels are referred to as 'multi- scale modularity' by Lier et al. [5].

Although multiple module definitions exist in literature, process plants are rarely planned and/or built based on modules [3]. This is due to the fact that neither suitable equipment nor consistent planning concepts are available for a general application in the process industry. The existing equipment and planning concepts will be reviewed in the following paragraphs.

2.1. Modular equipment and plant concepts

Modularization in the process industry is generally not limited to small-scale applications. Nevertheless, due to intensive investigation in the last decade, microstructured flow devices are a frequently referred example of a modular equipment concept [36–38]. Modular microstructured equipment concepts and toolboxes [38,39] are often designed for laboratory scale applications in the early phase of a project. For industrial production, scale-up strategies are required to relate equipment on laboratory scale with its counterpart on production scale. Two scale-up strategies for this equipment are discussed, the platform concept and the numbering-up or equaling-up concept.

Kockmann et al. [40,41] present a modular microreactor as an example for microstructured equipment with a platform scale-up concept. The platform concept is based on reactor plate sizes, selected according to the DIN standard paper format DIN A6 to DIN A4, such that the geometric ratios are kept constant. Thereby, each plate of the reactor is regarded as module.

As an example for the numbering-up concept, modular microsieve contactors for desorption are presented by Dercks et al. [42]. As laboratory scale device for desorption one single contactor is set to a higher capacity by stacking multiple contactors. Seris et al. built a scalable, microstructured miniplant for steam reforming with printed-circuit heat exchangers [43].

Suppliers of modular micro-structured equipment are for example FhG-ICT-IMM [44], Microinnova Engineering GmbH [45], Ehrfeld Mikrotechnik BTS GmbH [46], or Chemtrix B.V. [47].

Microstructured equipment can be integrated into the concept of 'modular and continuously operated small-scale plants' (MCSP) [17,37], developed e.g. in the F^3 Factory [48] project at the INVITE GmbH research center [49]. The MCSP consists of 'process equipment containers' (PEC) with the outer dimensions of ISO transport containers [50]. A PEC provides a grid for accommodating 'process equipment assemblies' (PEA), which are built on transportable skids and are regarded as 'modules' in this context [51]. A PEA consists of the main equipment and includes required pumps, heat exchangers, control units and electrical supply to fulfill the desired function or unit operation [52]. Within a PEA the components are exchangeable to enable different operation conditions, e.g. higher flow rates. The main equipment being implemented in a PEA is reused from former projects or selected from a database, containing predesigned equipment. A docking station, which is connected to the PEC, provides all required process utilities and includes the overall process control system [50]. PEA and PEC come with a documentation package, including documents for planning, construction, operation, and plant safety [53]. Similar plant concepts were reported by the Massachusetts Institute of Technology (MIT) and Novartis for continuous drug manufacturing in a single-product plant [54] and by the MIT in a reconfigurable multi-product plant [55]. By providing knowledge in form of a documentation package, the modularization concept of F^3 Factory [48] meets the requirements on modules stated above. However, similarly to microstructured equipment, these plants are limited to small-scale applications i.e. for a miniplant in process development or for a production plant for fine chemicals or pharmaceuticals.

An example for a realized module accommodating a complete process is the EcoTrainer, formerly called Evotrainer, which has been introduced by Evonik Industries AG and was developed within the EU project CoPIRIDE [56,57]. A mobile ISO container provides a common plant infrastructure. Other examples for mobile modular plants or plant sections can already be found in industry e.g. for sewage treatment [58,59] or industrial gases production, as provided by Messer Group for nitrogen generation [60]. For pharmaceutical industry Pharmadule Morimatsu AB [61] provides a modular plant concept based on ISO container modules to enable easier construction. Standardized bioreactors, vessels, Cleaning-In-Place-skids, formulation systems and many other process systems can be integrated in the container modules. The containers are transported to the site and connected there to the modular production plant. These modules for industrial applications focus on transportability from the manufacturing site to the site of operation. They are designed for providing one specific function and consider the requirements of the desired site of operation. Thus, matching of these modules to requirements in other application cases is not considered.

Modularization in the process industry also affects process automation and control systems. The need for automation of modular plants requires new control concepts resulted in the NAMUR (User Association of Automation Technology in Process Industries) Recommendation NE148 'Automation Requirements relating to Modularization of Process Plants' [62]. The recommended automation system focusses on the MCSP concept described before. Three automation strategies have been developed by NAMUR: the stand-alone box, the flexible box, and the integrated box strategy. Within the stand alone automation concept, the entire automation including the 'Human Machine Interface' (HMI) is integrated within the module or PEA, while the automation of different module cannot be interlinked. If the flexible box concept is used, the HMI is not included in the module or PEA and the automation of different modules can be interlinked. Within the concept of the integrated box, an automation module can consist of submodules and each system coordinates its subsystems, like the docking station developed in the F^3 Factory project coordinates multiple PEA in a PEC [62,63]. As various automation concepts for modular plants are proposed in the NE148, there is still an ongoing discussion of experts in this field. Therefore, automation will not be further addressed in this article.

A plant using automation modules, the 'modular engineering and automation research plant' (MEAR), has been developed by Urbas. Within this plant automated modules are connected in a platform system [64]. Each module represents a unit operation. It has standardized interfaces for fluid, power and information exchange and has an integrated automation system. As knowledge documentation, e.g. about the equipment performance, is not included the MEAR process modules do not meet the requirements on modules stated in 1.3. Furthermore, the MEAR plant is as well limited to small-scale applications.

2.2. The module-based planning process

Utilization of modules has a huge impact on the process and plant design approach. First the conventional process and the state of the art plant design approach will be summarized to clarify the differences to module-based plant design approaches being proposed in literature. The conventional approach is stepwise. Based on the product development, the process development is carried out. During plant design, consisting of basic and detail engineering, the planning of a production plant is completed. The engineering is accompanied by frequent economic evaluations [65]. The conventional plant design is an iterative approach, where every decision of the basic or detail engineering phase can have an impact on previous and later decisions [66]. Knowledge generation and stepwise refinement is thus a key goal in conventional plant design.

Shifting from conventional to module-based plant design the importance of proper information handling increases, as reusing engineering knowledge is the key goal. Thus, new planning concepts are required, which also require innovative approaches for data and information handling [4]. Distinguishing between data and information in this context underlines that not only data in form of numbers but also information in form of qualitative facts have to be handled. In the following, both will be summed up in the term 'information'.

Module-based plant design has to include most planning tasks belonging to the conventional plant design approach, such as the equipment selection, piping, instrumentation and 3D layout planning. But, modules, representing the value adding functions of a plant, and strategies for their selection have to be designed and developed for each planning task. Database concepts for storing the predefined modules were presented, e.g. by Hady et al. [3,29], Uzuner et al. [35,69] and Krasberg et al. [17,18]. These databases shall enable the design of modular plants by reuse of the planning documentation. Hence, in a module-based plant design project information about the modules will be available right from the beginning of the engineering phase, e.g. the equipment dimensions, operating condition limits, or costs. Thus, the module-based plant design focusses on a different base for decision making compared to the conventional plant design. From the equipment point of view the most suitable equipment module fulfilling the function needs to be selected instead of individually designing a tailor-made apparatus. This equipment module is no longer designed for a specific application case, but has to be selected and configured to suit the given boundary conditions. Selection and configuration means to match existing designs with process and project requirements. For this approach selection and configuration tools are required that bring together property data and process requirements on the one hand and geometrical equipment data on the other hand. As presented by Bramsiepe et al. selection and configuration can be supported by software tools [4]. Similar concepts are required for planning elements, e.g. PFD modules.

Lier et al. and Seifert et al. investigated flexibility and economic criteria for the selection of favorable modular plant setups for production scale. Lier et al. [5,67] studied a modular production line with two scales of modularity or 'aggregation levels': the equipment and the plant scale. In contrast, Seifert et al. [6,8,68] defined 'bare equipment' as basic equipment modules. These basic equipment modules are rated by volume flexibility, describing the width of the capacity operation range and economically by net present value (NPV) and real option calculations. The volume flexibility can be used to match project requirements and basic equipment module characteristics.

Krasberg et al. presented a concept for model-based selection of equipment [17,18]. For the production of fine chemicals and pharmaceuticals they developed a method for selecting reactor setups from a pool of existing equipment during the process development phase. This tool meets most of the requirements defined in 1.3, but is limited to continuously operated homogeneous liquid phase reactors. For configuring equipment, piping, and instrumentation Uzuner et al. [35,69,70] developed predesigned P&IDs and a knowledge-based design method. Within this method, the modular P&ID is configured out of 'basic and auxiliary elements'. Basic elements contain the equipment and a set of elementary piping and instrumentation. Auxiliary elements are predefined units extending the basic elements. Modular P&IDs are created by applying a decision tree method based on design questions with immediate documentation of the answers. This knowledge-based P&ID module selection meets the demand stated in 1.3 on knowledge documentation in form of modular P&IDs. A similar knowledge-based method to create modular P&IDs has been presented by Obst et al. [71], but without the differentiation between basic and auxiliary elements.

In addition, approaches for module-based 3D layout configuration are available. The research group of Schmidt-Traub structured a chemical plant into 3D layout modules and defined the required space. The 3D layout modules can be used in a layout planning software called 'computer aided plant design' (CAPD) [72,73]. These 3D layout modules provide no link to the P&ID or the equipment type. Another modular 3D layout is presented by Rottke et al. [74] for a high performance liquid chromatography (HPLC) application in laboratory by means of 3D models. This concept is limited to HPLC applications in laboratory.

The concepts reviewed above represent first-of-its's-kind approaches to module-based plant design in single planning steps. Most of them are limited to specific application cases and it is not possible to combine them to a consistent modularization concept. One reason for this lack of consistency is a difficult transfer of information between the different concepts due to different module definitions and information structures. Moreover, a suitable software support is missing. To enable a module-based plant design, a concept meeting the requirements stated in 1.3 has to be developed. The most suitable starting point for such a module definition apprears the knowledge-based concept for the design of modular P&IDs of Uzuner et al. [35,69] . It will be used as the basis for the concept presented in this work. To cover the whole process and plant planning this approach has to be extended to selection and configuration tools as known exemplarily from Krasberg et al. [17,18].

3. Concept

As pointed out in the previous chapters, a suitable concept for modularization, module-based plant design, and information handling throughout the life cycle of the process industry is still missing. Such a concept must cover all phases of the process and plant life cycle from laboratory studies to production and dismantling. Moreover, it has to pay tribute to aspects of product and process development, basic engineering, detail engineering, equipment manufacturing, plant construction, operation, as well as safety, environmental and regulatory topics. Beside a general terminology of modules, modular assemblies, and the considered module types, as proposed in chapter 1.2, the information handling has to be addressed.

3.1. Information handling throughout the process and plant life cycle

Before starting a module-based plant design the 'presettings', such as an estimation of the required capacity for production, a block diagram with additional information (BD) [31], representing the basic process concept, and further constraints for the production plant, have to be available. Additionally, key process parameters and properties data have to be determined, in order to describe the function of the blocks in the BD, so calles 'block functions'. Block functions can be defined on various aggregation levels, e.g. unit operation (UO), plant section (PS) or a plant (P) according to [31], see Table 1. One 'block representation frame', see Fig. 2, can then be defined for each block from the BD. In the following, a block representation frame is regarded as a structured information storage framework, providing 'slots' for storing all necessary information which are connected to the block. The block representation frame covers all phases along the process and plant life cycle and all 'levels' of process development and realization, namely: laboratory, miniplant, production plant, and operation. Proceeding from level to level and in the life cycle, more slots can be filled with information. So, the information content of the block representation frame increases with increasing realization level and throughout the life cycle.

Introducing block representation frames during process synthesis, all available information on the block, e.g. temperature, pressure, concentration of involved components or on relevant physical/chemical properties can be stored in the corresponding slots to create the base for further steps, as shown in Fig. 2.

On each realization level, the block function can be realized by equipment modules. The equipment type and size can change from

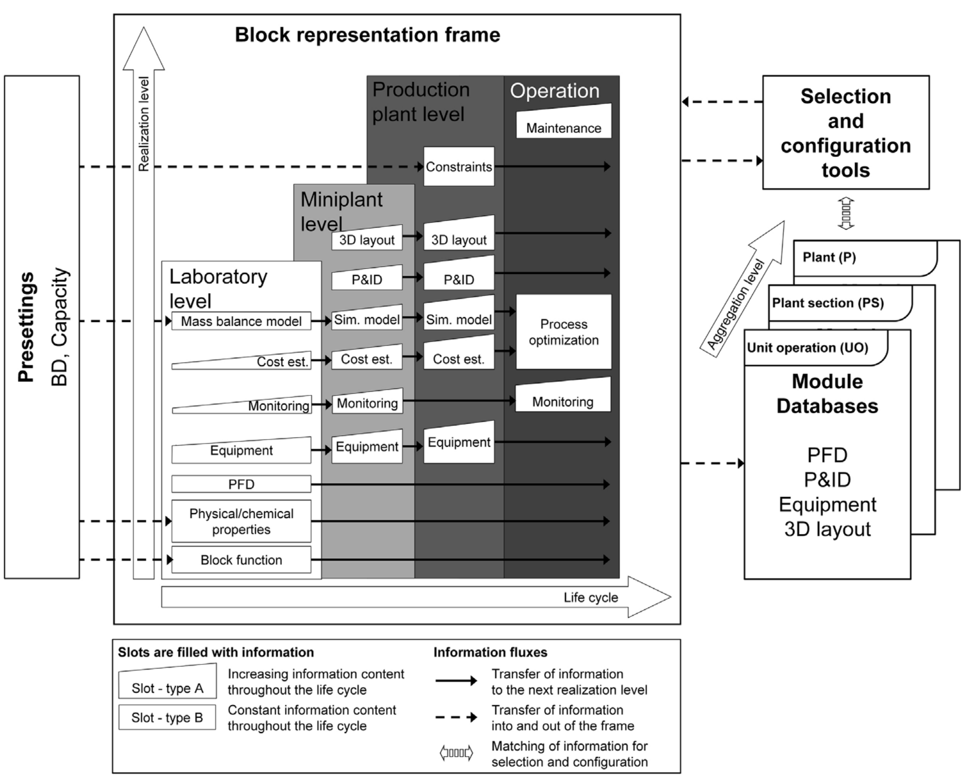

Fig. 2. Concept for modularization, module-based plant design, and information handling in a block representation frame throughout the life cycle of the process industry. Three aggregation levels according to DIN EN ISO 10628 [31] are visualized for the module databases.

one level to another. Hence, a new placeholder is provided on each realization level. Equipment documentation, e.g. operating condition limits, dimensions, technical drawings, can be stored in the block representation frame and corresponding slots. Moreover, the block representation frame provides slots for further information, e.g. on, mathematical models for production cost estimation and process simulation, PFD, P&ID, and 3D layout module representation the block, process monitoring information, or maintenance information.

The information content of a slot can be transferred to the next realization level and is subsequently maintained, e.g. the block function, or physical/chemical properties of the products. Furthermore, it is possible to replace information being stored in one slot, e.g. on the utilized basic equipment module as explained in the paragraph before. As another possibility, an increase of information stored in a slot within one realization level is possible, e.g. models or monitoring data. The slots can be filled with information from different sources, e.g. the presettings, experimental results from laboratory level or with various modules from the module databases, representing the block for the corresponding planning and realization step.

For using information, e.g. on PFD modules, equipment modules, or P&ID modules out of databases, selection and configuration tools are required. These tools match the project requirements, given by the information already stored in the block representation frame, with the characteristics of existing designs stored in the databases. Moreover, new information being stored in a frame for the first time, e.g. a new equipment module, can be transferred to the databases to make it accessible for other projects.

Both a planning and a realization perspective is contained in Fig. 2. These two perspectives and the structure of required databases and tools are further described in the following sections.

3.1.1. Planning perspective

The block representation frame as sketched in Fig. 2 organizes information handling during process and plant development. The block representation frame acts as a questionnaire and requires for adequate information input to the slots on each realization level. On laboratory level information being required for scale-up can already be obtained, physical/chemical properties and product specifications can be generated, structured early and utilized along the whole life cycle. Similar to the block function itself these slots are maintained during the whole life cycle.

The relevant planning documentation added on miniplant level is passed on to production plant level. As a result of this level-wise approach, information and even decisions can be tracked over the life cycle and reused in future projects [75,76] . On operation level, process optimization can be supported due to the availability of structured information and mathematical models. Furthermore, optimized maintenance, repair and operation are enabled by comparing the equipment performance with the performance of similar equipment modules in other processes and block representation frames. Suitable data models and tools for information handling are under current investigation as they are a core feature for reusability of information [77].

3.1.2. Realization perspective

For the realization of ‘modular plant setups’ consisting of unmodifiable equipment elements/units, multiple terms are common in literature, such as ‘module’, ‘modular equipment’, ‘equipment module’, ‘standardized equipment’, ‘predefined equipment’, as reviewed by Bramsiepe et al. [4]. In this work, the term ‘equipment module’ is utilized to describe equipment elements/units on all realization and aggregation levels.

Basic equipment modules are defined by the following characteristics:

- Fulfill a block function on a defined level off aggregation, see Table 1.
    - According to DIN EN ISO 10628 [31] the aggregation levels UO, PS, and P should to be considered
    - According to Uzuner et al. [35] , an aggregation level beneath the UO level can be considered to describe less complex block functions, such as ‘storage’, ‘mixing’, ‘splitting’, ‘pressure change’, ‘temperature change’, or ‘phase change’.
- have all necessary equipment information available, such as a defined structure, construction material, internal setup, volume, weight and limits of operational conditions, such as maximum operating pressure and temperature

Furthermore, basic equipment modules are well characterized and documented. Therefore, the following information is available:

1. corresponding basic PFD modules
2. corresponding basic P&ID modules
3. instrumentation and control engineering (I&E) documentation
4. technical drawings and corresponding basic 3D layout modules
5. specific correlations for heat, mass and momentum transfer estimations
6. estimation models for resource consumption/efficiency (e.g. feedstock, utilities, construction material)
7. estimations models for equipment manufacturing and operation cost

The characteristics of basic equipment modules have to fulfill the requirements of the given block function. Due to different production capacities on the realization levels the selected equipment modules might differ with increasing realization level. The selection can be assisted by computer-aided matching approaches. The example of Krasberg et al. for the block function ‘reaction’ has already been discussed [17,18].

A pool of basic equipment modules, referred to as ‘equipment module database’ in the following, should be designed for a wide capacity range of applications and needs to be suitable for the whole life cycle. Pools of basic equipment modules are already commercially available for lab and miniplant level, as presented in chapter 2.1. For the block function ‘reaction’ on a small-scale capacity the pool of basic reactor modules is already quite extensive [38,39]. These basic equipment modules can be selected from catalogues, if enough equipment information is available to match with the process requirements. Then, the basic equipment modules can be ordered from a supplier. If no suitable equipment module can be selected, new equipment modules have to be engineered, extending the equipment module database. For new applications the equipment development has to start in laboratory, if equipment modules for a block function are not available, yet. There, proof of concept is performed followed by experimental characterization and scale-up studies for the basic equipment modules.

However, in order to realize an operational modular assembly, it is not sufficient to have the basic equipment modules available fulfilling the block function, but auxiliary equipment modules required; e.g. measurement and control devices. It is reasonable to have the full installation including the basic equipment modules and the auxiliary equipment modules available, if frequent equipment reuse can be guaranteed, e.g. on laboratory or miniplant realization level, or in small-scale production with limited product cycle times [2], e.g. in an MCSP concept, see chapter 2.1. In this case it might be beneficial to define equipment modules with standardized interfaces for mechanical, fluidic, electric and

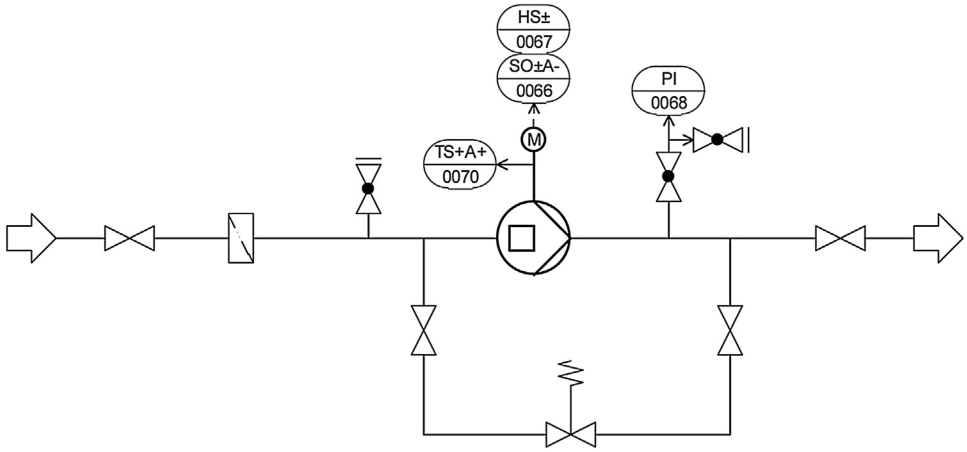

Fig. 3. Basic P&ID module for the block function 'pressure change' realized by a positive displacement pump module.

informational connections to other equipment modules, to utilities, to a process control system or to supply chain and logistics system.

For large-scale applications, it is more reasonable to have basic PFD, basic P&ID, and basic 3D layout modules available, representing equipment modules, which can be chosen by selecting them based on process requirements. The auxiliary PFD, P&ID and 3D layout modules then have to be configured, accordingly. Large scale production equipment manufacturers do typically not prepare equipment ready to order. Here documentation from previous projects can be reused in order to save iteration cycles, e.g. for detailed design drawing discussions. Reusable equipment modules will not be available in this case.

In the future, modules shall be designed and documented in a manner that reuse is possible. The basic equipment modules shall cover a wide capacity range on each realization level. Once a process has reached a certain level of maturity on laboratory or miniplant level, the block representation frame can be transferred to production plant realization level and the laboratory or miniplant scale equipment modules can be used to realize another process. This enables the reuse of equipment modules, either meaning a reuse of an existing equipment module or using similar equipment modules, which are constructed and manufactured by reusing the equipment module information, such as corresponding PFD, P&ID or 3D layout modules.

Cost reduction achieved by reuse of modules results not only from improved development and engineering, but also from improvements on operation level. Well documented, standardized basic equipment modules enable simplified replacement. Hence, debottlenecking by numbering-up of the same equipment module [2,8,9] or replacement by equipment providing a higher capacity or increasing efficiency is enabled. Replacement of equipment for maintenance and repair can be facilitated as well.

3.1.3. Selection and configuration tools, module databases

Selection and configuration tools as sketched in Fig. 2 require information on the block function, key process parameters, properties data, a suitable selection approach or algorithms, and module databases with existing designs, such as for PFD, equipment, P&ID and 3D layout modules. The modules in the module databases have to be structured by block function and aggregation level and are independent from a particular project. Modules in the databases are not limited to one realization level, e.g. a heat exchanger equipment module can be used both on miniplant level and on production plant level, depending on the required capacity, process conditions and presettings.

The further structure of such databases can be adapted from the work of Uzuner et al. [35,69] which was focused on modular P&IDs and P&ID module databases, only. Accordingly, the module databases contain information about basic and auxiliary modules. Basic P&ID modules represent the P&ID of a basic equipment module, together with associated piping and instrumentation, which is required in every application of this specific equipment module. As an example a basic P&ID module for the block function 'pressure change' being realized by a positive displacement pump is sketched in Fig. 3. Auxiliary P&ID modules represent of further piping, instrumentation, or other auxiliary equipment modules, which are required in combination with basic equipment modules for a particular application. Auxiliary equipment modules ensure safe and robust operation within the given process conditions and with the given physical/chemical properties, see Fig. 4 for an auxiliary P&ID module representation for 'pulsation damping'. Auxiliary equipment modules for pumps can be structured in different categories:

1. Control and measurement of process variables, e.g. pump speed control
2. Robust start-up and shut down, e.g. trace heating for pipes or additional pipes to empty a pump, when it is shut down

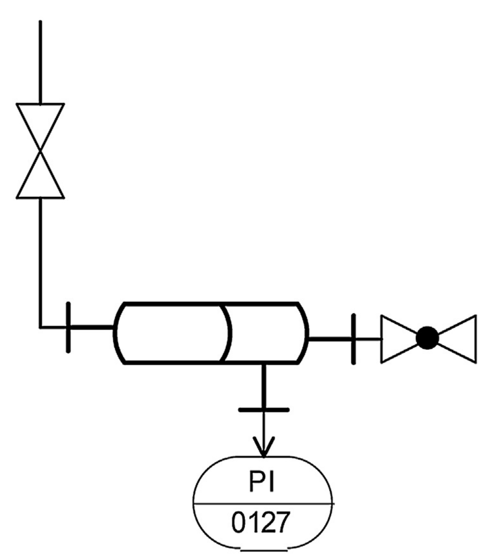

Fig. 4. Auxiliary P&ID module for pulsation damping of a positive displacement pump module.

3. Safe operation e.g. safety venting line to collecting vessel
4. Additional auxiliary modules for improved operation, e.g. pulsation damping
5. Cleaning and sanitation, e.g. cleaning in place (CIP)

As discussed in chapter 3.1.2, equipment module information being stored in the equipment module database can origin from different sources, e.g. past projects or manufacturers. Entries in the equipment module database can provide information, whether an equipment module is existing and/or available and if it can be reused in a further project.

At present, no fully defined module databases are available, neither for PFD modules, nor for P&ID, equipment, or 3D layout modules. Databases have to be successively filled with module information, so all relevant block functions can be represented along the life cycle, and on the different aggregation levels. Furthermore, computer-aided tools and data models are required to benefit from modules and module databases and in module-based plant design.

3.2. Concept application

In the following paragraphs, the application of the presented concept of information handling with the block representation frame will be discussed for the different realization levels throughout the life cycle and during module-based plant design. These considerations are independent from the aggregation level.

3.2.1. Laboratory level

Module-based plant design for new processes generally starts on laboratory level. Important information about the block functions, e.g. process conditions and production plant capacity have to be embedded in the representation frames for each block. Relevant physical/chemical properties have to be extracted from common property databases or determined experimentally. The planning information for each block, which is generated on laboratory level, is made available then for the whole process and plant life cycle by means of block representation frames, see Fig. 2.

Laboratory scale realization of block functions can already be applied in the early phase of process development, by establishing standard experiments on laboratory level. Therefore, a pool of existing equipment modules can be matched with the requirements, equipment modules can be selected and configured by the tools, from the equipment module databases for the desired block functions. Basic equipment modules, providing the desired block functions, can be completed by standard laboratory infrastructure, such as tubing, tube fittings, thermostatic bathes, or process analytic tools (PAT), to operate the basic equipment modules in ‘stand-alone’ manner. These early experiments can be used to validate the proposed upstream and downstream concept, including process intensification [36]. Furthermore, a PFD module can be embedded to the block representation frame and simulation models and scale-up strategies can be elaborated and validated for operation on later levels.

Compared to conventional pilot-scale plants, it is advantageous to use modular equipment assemblies on laboratory level, as small experimental setups are faster to construct with significantly lower investment cost, especially if existing basic equipment modules can be reused. Furthermore, safety issues are lower compared to pilot-scale due to the handling of small amounts of chemicals and a setup fitting into a standard fume hood [78].

3.2.2. Miniplant level

Modular miniplants can be realized with the same basic equipment modules that were utilized on laboratory level. From module-based design of the modular miniplant, a modular P&ID assembly, and a modular 3D layout assembly can be embedded to the block representation frame. Therefore, more information is necessary and available on miniplant level paying tribute, e.g. to automation and control, to recycle strategies and to more extensive safety aspects [53] and to process monitoring being carried out during operation of the miniplant. Thus, the content of each block representation frame has to be significantly expanded when transferring it from laboratory to miniplant level. Furthermore, steady-state and dynamic process simulation models can be improved and validated using experimental results from laboratory level and miniplant operation.

3.2.3. Production plant level

Modular production plants with the desired capacity are regarded on the third realization level in Fig. 2. Considering the production plant level, more detailed investment and operating cost estimation, and resource efficiency estimation are available using miniplant level information. Due to the typically higher capacity, the equipment modules used in the modular production plant are larger and can be more complex than on miniplant level. Additional information has to be embedded to the block representation frames, e.g. security or maintenance measures in form of further auxiliary modules.

The documentation and planning outputs of the presettings and the information being available from laboratory and miniplant level are inputs for the block representation frames on production plant level, as presented in Fig. 2. From laboratory level, the block function, and the physical/chemical properties can be retained. The embedded process balance models, e.g. short-cut modeling or steady-state process simulation, can be used to define the required dimensions of basic equipment modules, e.g. by matching the operation condition limits of the available equipment modules in databases with the process conditions resulting from simulation.

As pointed out before, the type of basic equipment modules being chosen for block functions on production plant level can differ from the utilized equipment modules on lab and miniplant level, e.g. pump or heat exchanger types for realizing block functions such as pressure change or temperature change. Furthermore, modular assemblies on production plant level can contain additional auxiliary equipment modules, to meet constraints of the production environment, e.g. safety and environmental regulations. Further constraints may result from location specifications, such as available utilities, power supply, available space, and local standards.

3.2.4. Operation

The block representation frame concept is not limited to process development, module-based plant design and construction of modular plants, but also supports process optimization during operation and enables optimized maintenance, repair and operation (MRO) of the modular production plant. By rigorously collecting and storing operational information in the block representation frame, followed by transferring and attaching this information back to the equipment module databases, superior improvements on operation level can be enabled.

Monitoring data can both be used for process optimization of the current process, and can extend the knowledge on operational experience of the equipment. Additionally, the process monitoring data together with the simulation models and flow diagrams used for planning enable efficient analysis of problems occurring during operation as well as process optimization.

Information on the various components of a basic or auxiliary equipment module, e.g. on lifetime, or wear of seals, as well as operational experiences with the equipment modules enables optimized long-term planned maintenance or even predictive maintenance. This information can originate e.g. from former experience with the equipment modules or from the equipment manufacturer. It can be drawn from the databases in addition to the equipment modules characteristics and is extended while operating them. Replacing equipment modules that will break or are already broken is simplified, because equipment modules with the characteristics listed in chapter 3.1.2 are easier to reorder compared to conventional equipment.

Debottlenecking by replacing or numbering-up of single equipment modules [2,8,9] can be facilitated, due to the availability of information on the process requirements, the physical/chemical properties of the system, the utilized equipment modules and corresponding mathematical models.

3.3. Example

To illustrate the modularization and block representation frame concept during process development, module-based plant design, and operation the concept is applied to a generic task: In one block of the BD of the continuous process X, liquid A is cooled from 70 °C to 20 °C. Thus, 'Cooling liquid A' corresponds to a 'temperature change' block function on the unit function aggregation level according to Uzuner et al. [35]. Therefore, a block representation frame for this block function' with corresponding slots is generated and used to store all information throughout the life cycle of this block.

At the beginning of process development on laboratory realization level the cooling of liquid A can be realized by a tubular coil being placed into a thermostatic water bath (Fig. 5A),

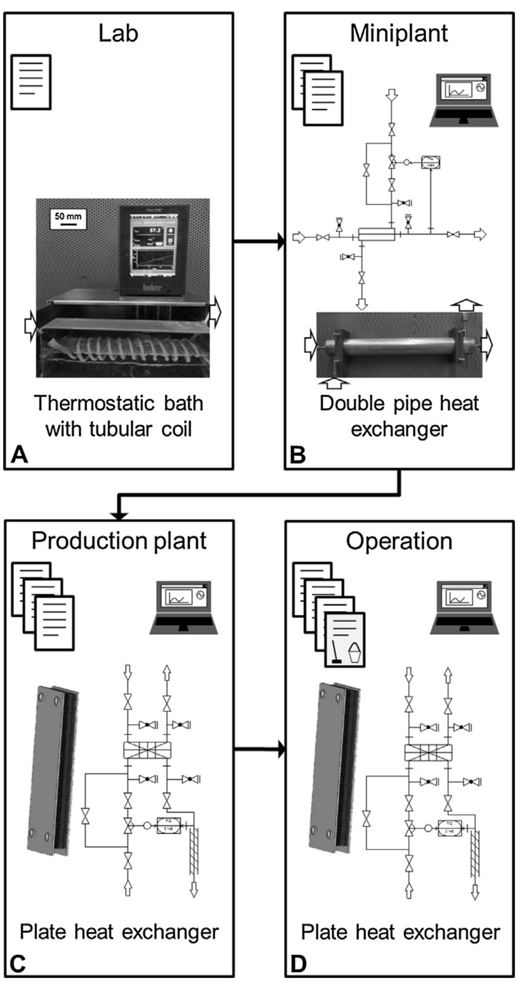

Fig. 5. Realization of the block 'temperature change' on different realization levels.

which is a common and frequently used basic equipment module for continuously operated temperature changes on laboratory level. Due to a milli-structured design the basic equipment module is providing a huge specific surface area and the outlet temperature can be controlled by adjusting the temperature of the thermostatic bath. The relevant physical/chemical properties of liquid A, such as thermal conductivity and heat capacity are determined by standardized laboratory procedures, as no literature data is available for liquid A. The fouling potential is determined on laboratory level, by varying flow velocity, mean residence time, and tube material as liquid A contains slightly soluble impurities which might precipitate during cooling. A minor fouling tendency was observed in stainless steel during these laboratory level experiments which is documented in the monitoring slot of the block representation frame. A first cost estimation for miniplant and production plant scale is possible by black-box simulation based on the amount of heat being transferred.

On miniplant level the type the basic equipment module has to be changed, as a higher capacity is required for operating the modular miniplant (Fig. 5B). A counter-current flow double-pipe heat exchanger made from stainless steel is available from the equipment module database and matches with the process requirements according to capacity, heat transfer performance, and operating limitations, e.g. allowable temperature and pressure range. Thus, it can be reused. Water remains as utility. The double-pipe heat exchanger in the modular miniplant is controlled by adjusting the inlet mass flow rate of the utility at constant inlet temperature. Based on properties data from laboratory level and temperature profiles depending on mass flow rates being determined on miniplant level, an extended simulation model of the heat exchanger can be embedded and used. Corresponding P&ID and 3D layout modules for this block function are now available on miniplant level.

The block function 'cooling liquid A' in process X cannot be realized in a stainless steel double-pipe heat exchanger equipment module on production level any more. This result from fluid dynamic limitations of the available equipment modules, which were identified by means of the selection and configuration tool. A new design of a suitable double-pipe heat exchanger should be avoided due to economic considerations. To realize the block function on production plant level an existing plate heat exchanger design from the equipment module database is configured to fulfill the process requirements (Fig. 5C). A thermofluid is available as utility. Basing on this selected basic equipment module a new basic P&ID module 'counter- current flow plate heat exchanger' is embedded to the block representation frame of production plant realization level. It is completed by adding the auxiliary P&ID and equipment modules 'isolation of the heat exchanger and the pipes' and 'temperature control' are selected and configured. The simulation model used on miniplant level is extended to production plant level by a more complex control strategy and plant operation, e.g. start-up and shut-down.

For operation of the plate heat exchanger module (Fig. 5D) experience with similar equipment modules from other processes is used to plan start-up, shut-down times, cleaning of the plates and replacement of e.g. the gaskets. Furthermore, additional information about operational performance is recorded and stored in the block representation frame to optimize the operation of the equipment module e.g. the heat exchanger control.

4. Summary and outlook

In process engineering various module definitions are currently available, each covering several aspects and perspectives of modularization. In this work a general module terminology has been introduced and a concept for information handling throughout the entire life cycle of the process industry has been developed. This concept covers planning and realization on various level from laboratory to production. Modularization can be carried out on various aggregation levels, depending on project goals, and branch. Process development, module-based plant design, and operation can benefit from a structured and traceable information handling throughout the life cycle by means of the introduced block representation frame concept. Reusable well-characterized modules, structured module databases, and novel tools for module selection and configuration can reduce the engineering effort, project time and cost.

Nevertheless, modules for various block functions, module databases, selection and configuration tools, and block representation frames with corresponding slots and questionnaires are not available, yet. Thus, it has to be investigated, which information is essential to represent and realize a block function with basic and auxiliary modules and how this information can be traceably stored in block representation frames. Moreover, selection and configuration tools and a holistic approach for module-based plant design have to be elaborated, being capable to extract information from frames, compare, and match with module databases. Furthermore, design strategies for modules and module databases are required to cover multiple applications with a limited number of designs. Finally, the handling of information of various structures and origins has to be facilitated in an integrated manner.

Conflicts of interest

The authors have declared no conflict of interest.

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