PROGRESS REPORT

Modular Plants

Paradigm shift – describing process functionalities instead of specifying equipment

EINE INITIATIVE VON DECHEMA UND VDI-GVC

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Introduction / Motivation

This progress report is the result of a common initiative of the ProcessNet Working Group MODA (modular plants). The objective of this report is to describe the differences and changes required in the paradigm shift for operators to use and install and for manufacturers to supply modular (sub)systems, compared to the current approach of buying and supplying equipment according to equipment specifications. In that context, the Working Group MODA teamed up with a number of selected manufacturers and system integrators to understand current potential and challenges.

Several business drivers for modularisation sparked the interest for the concept of modular production within targeted markets of the process industry, see Figure 1. "Reduced time to market" for newly developed products or processes, "reduced investment risk" for new production capacity at market entry, lower entry barriers to develop and enter new markets, more "flexibility" in client-oriented production and more flexibility in production capacity within highly volatile markets, just to name a few. In addition, the increased opportunities for a more sustainable operation (e.g. by more enhanced and efficient cleaning procedures and the possibility for optimisation of equipment for a wider scope of processes) are drivers for modularisation in the process industry. The most obvious markets to benefit from modular production facilities are within the area of fine chemicals and (bio-)pharmaceutical intermediates, where typical product volumes are relatively small and production is highly versatile.

Reviewing the disturbances in the supply chain as currently faced resulting from the pandemic, plus the need for more sustainable production (e.g. by reducing unnecessary transport activities), the call for reshoring of production capacity is increasing as well. To some extent the production at world-scale capacity may be transferred to a more national or continent based distributed production. In such cases, too, the standardisation and modularisation concepts may offer major advantages.

Knowing the advantages from the business drivers, these advantages will only materialise, when the investment for modularisation and the reliability of the modularised plants can compete with or outperform the current traditional approach, where new plants are designed, engineered and installed.

Over the past number of years, several initiatives have started and also first projects on demonstration scale and even on a smaller commercial scale have been demonstrated to the public, thereby proving the concept of modular production. However, to ensure that modularisation is also economically attractive, modules called Process Equipment Assemblies (PEAs) need to be widely available to the market within a limited number of varieties to enable cost-effective manufacture by the suppliers. In addition, PEAs from various PEA suppliers need to have the possibility to be connected to form one modular plant. This will lead to a different type of alignment on requirements and technical feasibilities between manufacturers and operators. It is therefore important that all stakeholders in this paradigm shift understand the benefits and needs of each other.

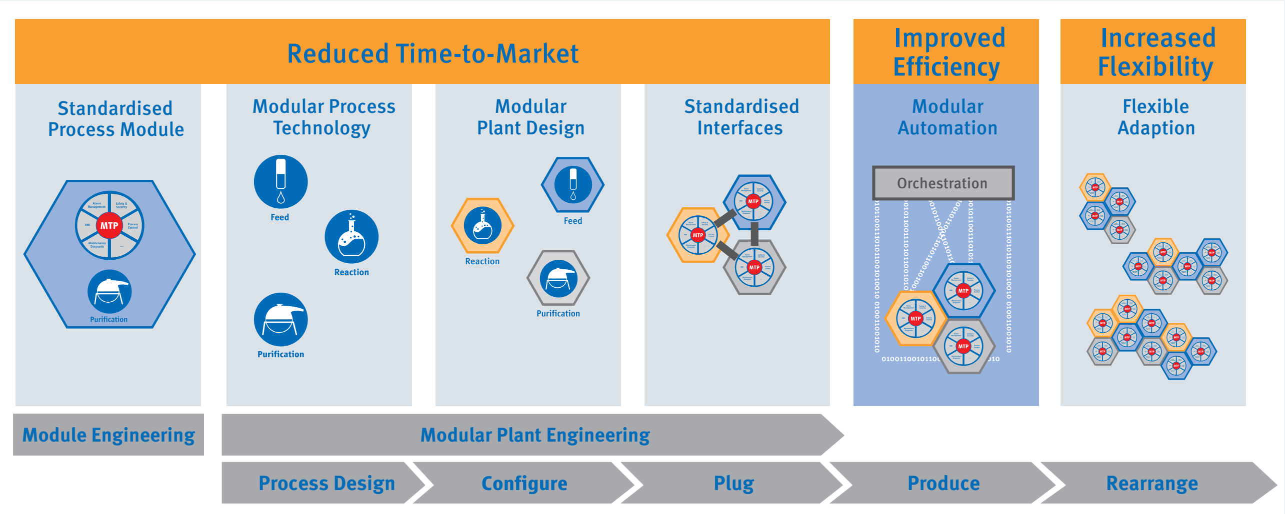

Figure 1: Concept for modular plant engineering [1]

When PEAs with sufficient quality will come available to the market, this will undoubtedly influence the approach for the design of new plants. The engineering process will see a radical change from specification of individual components to form a dedicated and technically optimal designed plant, towards a selection of PEAs that are capable to address certain required process functionalities. If such designs of PEAs -or even the PEAs themselves- are already available, a proper selection of suitable PEAs will allow an expedited design and assembly process to erect an entire new modular plant setup. When these PEAs are designed according to standardised design guidelines and automation guidelines to enable communication between the PEAs (either direct or indirect), the concept of plug-and-produce is within reach.

This procedure is visualised in the bottom scheme of Figure 1. The selection of process functions during the conceptual or basic engineering process drives the functional process design. The different unit operations are determined and configured to a modular plant design. Suitable PEAs (either available or newly developed) are selected, whereas the combination of suitable and interconnectable PEAs will finally result in the modular plant for production. With the availability of sufficient different PEAs for a variety of unit operations and for different operation windows, the standardised and well-documented PEAs can easily be rearranged for a different process. The standardisation of automation architecture for the PEAs further enhances the plug-and-produce concept and together they have the potential to become a game changer in industry.

Through working groups within the German association of engineers (VDI), a first series of guidelines on standardisation and automation of PEAs and modular plants have been published. Reference is made to the guidelines VDI/VDE/NAMUR 2658 and VDI 2776.

The above mentioned active group of operators and system integrators in driving the concept joined forces with interested equipment manufacturers to discuss and align the required changes in the design process of PEAs and entire modular plants. Discussion was done in several workshops in the light of a "Dosing PEA" as a typical example focusing on the following questions among others:

- Where do the expectations of owner/operators meet with the specifications for individual equipment from the equipment manufacturers?
- What needs to be specified as a minimum and by whom?
- How can equipment specifications be translated to functional operation windows?
- What is generally seen as a minimum required assembly of various equipment to form a functional PEA?
- What are the responsibilities of wach partner?
- What future potential business models are developing for each partner?

This preliminary selection of questions forms the basis, the current findings are addressed in this progress report. The questions are important ingredients to close the gap between the demand and supply side of the value chains. This progress report will further address the lessons learnt and some of the most pressing white spots that still exist.

1 Modular Concept – distinction to conventional specification: Description of global parameters and process functions

Following the motivation of this report, the concept of continuous production with flexible modular plants is a promising approach to meet the challenges mentioned above. In recent research projects the technical and economic potential of modular production plants has been demonstrated. Modularisation plays the key role in this concept and has been defined for chemical process industry by DECHEMA and VDI in the 2016 Whitepaper "Modular Plants – Flexible chemical production by modularisation and Standardisation – status quo and future trends" as

> *„Designing functional building blocks with standardized units, dimensions or interfaces, which can be easily assembled, maintained as well as flexibly arranged and operated".*

However, recent developments in the subject area have shown that defining fixed dimensions of PEAs (process equipment assemblies) and FEAs (functional equipment assemblies) is not always required and often even not useful. This part of the definition has thus lost importance. The definition however indicates two major differences between conventional and PEA-based plant design. The first is the focus on a fixed set of process functions to describe process needs on the one hand and PEA capabilities on the other hand. The second is the desire for hardware reuse, which can only be successful when the hardware to be reused is standardised to a certain degree. In PEA-based planning the hardware building blocks to be reused will be developed on PEA level instead of individual equipment level.

Basis for the concept was laid in VDI guidelines 2776 and 2658 describing the elements of the modular plant concept depicted in the following Figure 2.

1.1 Function-oriented planning

The concept of PEA-based plant design is based on matching the requirements of a process engineering operation with the capabilities of available PEAs and FEAs. For this matching it is necessary on the one hand to describe which functionalities the process requires, and on the other hand to describe for the available PEAs and FEAs, which functions they can realise. For the final alignment, the definition of the requirements and the description of the capabilities must be based on a uniform catalogue of functions. VDI Guideline 2776-2 makes an initial proposal for such a function catalogue.

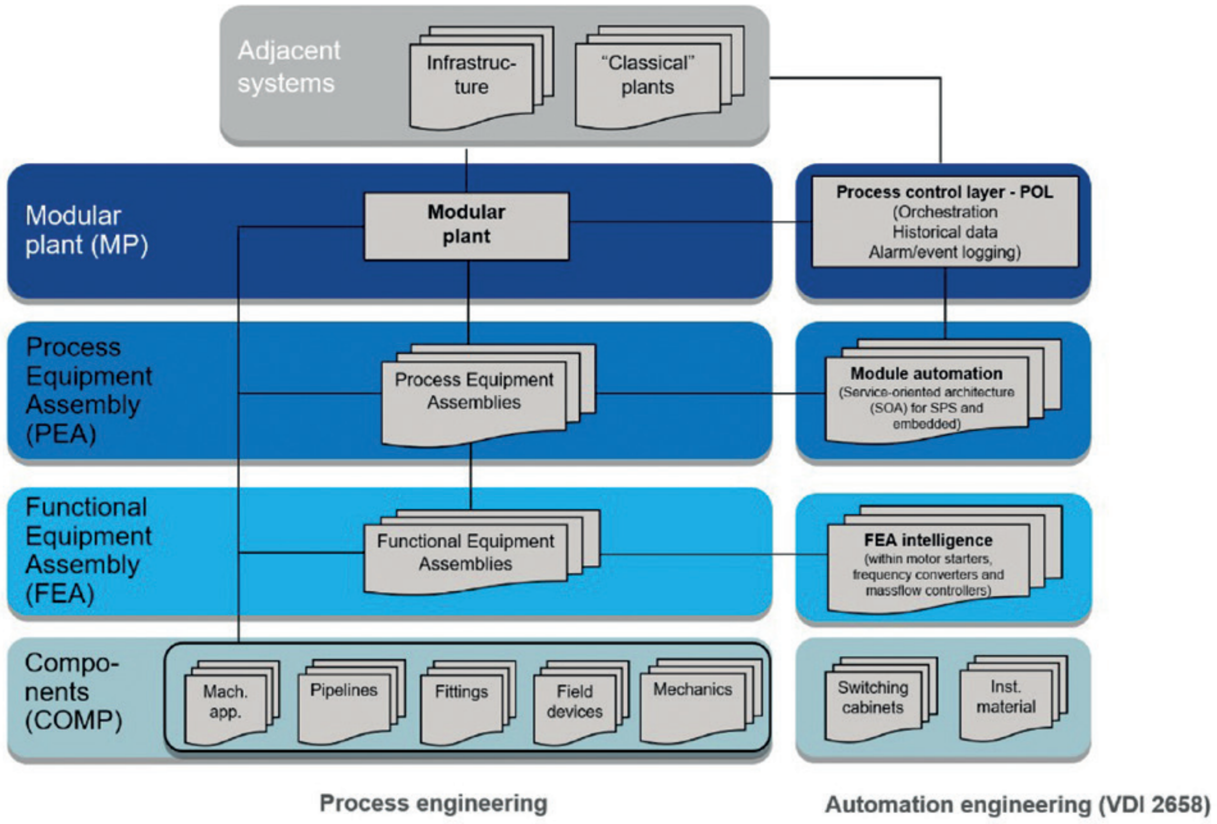

Figure 2: Elements of the modular plants concept [2]

Structure of modular plants (VDI coordinated, revised 12/2019)

For the selection procedure, global boundary conditions must be defined first, analogous to the development of a conventional plant. Examples for these boundary conditions are:

- Corrosiveness of the media to be treated and the resulting requirements for apparatus, piping and sealing materials.
- Installation site and resulting requirements for insulation and explosion protection.
- Reasonable pressure and temperature ranges

Once the global requirements are defined, the process engineering workflow must be characterised based on a defined catalogue of process functions. For each of the required process functions, the operational parameter range must then be defined. For this purpose, VDI Guideline 2776 proposed both a set of process functions and, for each of them, a set of parameters with which it is defined.

This catalogue of process functions is later used for the definition of the required automation functions as modular automation services. Automation services are defined according to VDI/VDE/NAMUR 2658-4 summarizing automation functionalities within a PEA. A detailed description of the corresponding procedure can be found in VDI Guidance "Zusammenspiel von automatisierungstechnischen Diensten und prozesstechnischen Funktionen – Interaction of automation engineering services and process engineering functions" [3].

1.2 PEA selection

Once the required process functions are known and characterised, the required PEAs can be selected. For owner/operators it is advisable to first conduct a search for PEAs already existing within the company and then identify PEAs available on the market. The search can be limited in the first step by the selected global parameters / boundary conditions. The search can then be conducted based on the function-specific parameters. For this search concept to work, both existing PEAs and those available on the market must be characterised according to the process-specific functions, so that it is described which functions a PEA can implement and in which range of the characteristic parameters. A detailed description of the PEA selection procedure can be found in Schindel et al. [4] and Harding et al. [5].

1.3 Standardisation

If no suitable PEA can be found, a new PEA must be developed. Care should be taken to ensure that the PEA is not planned exclusively for the parameter range required in the current project. Rather, possible future application scenarios should be considered to define a reasonable range of potential operating area. From this, a reasonable parameter range can be derived for the current planning, which increases the chances of future reuse. These activities will produce versatile and widely applicable PEAs that will unlock future reuse.

To be able to use the advantages of modular planning concepts in a broad range of applications, the aim is to make basic functionalities, in which there is no inhouse process know-how, available to the entire market of the chemical industry. Through these pre-competitive activities, standard PEAs can be developed, thus significantly reducing investment costs for future projects.

A step-by-step approach seems to be reasonable, which first looks at a rather limited area of a company. In the next step, the dissemination of a solution can be aimed for within the company once it has been found, to finally strive for market-wide standardisation. Alternatively, it could make sense for PEA manufacturers to offer their customers a price advantage on PEAs if they see a high potential to sell the PEA several times in the future and take benefit from the learning curve. For this purpose, the planning documentation will be owned by the PEA manufacturer after the end of the project and will be available for future projects.

2 Roles & Responsibilities

With the planning, construction and operation of modular plants, the aim is to achieve rapid process development and early production for the fine chemicals and pharmaceutical industries. The adapted workflow also leads to changing roles and responsibilities of the involved parties.

2.1 From Manufacturers to Operators – Division of Work

As usual in classical plant technology approach, the operator of modular plants should have a good, assessed competence of the plant itself and the components intended for use in the process. They must be able to assess the suitability of the PEAs available on the market for their process. For the manufacturer, the main difference is in the design of the plant components; these are not, as often in classical plant engineering, developed only on the application specified by the customer. The PEA maps just a single process engineering step – for example dosing - and is therefore more generally oriented in its design in order to be reused. For such general design of the PEA, an indepth knowledge of the process technology and products of the potential customers are required by the manufacturer in order to cover the largest possible customer base.

Another fundamental difference to classical plant engineering is the integration of automation engineering into the PEAs. For general design, this means that as many functions as possible must be realised in the structure of services in accordance with VDI/VDE/NAMUR 2658-Sheet 4. A PEA manufacturer who has so far only offered primary components perhaps equipped with junction boxes needs in future also knowledge of the process control and process automation. Of course, the same applies analogously to the manufacturer from the PEA area, who now offers process engineering components in the PEA.

The general design approach of the PEA and the integration of modular process automation also result in a change in the approach to hazard analysis. A combination of different PEAs, based on their function or from different manufacturers, into an overall process engineering concept requires a uniform concept for the PEAs. Manufacturers of PEAs must be able to assess this from a plant safety perspective within the framework of a modular hazard and operation study (mHAZOP), see VDI 2776-Sheet 3.

Until now, the operators had to consider and assess the suitability of plant components only for a specific application. With the modular concept, they are required to take a much broader view about future requirements for their plant. The selection of the right PEAs from the manufacturers' range for the respective process and possible applications in future will certainly be another challenge. In addition, it is necessary to define a suitable infrastructure as a framework for the operation of the modular plants. Compromises may also have to be made to make available PEAs usable for one's own processes. Figure 3 summarises the deliverables and responsibilities of manufactures and owner/operators companies in modular plant design as described here.

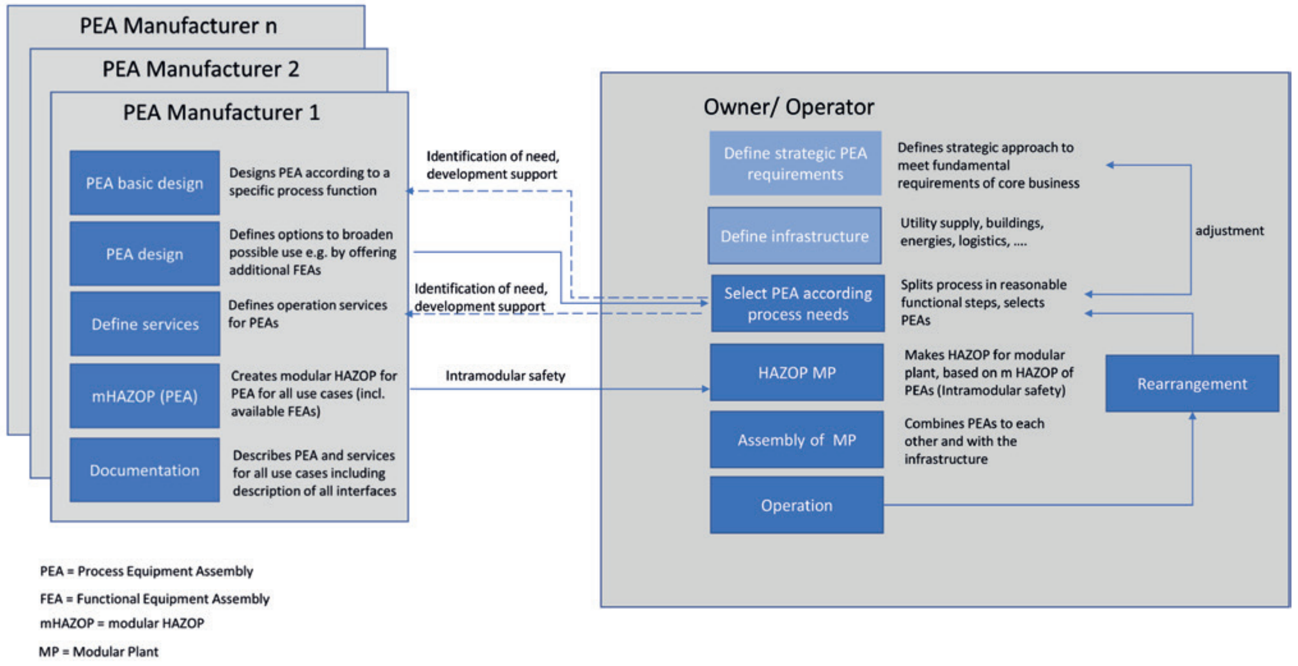

Figure 3: Deliverables and responsibilities of manufactures and owner/operators in modular plant design

2.2 Documentation

The PEA manufacturers must describe very precisely the framework conditions for the operation of their PEAs. This means that a detailed description must be prepared for which operating conditions the PEA is suitable (positive list). This concerns material limits and physical, but also organisational boundary conditions. It must be pointed out that the operator takes on the role of manufacturer if they use PEAs outside the range specified by the manufacturer or modifies PEAs beyond the range intended by the manufacturer.

In order to increase the flexibility of PEAs, possibilities for adapting PEAs to future tasks (e.g. the exchange of PEA-internal FEAs or components) are to be described as far as possible as well. This leads to a much wider PEA application range. The detailed description also concerns services according to VDI/VDE/NAMUR 2658, which can be selected for the respective PEA. The description is not to be limited to ongoing operation, it shall also cover the entire life cycle of the PEA, in particular conditions such as flushing or cleaning, decommissioning and disposal.

The combination of process plants with different PEAs requires a safety consideration for the overall process. This task is the responsibility of the manufacturer of the overall plant (and thus in many cases the operator). The safety considerations in a modular hazard and operation study (mHAZOP) of the individual PEAs that were used to construct the overall plant are used as a basis for this. The disclosure of these in the mHAZOP with a detailed description of the risks and boundary conditions already considered is essential and must be part of documentation scope for PEA delivery (see Figure 3)

3 Descriptive example: Dosing-PEA

To illustrate and discuss the before mentioned engineering workflow for specifying and designing process equipment assemblies (PEAs) and the interplay between owner/operators and manufacturers, an attractive example was selected demonstrating different process functions and their possible implementations. From the multitude of unit operations and process functions in chemical and biochemical plants, a "Dosing PEA" was chosen, which is described in more detail for pilot plant application. The related workflow is summarized at the end of this chapter.

The starting point for the "Dosing PEA" is given by the definition of process functions that the PEA should offer. Here, the process functions were chosen as Dosing, Storage, Inerting, Temperature Control of the vessel or the feed stream at the outlet, as well as the optional process function Mixing. For each process function, a set of parameters was defined to be fulfilled by potential solutions offered by equipment suppliers. The process functions are described with their definition in Table 1 together with the necessary services/application areas to be performed.

In addition, each process function has to fulfil certain operating ranges (functional relevant attributes) that were specified as well. Besides the definition of process functions, some global attributes have to be set and described. These can be classified into three categories "Global", "Definition of interfaces", "Material specification". Table 2 exemplarily shows the parameters defined for the "Dosing PEA".

An exemplary Piping & Instrumentation Diagram is given in Figure 4 for the "Dosing PEA". It must be mentioned here that the P&ID does not describe a final and complete PEA and should only serve as a base diagram for the presented functions and services.

In the following a few points of the discussion with the manufacturers during the workshop are mentioned to show how the final design of such a PEA can be interpreted and finally be realised. The main parts of the "Dosing PEA" consist of a storage vessel and dosing pump, exemplarily depicted in Figure 4. The storage vessel is filled from the top left side by a control valve connected to a level control sensor. Type and size of the valves and sensors depend on the PEA size (vessel size) and must safely fulfil their functions. From top left side, the inert medium is connected to the storage vessel, secured by a check valve. On the top right side, the venting valve for the inert medium as well as the safety valve are connected to the storage vessel. Both lines must be connected to a safe exit line depending on the process media and local conditions.

According to the functional relevant attributes of the storage function, the storage vessel should serve for a nominal process volume of 1.0 to 1000 L, which means slightly higher realised internal volume to prevent flooding or malfunction of head space functions. The nominal process volume should be realised in certain steps according to existing norms or supplier´s experience. The dosing

Table 1: Global description of the process functions with their services.

Function	Dosing	Storage	Tempering PEA	Tempering Outlet Flow	Interting	Mixing
Definition	Transport of a fluid without or with precisely defined flow rate without explicit pressure increase	Providing a volume for the storage of one or more liquids or gases	Temperature control for the storage function, i.e. vessel and all media-wetted parts of the system must be temperature controlled.	Tempering for the function Dosing, i.e. only the outlet stream must be tempered	Displacement of atmospheric oxygen with suitable inerting agent to avoid flammable/ explosive atmosphere before and during operation/resp. quality requirement	Mixing = homogenisation of concentration and temperature distribution
Services / Applications	Provide mass/volume flow (stationary) (fixed/variable (external) setpoint)	Intermediate storage of a liquid e.g. for vessel change, hold between 2 levels	Heating (parameterisable ramp)/ explanatory	Temperature constant on hold	First inerting via flow through to target value (O_2/time/interval)	Keep homogenity via variable power dissipation (on given value)
	Fixed amount/volume dosing (batch) (fixed/ variable (external) setpoint)	Manual filling (evtl. procedures)	Cooling (parameterisable ramp) / explanatory		First inerting via pressure swing (overpressure) to target value (O_2/time/interval)	Generate homogenity via variable power dissipation (on given value)
	Empty „internal“ container/system emptying	Automatic filling (evtl. procedures)	Temperature constant on hold / explanatory		First inerting via pressure swing (vacuum) to target value (O_2/ time interval)	Analytics measurement point
	Ramp functions (internal parameter setting)		Set point temperature (parameterisable ramp)		Permanent inerting via flow through (on flow rate)	
			Parameter: inner temperature/jacket temperature/optional inlet temp. /optional outlet temp.		Permanent inerting via flow through (on pressure)	

Table 2: Global attributes defined for the "Dosing PEA".

Global			Aligned
1	Inertable / optional FEA	[Y/N/other]	Optional FEA(s) integrated into PEA in terms of automation and thus safety technology
1.1	Pressure-swing excess pressure	[Y/N]	Y
1.2	Pressure-swing vacuum	[Y/N]	Y
1.3	Purging	[Y/N]	Y
2	Media resistance	[material(s)]	stainless steel, 316 L, 1.4571
2.1	Sealings	[sealing material(s)]	PTFE, FFKM
3	Suitable for operation in hazardous areas	[Y/N]	Y
3.1	Equipment category 1/2G		ATEX zone 0/1
3.2	Temperature class		T4
3.3	Explosion group		IIB / IIC
4	Operating time	[h/day]	24
5	Service life (taking into account the maintenance intervals)	[h]	20000
6	Permissible load cycles/shift frequency	[-]	5/min
7	Operation mode	[batch / conti]	both
8	Insulation	[Y/N]	Y
9	CE certification	[Y/N]	Y
10	Design code	[DIN, ANSI, AISI, ASTM, ASME]	DIN

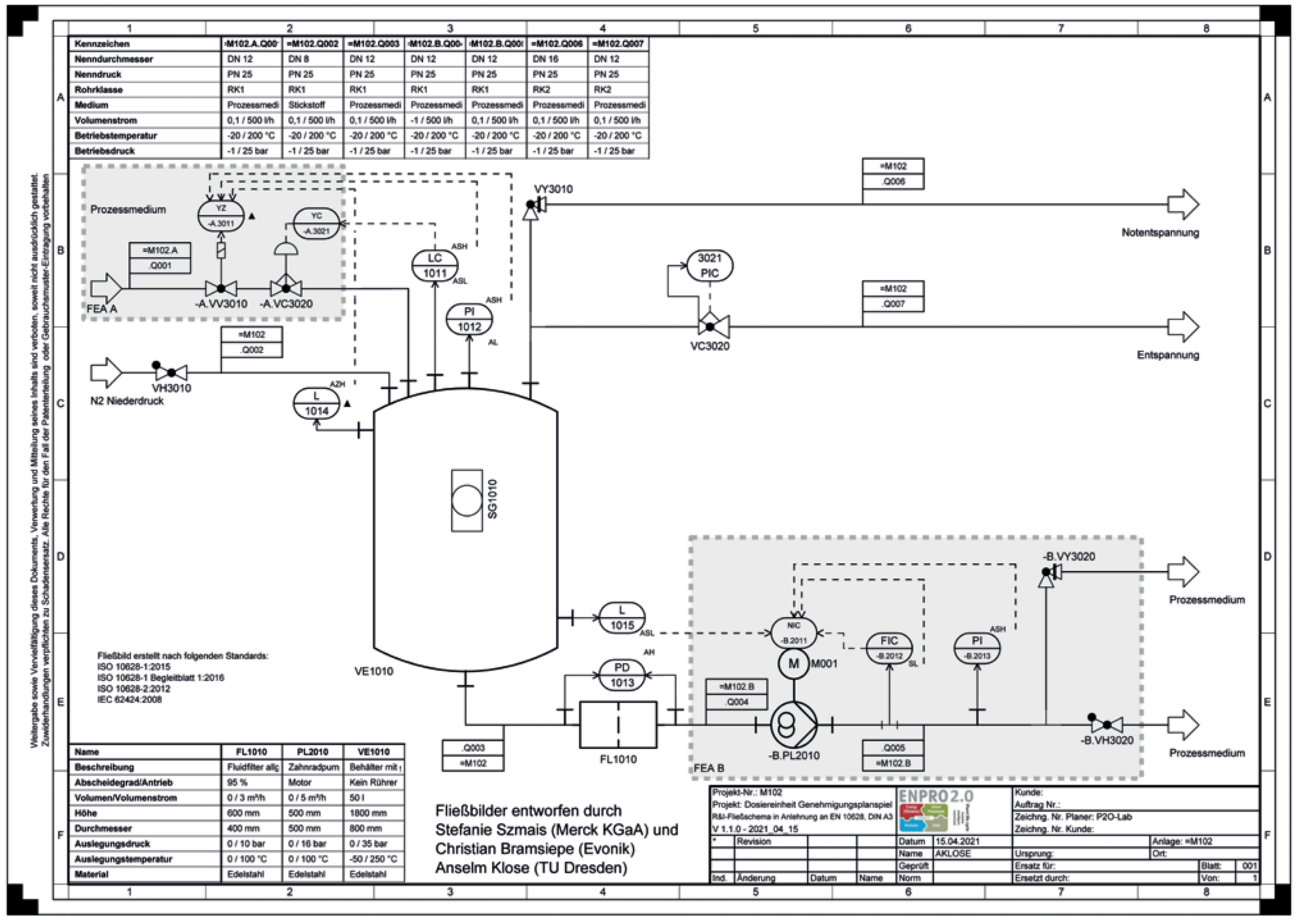

Figure 4: Exemplary pipe & instrumentation diagram of the "Dosing PEA"

Table 4: List with process media properties

Properties (20°C, 1 bar abs)	unit	Typical values
density	[kg m^{-3}]	750 to 1500
viscosity	[mPa·s]	0.2 - 500 Newtonian behaviour
vapour pressure	[Pa]	solvents, acids, bases
boiling point	[K]	see global parameters for temperature range

pump is depicted in the lower right part of Figure 4 and should deliver a feed rate ranging from 0.5 to 500 L h^{-1} (see functional relevant attributes of the dosing function in Table 3), eventually split into two or more ranges depending on the vessel size. The feed rate of the pump is controlled as well as the supply pressure up to 25 bar g. The dosing pump is protected against particles (if necessary) and dry run with a level control sensor or other suitable control setup. The feed line is protected against high pressure and back flow from the succeeding process steps. The entire PEA is controlled by an own control unit providing a MTP protocol (Modular Type Package, see guideline VDI/VDE/Namur 2658) with the elements (services) of Storage & Filling, Dosing, Inerting, Tempering, and Mixing (optional) together with the related operational & safety measures. Thus, the PEA has its own logic controller "on board" and can be operated as single, independent unit, but also integrated into a larger plant following the POL concept (Process Orchestration Layer, see VDI/VDE/Namur 2658 in Figure 1).

According to the global attributes of the PEA (see Table 2) the operating time is 24 h/day with standby/hot standby of most relevant parts. The replacement of the pump must be possible (FEA concept) for a better regular maintenance and control. The PEA redundancy is often better given by a second PEA than by a redundant pump. The service life must be 20 000 h considering the typical maintenance intervals. The permissible load cycles/shift frequency are 5 min^{-1} with possibly lower values for large pumps. Both operation modes of batch and continuous dosing should be covered by equipment and via the control system / services. Main parts must have a thermal insulation, which is described in more detail in the process function Tempering / Temperature control. The entire PEA must have a CE certification following the design code of ASME / DIN / DGRL.

Table 3: PEA process properties at interfaces to prior or succeeding PEAs

	per interface (process + utility)			
Feed in	perm. temperature (max.)	[°C]	200	limiting for polymers, possibly 150 °C as upper limit, 200 °C as option
	perm. temperature (min.)	[°C]	-20	Temperature range for seals and oils as option, approx. 2-3 intervals depending on pump type
	perm. pressure (max.)	[bar g]	25	possibly divide pressure ranges into approx. 2-3 ranges, high pressure rather at higher temperature; storage tank (-1) -0.1 to 0.5 bar g usual; pressure protection accordingly
	perm. pressure (min.)	[bar g]	-1	Limitation high tank wall thickness, mechanical seals, increased conditions list separately
	perm. volume flow rate (max.)	[L/h]	500 (FEA option)	divide into areas, adjust tank size to delivery volume, e.g. day-shift tank; 1000 L-> 1100 L working volume; e.g. 80, 250, 1100 L
	perm. volume flow rate (min.)	[L/h]	0.1	
feed out	perm. temperature (max.)	[°C]	200	generate high temperatures better on the pressure side
	perm. temperature (min.)	[°C]	-20	Generate low temperatures better on the pressure side
	perm. pressure (max.)	[bar g]	25	Behind the pump higher pressure up to 25 bar g permissible for diaphragm pumps OK
	perm. pressure (min.)	[bar g]	-1	
	perm. volume flow rate (max.)	[L/h]	500 (FEA option)	divide into ranges, match tank size to delivery volume, 1:20 can be realised; 0.5.-5, 5-50, 50-500 L/h staged
	perm. volume flow rate (min.)	[L/h]	0.1	0.1 - 5 is also possible

The liquid process medium can have a wide range with properties given in Table 4. Due to this wide range, the suppliers are encouraged to provide PEA-related information on the possible process ranges, e.g., a positive list of materials used for the equipment and sealing of the pump related to potential working fluids. This list may also give a narrower range and suggestions for alternative material outside of the positive range.

Due to the (bio-)chemical environment, the "Dosing PEA" must be suitable for operation in hazardous areas with particular emphasis on electronics/control units. Within the workshops the typical ATEX condition of EX zone (inside/outside) were excluded to simplify the discussion. All equipment should meet Eex II 1/2G IIB/C T4.

The important parameters at the interfaces are summarized in Table 3. They have to be checked with the parameters from connected PEAs (up- and downstream) as well as to the existing infrastructure.

The previous considerations show the specific workshop results of the ProcessNet working group "Modular Plants" and potential PEA manufacturers. These results are the thoughts of the persons involved in the workshop and should not be regarded as generally valid or binding. However, the approach can be generalised and transferred to other unit operations and PEA types. Figure 5 summarises this procedure as a flow chart.

From the anticipated process, a unit operation is chosen, and the required process functions are defined. These are transferred to automation services according to VDI/VDE/NAMUR 2658. Detailed process requirements are determined from the operation range(s) and further detailed by attribute values of the process functions according to VDI 2776. After the complete definition of the particular unit operation, the next one is defined according to this scheme until every process unit and utility requirement is defined for the entire modular plant MP. With these specifications, suitable PEAs can be chosen from an existing PEA pool or from different suppliers. The modular plant is configured from the defined PEAs and can be reconfigured according to the wider specification range of the PEAs.

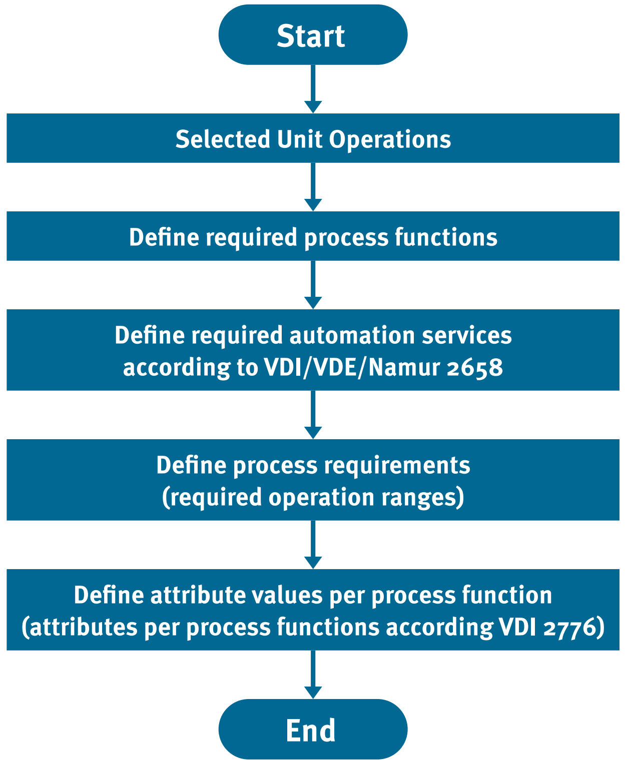

Figure 5: Generalised flow diagram for PEA development

4 Lessons learned

In several workshops, the “Dosing PEA” was discussed with experts from different owner operators, manufacturers and research institutions. Beside some specific findings for the different process functions of the “Dosing PEA”, some more general findings are summarized in the following that can be used as guideline for further PEA realisations. After typical information related to process functions, some remarks are given to common material selection and to potential open issues to be negotiated between manufacturer and plant operators. Table 5 gives a preliminary proposal for assembly clusters.

Process function *Dosing*:

» Volume flow rate should be given in typical ranges, e.g. 0.5.-5, 5-50, 50-500 $L\,h^{-1}$. A positive list for tolerable process media (organic solvents, acids, bases, …) and related parameters (temperature, pressure, concentration, …) should be provided by PEA suppliers.

» A suction side filter is suggested as protection for pump for higher reliability.

» The pump should be easily changeable as defined in the FEA concept.

» It should be checked, if the dosing pump with a feedback line to the vessel can be used for mixing purposes in the Dosing PEA.

Process function *Storing*:

» Operating pressure should be realised in typical ranges (-1 bar g to 0.5 bar g; -0.1 - 0.5 bar g; -1 - 25 bar g for special applications). Some vessels may come with stage-wise pressure ranges due to material and design constrictions.

» Operating temperature should be realized in typical ranges (<0 °C; <150 °C; <200 °C). Material and media resistance should be defined in a positive list with typical material such as stainless steel (316 L, 1.4571, or similar) for construction material or PTFE or FFKM for sealings. Other material may be available on request.

» The vessel size can be given in reasonable steps, e.g. in a range from 5, 20, 50, 80, 250, to 1100 L.

» The vessel should be completely drainable.

» A protection against dry run of the pump should be provided.

» The vessel can additionally be equipped with spare nozzles at vessel head, additional sampling points and connections, and drain connections at low points.

» An initial shut-off valve beneath the vessel is helpful for pipe work or pump exchange. For large pipelines, thermal expansion elbows might be necessary in the pipes under the vessel.

Process function *Inerting*:

» It is recommended to manually perform the initial inerting.

» For overlay with nitrogen, a flow monitor/O_2 sensor is necessary, the related mHAZOP is supplied by the vendor.

» Vacuum and overpressure inerting are recommended in glass and stainless-steel vessel, respectively.

» The service **Inerting** is mandatory for the dosing PEA and must be performed automatically in most cases.

Process function *Temperature control of the vessel (optional)*:

» It is recommended to maintain the vessel temperature by electrical trace heating; rapid heating of the vessel by a heating jacket, or alternatively by an electrical heating rod.

» Cooling media should be compatible with chosen material (e.g. chlorides).

» If necessary for heating/cooling, it should be determined whether an additional thermostat is provided by vendor or supplied by operator.

Process function *Temperature control of the outgoing medium (optional)*:

» This arrangement is often the preferred solution with heat transfer at outlet (FEA concept).

» It might be necessary to provide ATEX proofed electrical heaters.

» Tempering the outlet flow is only valid for the service Dosing, i.e., only the outlet stream must be tempered.

» In case of non-sensitive process medium this might be the better option than heating the entire vessel.

Process function *Mixing (optional)*: The optional process function ***Mixing*** can be performed with a recycle line from behind the pump to the vessel instead of a stirrer in the vessel, see process function Dosing.

4.1 Materials selection

The corrosive properties of the chemicals used as well as the operating conditions temperature and pressure have a decisive influence on the materials selected. How

Table 5: Proposal for possible clusters or assembly groups of modular equipment

Matrix Dosing

	Feature	**division to sub-groups or clusters**			**no. of sub-groups/ feature**	**Remark / reason for division into sub-groups:**
Function “Dosing”	Pump delivery rate [$L\,h^{-1}$]	0.5 - 5.0	5.0 - 50	50 - 500	3	Division to similar control range 1:10
	Max. discharge pressure [bar g]	25			1	Pressure may be higher e.g. 100 bar g
	Material piping	acid / brine		solvents	2	Materials shall be distinguished. There is no “universal material”, especially when considering the wide range of application and operation conditions.

Matrix Storing

	Feature	**division to sub-groups or clusters**			**no. of sub-groups/ feature**	**Remark / reason for division into sub-groups:**
Function “Storing”	Tank volume [L]	5, 20, 80, 250, up to 1100			5 or more	steps depend on manufacturer
	Classification acc. to PED (DGRL)	no category, P <= 0.5 bar g	Category I 0.5 < p <= 10 bar g	Category II p > 10 bar g	3	Within EC, PED is applied. Without division to sub-groups the tank will be subject to category II, which may cause higher costs, although for the particular application a category II classified tank will not be required.
	Material tank	stainless steel grade 5, e.g. 316L (1.4404)	acid / brine		2	Materials shall be distinguished. There is no “universal material”, especially when considering the wide range of application and operation conditions.
	Temperature [°C]	e.g. < 100	e.g. > 100		2	Potential division e.g., due to characteristics of substance handled or the combination of substance and tank material
	Heating/insulation	no category, P <= 0.5 bar g	yes		2	It may be useful to plan for tanks with and without heating. Heating requests insulation as well, even if it is only meant for protection of personnel. It may just cause additional costs without any need.

Legend: The division should be read in horizontal direction only.
Blue shaded cells show the proposed no. of sub-groups
Cells vertically below the other have no relation to each other

these parameters can lead to numerous possible material selections is shown in the following with sulfuric acid as an example, which is probably the most common industrial reactant. Not every combination of pressure, temperature and acid concentration can be handled by a single material in a technically safe and economically feasible manner.

PVC (polyvinylchloride) and PVDF (polyvinylideneflouride) offer an inexpensive solution with a high resistance against chemical attack for sulfuric acid concentrations up to 98 vol.%, but have rather poor properties, when it comes to elevated temperatures or pressures. Series 300 grade stainless steels have excellent temperature and mechanical properties, while being modestly priced. Besides this they show good corrosion resistance at higher acid concentrations, but in a range between 20-90 % this dramatically decreases, which makes these materials unsuitable for several applications. Nickel based alloys such as Alloy 20 have extremely good mechanical properties, which enable them to cope with high pressure similar to 300 grade stainless steels, while having superior temperature and corrosion properties, which covers the complete concentration range of sulfuric acid. The drawback of these materials is their often prohibitively high price, which limits their use to few applications.

Table 5 summarizes possible clusters for dosing and storage PEAs as example taking in account to balance the requirement for a wide range of application and limitations by pressure, temperature, corrosiveness, standards, and regulations. The described subgroups are suggestions from participants in the working groups and might differ from vendor to vendor.

Besides the specific findings on the “Dosing PEA” some more general findings are summarized in the following that can be used as guideline for further PEA realisations.

4.2 Field of tension between conventional design and PEA approach

Operators of modular equipment have different and very specific requirements for dosing systems, which are shaped by the company-specific portfolio, processes, typical chemicals, and standards. The corresponding design is precisely geared to these requirements and limited (also for liability reasons), although a wider range of applications would be possible. For a module that can be used in a very broad field, the requirement profile changes from the specific to a performance spectrum as broad as possible. However, the associated variety is enormous for process engineering operations, physical and chemical properties of possible materials and associated boundary conditions. These demands can hardly be realistically achieved for the manufacturer, also with regard to an economic pricing of his product. The technical implementation, with which maximum coverage can be achieved creates a field of tension (controversy) between process requirements and possible performance parameters of the equipment. A possible solution can be the (smart) creation of different clusters that cover as many of the requirements as possible, see Table 5 as preliminary suggestion.

In addition to the technical limitations, official requirements and approvals for operation in regard to environmental protection for such a dosing PEA must also be considered. This dilemma can be solved using a **“positive list”** with physical and chemical properties, as well as suitable “**operating windows**” for the corresponding module. For the dosing PEA, it can be shown very clearly how process and equipment performance can lead to **clustering**: Formulation ingredients can have very different quantities but must be incorporated into the reaction in a reproducible manner with a high degree of accuracy. This refers to both: the delivery and its control via measuring instruments.

Since delivery rates of pumps and measuring instruments only have a decided accuracy over a certain range, a suitable clustering is required. As a result, the pipe cross-sections and internal volumes must also be adjusted accordingly in order to avoid or at least minimise dead volumes, high pressure loss, and possible ageing of process media.

5 White spots & outlook

The former DECHEMA Whitepaper Modular Plants [6] introduced the usage of modular logistics stressing important aspects as mobility and decentralisation of a modular production factory. These topics can as well be applied to research laboratories or to small-scale test pilot plants. Modularisation seen from such a wider system perspective may then cover building logistics and even internal modular reactor design as well (example: a modular fuel cell reactor offers up-scaling by up-numbering). The specific link to a smaller scale and some additional more generic topics which connects all scales will be exemplified in this chapter.

5.1 Aspects of (PEA) product management

At first glance product management does not seem to be the focus in research and development. However, this could be a missed chance. Research cycles are likely to shorten compared to the past seen from the background of a pressing need for new sustainable production technologies. This means that research projects should not only be faster compared to the past but also be more cost-efficient when dealing with limited research resources. Both aspects are core business in product thinking. Product thinking could mean that a PEA gets designed by a devoted team, which defines its scope, describes possible variants, and finally sells their “product” to the project team [7]. A product line might then consist of a larger number of standardized PEAs (e.g., in supply and analytic) and ideally a smaller number of more specific PEAs (e.g., with reaction capabilities). Such a practice allows for a fast exchange of PEAs among different processes including parallel prototyping and engineering. It also enables a shared-components approach among competitors as proprietary knowledge (a specific reactor design) may well be protected by sharing only less valuable supply or analytic PEAs among suppliers.

5.2 Work Environment

The type of modularity does not only depend on the application but depends also on the environment, in which the application shall be processed. A major distinguisher consists in the protection class like EX-zone or pressure conditions and scale of processing. Container plants might be the proper choice for the former two, while laboratory-type plants will fulfil most of other less protection-needing but perhaps more variation-requiring applications during experimental testing. There are similarities among both types of plants nevertheless which could be a base for common infrastructure standardisation. PEAs rely on supply and they come with interfaces. Both prefer ceiling type of supply rails before wall or (subfloor) rails [8]. Flexibility requires process granularisation in both types as well but with a lab-specific differentiator. A typical granule in a lab is a fume hood or a work bench which gives limits to the available PEA dimensions. Thus, a plant designed for a laboratory will ideally possess fume hood or work bench dimensions allowing for a simple integration in laboratory floor space planning (including lift accessibility) and even for a future exchange of work benches against such a plant [9]. Pilot-scale PEAs may follow other standards from transportation, e.g., transport palettes for forklifts, or infrastructural connections.

5.3 Setup of Test rigs & pilot plants

In addition to the need for a standardised building or laboratory layout (“vertical” standardisation) oriented on the ISA95 layer architecture [10], “horizontal” standardisation address PEA-to-PEA interfaces. Such interface functions could be considered a common task provided by a common supply (pipe) rail for all fluidic or gaseous media and get complemented by local PEA-assigned control cabinets for electric and data media rails. In this approach, a certain area in the plant is reserved for these tasks. The setup enables a future extension of the plant if a new PEA should be added. In the future some tasks of a central control system (PLC) could be executed directly by a local PLC in the PEA (advanced signal processing as predictive maintenance, self-optimizing control loops), but must be connected to the central control system for data display in the control room.

A certain degree of compactness, an advantage which both, containerised as well as lab-scale plants share, allows for a large degree of plant autonomy. Self-surveying safety measures and also individual waste management improve availability of the plant. Thus, a local issue as a plant shutdown due to a gas alarm does not influence other plants which are operated in the same lab.

5.4 Modularity on the PEA level

Data bus systems could be an archetype for fluidic supply to PEAs in a similar bus-like way. Analogue, the method of a fluidic bus system is then, not to pass pipes through a PEA but to pass by the PEA, which is a small but important difference to traditional plant engineering, which mostly uses shortest pipe routing. “Passing-by” means here interfaces can be collected on one side of the PEA and not on two or more sides as in the case of passing through a PEA. This approach allows for data bus architecture to establish standards as the known Modbus, Profibus or Ethernet systems. A data bus hardware which delivers an additional value for modularisation was recently developed with the EtherCat-P system. They proposed a system which combines electric power supply and indicates that power supply plus signal voltage supply as well as data transport can all be combined in one single cable with standardised plugs that could connect the abovementioned local control cabinets [11].

When combining data bus, electric bus and fluidic bus systems including pneumatic as a set of standard interfaces one comes close to the PEA-centered approach proposed by Nicklas [7], in which a project team is dedicated to a specific PEA and responsible for its plug-and-produce functionality and commercial success on the market. The latter aspect stresses the importance of product management as the driving force in modularisation.

5.5 Outlook/next steps

The authors and creators of MFD – Modular function development [12] distinguish between “primary development” and “product development”. Primary development means evolution of new functions which are unknown to the company. Product development then uses these new functions and combine them with already known and developed functions. The increasing demand for frequent new product launches cannot be met with an everincreasing speed of general development but with a modularized product that would permit to focus on new functions utilizing less company resources and time. The organisation will then be able to concentrate on thrusting challenges we are facing in energy transition by tackling new innovative technical solutions in their own product portfolio.

Although decentralisation of services can be encountered throughout our society to mention block-chain banking, remote server architectures or the web itself and renewable energy harvesting, we still rely on huge central factories for our (bio-)chemical processes. In the past, energy sources and their huge refineries were concentrated on a limited number of spots, while new sources such as wind and solar energy are essentially distributed sources allowing for new production ways. Onsite production next to local sources of energy will presumably deliver intermediate products to final producers in chemistry in the near future. The latter require new factory design principles. Due to increased transport costs for their refined value product (NH_3, MeOH), installation costs of local installations must be reduced. Here, modularity will help to decrease expenditure significantly.

Scalability could be a major driver as well. Recent reactor designs based on flat planar reaction chambers avoid such problems often encountered in voluminous tube or tank reactors. Circular economy demands reuse of substances to avoid waste substances. A revamp of chemical plants will not be a most obvious matter but could avoid waste facilities in addition when foreseen in a then modular design. It seems reasonable to assume that modularity coupled with scalability would foster reuse of existing PEAs during revamp of a facility. Herein, “reuse” includes design recycling as well.

Will decentralized production increase lot sizes of components? Most probably it will, when modular interfaces allow an easy exchange. This holds true for a wanted resilience in delivery queues, which was in pandemic situations a limiting inhibitor as recently shown. Energy dependency especially from centralized sources such as oil and gas can be a devitalizing factor to western economies just because of the comparably small number of resource owners with their own and sometimes contradictory political intentions. A self-sustainable independent and delocalized energy harvest of non-centralized wind and solar sources could avoid this.

So, how could the European Chemical Industry anneal itself against such challenges? There is a certain likelihood that - as always - cooperation helps. Meaning a European-wide cooperation supported by appropriate industrial principles which set modular standards as the here proposed set of PEA toolboxes. The latter could be the driver to create up-to-date facility design, decentral energy independency and circular economy just to mention some major aspects we will have to face.

Glossary

ASME:	American Society of Mechanical Engineers
ATEX:	ATmosphères EXplosibles, explosive atmosphere
Compatibility:	capacity of two or more systems for the exchange of information, materials, energy and media
Engineering process:	conceptual, basic and detailed engineering including automation
DECHEMA:	Society for Chemical Engineering and Biotechnology
DGRL:	German pressure vessel code
DIN:	German Institute of Standardisation
EX:	see ATEX
FEA:	functional equipment assembly
FFKM:	perfluoroelastomeric compounds
HAZOP:	Hazard and Operation study
MFD:	modular function development
mHAZOP:	modular Hazard and Operation study
Modbus:	communication protocol
MP:	modular plant
MTP:	module type package in automation
NAMUR:	User Association of Automation Technology in Process Industries
PEA:	process equipment assembly, similar to module
P&ID:	pipe & instrumentation diagram
Plug-and-produce:	Technology that allows an easy integration, removal or exchange of production equipment without the need of a specialist for the reconfiguration
POL:	process orchestration layer
Profibus:	communication protocol
PTFE:	polytetrafluoroethylene
Services:	Automation representation of process functions
VDE:	Association for Electrical, Electronic & Information Technology
VDI:	The Association of German Engineers
VDMA:	Association of German Mechanical and Plant Engineering
ZVEI:	German Electrical and Electronic Manufacturers‘ Association

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