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Automation architecture and engineering for modular process plants – approach and industrial pilot application

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Abstract: This contribution presents an architecture and engineering approach for modular automation systems that meet the requirements of modular production plants. The architecture is based on the German guideline VDI/VDE/NAMUR 2658 that describes the interfaces between process modules and the process orchestration layer. The approach has been tested within an industrial pilot application of Bayer AG. The novel automation engineering approach as well as the results of the pilot are shown in this contribution.

Keywords: modular plants, process automation.

1. INTRODUCTION

Modularization of process plants is seen as a promising way to solve upcoming requirements from process industry, such as improved flexibility and interoperability between plant assets [1]. A modular plant in this context consists of modules, which are encapsulated devices and apparatuses that likewise consist of process controllers and instruments. Every module has a small controller that takes care of automating the functions provided by the module, as well as fault handling and other automation tasks [3]. Each module (also known as "Process Equipment Assembly" – PEA) fulfills at least one process function, which is encapsulated and offered as a service [2]. All modules have process connections to other modules and an information connection to a so-called process orchestration layer (POL) [4]. Throughout this contribution, the term POL is used as defined in [17]. The POL in a modular plant is used to orchestrate the modules, i.e. to visualize the modules in a human machine interface (HMI) and to control and supervise the services provided by the modules.

One key element within the area of modular production plants is the standardization of the automation system interfaces between the module automation system and the POL. This has been standardized by a module description called Module Type Package (MTP), which allows the seamless integration of modules into the POL [4]. The MTP is a vendor independent description, which defines the interfaces to a module in AutomationML [5]. Therefore, it can be used to integrate modules into the POL, independent of the vendor and type of the controllers used for the module. The concepts of modules, MTP and POL have been implemented in a joint effort of the authors and tested in a pilot plant at BAYER AG.

The structure of this contribution is as follows: Section 2 provides the state-of-the-art of modular plants and their automation. In Section 3, the novel engineering approach for a POL is described; especially how the generic information contained in the MTP is transferred into a specific operation environment for the plant. Section 4 shows the industrial pilot application and how the prototype developed in the project has been used. Eventually, section 5 summarizes the results and concludes with an outlook. The scientific methods applied are described in more detail in [12], [16], [22], [23] and [24], whereas this manuscript focuses on the implementation and the results achieved. Together they provide the full picture of the approach.

2. State-of-the-art

Conventional process control systems are not able to meet the requirements of modular production plants, especially the fast integration of modules [7]. While in the manufacturing industry, the modularization of packaging cells is already established and can be implemented with PackML [8], until recently production plants in the process industry have always been designed in a monolithic fashion. Only recently, modularisation has been considered of importance in the process industry as batch sizes are getting smaller and the required time-to-market shorter. Requirements for a modular process automation system have been published in the Namur Recommendation 148 (NE148) [9]. Based on the NE148 and a white paper published by ZVEI [10], first approaches for the modularization of the automation system for the process industry have been shown on the Namur general assembly in 2014 [6]. The DIMA (decentral intelligence for modular plants, in German: Dezentrale Intelligenz für Modulare Anlagen) [11] concept, based on a proprietary automation solution, was the first working demonstrator of a modular automation system. Subsequent standardization effort resulted in several parts of a German VDI (Association of German Engineers) guideline, VDI/VDE/NAMUR 2658 Part 1-4 (called VDI 2658 hereafter) [10-13]. VDI 2658 describes the interfaces of modules in the process industry and has been submitted to IEC to become an international standard.

A basic concept of the modularization of the automation system is the encapsulation of the process functions into services. Such concepts are well known from software engineering, object-orientation and service-oriented architecture [12]. In the process industry, before modular automation systems have been investigated, a concept called state-based control [13] has been used. State-based control aims at a similar functionality by dividing a process into functions. Each function is represented by a state-machine that shows the current state of operation that is similar to phase-logic concepts from batch operation [14] or for continuous plants [15]. Considering those, first concepts for service based modular automation systems have been developed [16]. Before the VDI 2658 has been published, a very general engineering and architecture of modular plants have been discussed in [4].

The engineering of modular plants is divided into two phases, according to VDI 2658 part 1 [20]: a) project independent module engineering and b) project dependent plant engineering. The module engineering results in a pre-defined general module type that has an automation system inside, taking care of the module functions. The second result is the MTP describing the interface of the module, including the modules services [17]. The MTP is used during the second engineering phase for the POL to seamlessly integrate the modules [6]. The POL is used to orchestrate the module services. Orchestration in this context means executing the module services in a specific order that is required for the production process. The engineering workflow is depicted in Fig. 1.

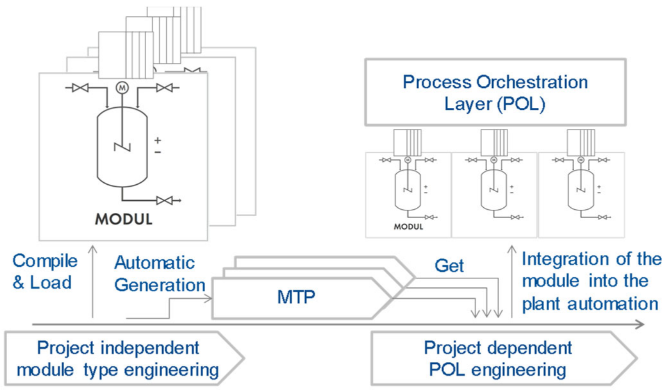

Fig. 1. Engineering of modular process plants (refer [4])

The modules each provide an OPC UA server interface that provides all information required for vertical communication.

The POL uses an OPC UA aggregating server in order to aggregate all OPC UA servers of all integrated modules into a single interface. In the following, the orchestration on the POL is described.

3. Engineering of the Process Orchestration Layer

The POL, as described in section 2 and in more detail in [17], is located above the modules in the automation hierarchy. The POL can in general be implemented by any automation vendor, however, this chapter describes the engineering of the ABB POL (basing on ABB System 800xA) [18]. The POL takes care of orchestrating the modules and their services, e.g. starting, stopping, pausing, holding and visualizing them and shows the module's HMI, according to the module specification as defined in the MTP. In the first engineering step, by evaluating the content of the MTP, the POL receives all required information to integrate the module into the operation of the plant (this is often called "plug & produce"). In a second engineering step, the topology of the plant is created, based on the inputs and outputs of the modules as specified in the MTP. The inputs and outputs are process input and outputs, described as *Source* and *Sink* objects in the MTP, according to [21]. The inputs and outputs of adjacent modules are connected, both in the real plant (to allow for product transport) and in the topology editor of the POL.

In a third step, the sequence control for the plant is defined by the plant's engineer. This is called "orchestration". This is similar to programming in Sequential Function Charts (SFC), one of the IEC 61131-3 [19] PLC programming languages. Within the SFC, it is possible to define steps, transitions, parallel and alternative branches, as described in IEC 61131-3. The major difference is that the actions assigned the steps are not programmed using IEC61131-3 programming languages. Instead, for every module of the plant, the engineer can chose the services offered by the particular module and can set the command parameter values and the service parameter values that should be send to a specific module service. An example for the definition of the orchestration is shown in Fig 2.

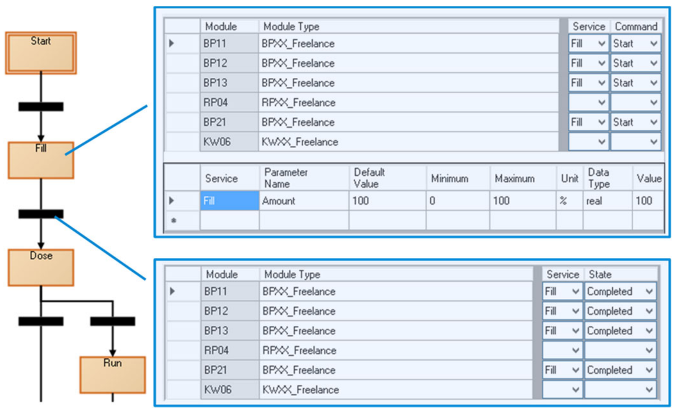

Fig. 2. Orchestration engineering tool. On the left side, the SFC is shown. The tables visualize the functionality engineered behind a step and a transition.

In a fourth step, executable software is automatically created for the POL, including the HMIs, module structures (hierarchical visualization of the modules in the POL), tags, and the faceplates (visualization of a single tags operation command, parameters and states). For each module, a display is generated, an example is shown in Fig 3. The display is taken from the MTP and the look and feel are adapted to the POLs look and feel. Within the MTP, the display as defined for the module is specified according to [21]. In [21] it is specified that every module visualization contains the equipment used in the module, the boundaries (buttons for navigation on the display) and the connection between these elements. The connections (pipes or signals) are automatically added to the display. Since the symbols of the POL objects and the lines of the POL are used for the visualization, the look and feel are automatically adjusted for all modules, independent of the control system used.

For every tag of every module, the faceplates and symbols immediately have access to the online values. The OPC UA nodes described in the MTP, as described in in Section 2., are referenced in the corresponding control objects. Based on the MTP description of the nodes and the information derived from the topology, this assignment can be done automatically. The server access is taken from the engineering of the topology that includes all relevant information about the modules' OPC UA servers.

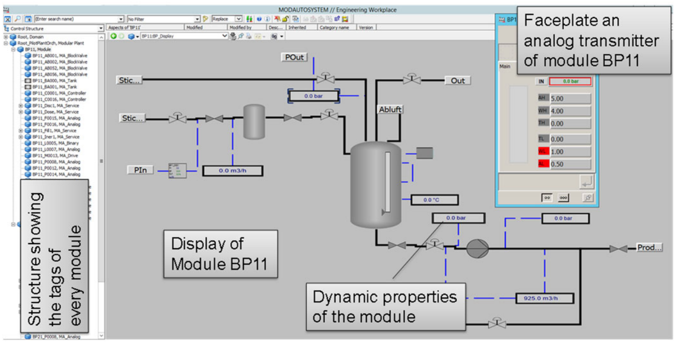

Fig. 3. Visualization of the modules in the POL. Left: Functional structures of the modular plant, right: visualization of a module and a faceplate for an analogue transmitter inside the module.

Service objects are automatically generated for every module, each containing a display showing the inner status of the service. From the MTP, the name of the service, the parameters used for specification of the service and the communication interface to the service are used to specify the corresponding service object. Like for the equipment, the OPC UA nodes that are used to control the service are specified in the MTP and can be assigned to the corresponding attributes in system 800xA for the service object. An example of a service display, containing the information about the inner state of the service and the parameters is shown in Fig. 4.

The sequences control, as specified for the orchestration, is automatically generated, either to run on a separate controller or within a PC based environment. An example is shown in Fig. 5 on the left side. Furthermore, an overview display is automatically generated, showing the topology of the modular plant and the sequences for the orchestration. An example is shown in Fig. 5 on the right side.

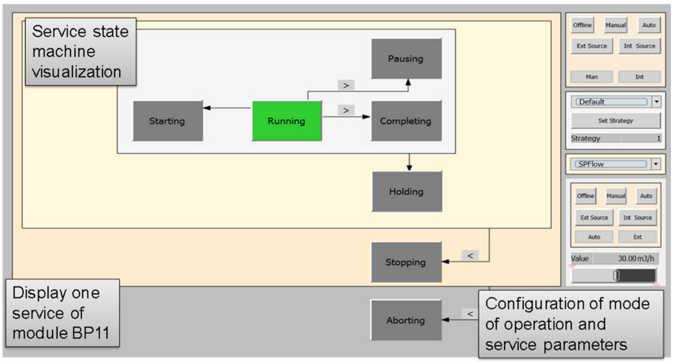

Fig. 4 Visualization of a service.

For every service of every module, such a display is automatically created. In the middle of Fig. 4, the current state is shown in green, and possible succeeding states are shown in dark gray. On the right, the mode of operation and the parameters of a service can be configured by the operator. All parameter visualizations, configurations and state machine are automatically generated in the POL.

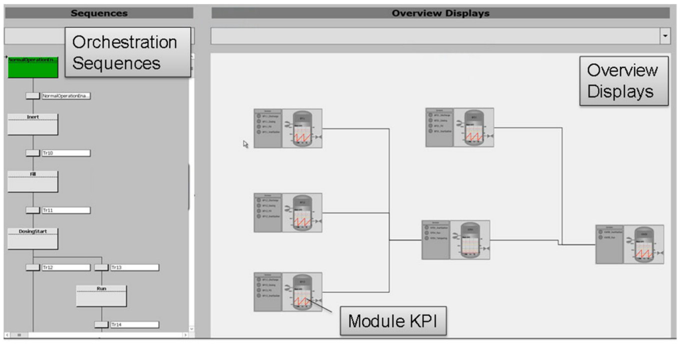

Fig. 5. Visualization of a modular plant. Orchestration sequences on the left, overview displays on the right. Every module symbol visualizes one KPI. The symbols show the state of every module service.

With the generation of the POL as described above, the engineering of the modular plant and setting up the POL is almost completely automated. The engineer gets a fully functional POL that complies with VDI 2658 and that is immediately able to orchestrate the modules once the network connection to the physical modules has been established.

4. Pilot application at a site of BAYER AG

The concept and the engineering tools for modular automation have been implemented at a site of BAYER AG in Leverkusen, Germany, on a modular pilot plant that is compliant to VDI 2658.

A. Module engineering

The pilot plant consists of three modules: pH measurement (left), filtration (middle) and heating and cooling (right), as shown in Fig. 6. Each module has its own controller and for each of them, an MTP had to be created by the module vendor.

The main function of Module 1 is filtration. Starting from a sterilized and disposable bag, the medium flows through a filter line. The filter line is redundant to enable a continuous process if one of the filters is blocked. Additional requirements for the process are to vent the filter lines and to clear the medium from the filter lines before and after the filter process respectively. To fulfil these main function, the following services have been defined and implemented: a) vent the filter line (fill the pipes with the medium), b) filtrate the medium through one specific filter line and c) clear the medium from the filter line.

Having redundant filter lines, the services add up to six services in total. Additionally, services relations have been implemented to prevent that both redundant filter lines run at the same time.

After the definition of the HMI, the tags, the services and the service relations, the engineering the first module were complete. This module was equipped with a Freelance AC700F controller.

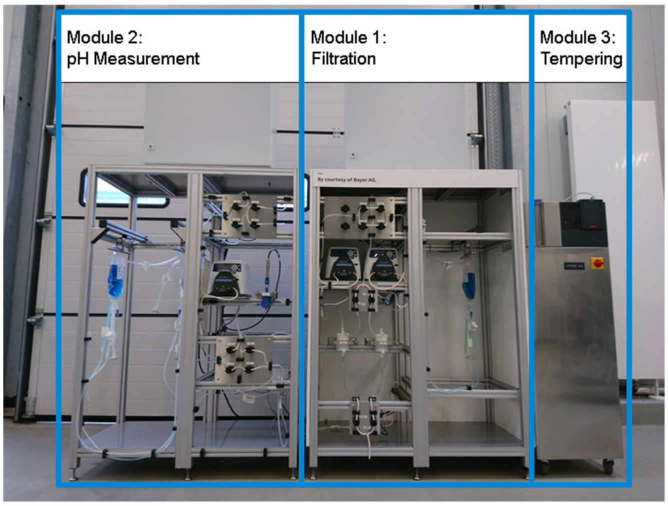

Fig. 6. Setup of the pilot plant at INVITE's demonstration area at the BAYER facilities in Leverkusen, Germany.

Module 2 has also been designed according to the bio pharmaceutical plant from Bayer. Therefore, the module type engineering workflow is similar to the first module. The services differ compared to the first module, since the needed functionality is different. The main function of the second module is to perform a pH measurement. This resulted in the following services: a) vent the measurement line, b) measure pH-value, c) clear the measurement line and d) calibrate the pH sensor.

Module 3 is a heating and cooling unit from the company *Peter Huber Kältemaschinenbau AG* (called Huber hereafter). Besides the module, the MTP has been provided by Huber. It consists of two services: a) circulation and b) tempering. Using the MTP, the main functions of the module can be executed from a supervising POL, because the MTP and the contained description of the services is compliant to VDI 2658. A deeper knowledge of the sensors and actuators of the module is not required to operate the module.

B. POL engineering

While the module engineering had been done on a module level and for every module individually, the POL engineering was done for the whole plant. As described in Section 3, the POL engineering was carried out in three steps:

First, the MTPs of the three modules was imported into the module type library of the POL.

Second, the topology has been defined. In this case it is a linear series of the three modules. Finally, the modules and module services have been orchestrated accordingly to implement the desired biopharmaceutical process.

C. Operation

Having the module engineering and the POL engineering finished, the commissioning of the real plant was done. At first, the flexible tubes for material flow were connected, and the communication was wired via Ethernet cables. The communication protocol between the modules and the POL is OPC UA which has been set up.

Regarding the commissioning of the modules, we observed significant savings in effort and time. Each module is equipped with about 15 field devices, has at least 2 safety functions and comes with 2 to 6 services. Although the necessary time for programming depends on the programmer, one can estimate a workload of 40 hours for hardware configuration, internal logic and service description if one had to start from scratch.

Using the modular approach, we have that information already stored in the MTP file. After the import of the MTP files, we just have to set up the communication to the respective OPC UA Server, which took not more than 30min.

In conclusion, the commissioning time dropped from 40 hours to 30 minutes since the module vendor has already done the hardware configuration, internal logic and service description. Therefore, the desired significant reduction of commissioning time has been confirmed during a live demonstration.

After commissioning, the service-based control of the pilot plant is has been validated. The plant has been operated using the automatically-generated displays as shown in Fig. 5 for every service. The plant has been operated on a service-based level, i.e. no knowledge of the modules' internal was required. This results in a significant reduction of complexity for the operator.

Plant safety is provided by internal interlocks. For instance, the valve at the input of the filtration module closes if the storage bag of the module is full. The preceding module, which is the pH measurement module, notices a rise of the pressure at the output and stops pumping. The intrinsic module safety was demonstrated using the pilot plant. It could be shown that the modular concept operates as expected.

Information about the process is provided to the operator by the different states of the services. Thus, the operator has all important information about the process and the plant, just by knowing the states of each service. For instance, in the case of an internal error, the filtration module switches from the state "running" to the state "stopped". In this situation, the preceding module has to stop as well. Therefore, when noticing that the filtration module is in the state "stopped", the pH module switches from "running" to "held". Now, the operator can identify the module where the error occurred by checking the state of the services. Again, this is a significant reduction of complexity.

Not only the manual control, but also the orchestration is on a service-based level. The chronological sequence of services runs in the order defined during POL engineering. Since safety is provided by each module individually, there is no safety issue when running services in different modules at the same time.

5. CONCLUSION AND OUTLOOK

The industrial pilot application has shown that the modular automation concept is valid. The engineering effort for the automation of modules could be reduced to a minimum. Subsequently, once a module has been commissioned, the engineering and commissioning of a modular plant, by combining these pre-commissioned modules, takes only a few minutes. The effort for plant commissioning is thus reduced to a minimum as well.

In addition, the project delivered valuable input for the standardization of the MTP. Results gained within the project have been fed back into the standardisation community (GMA, ZVEI, NAMUR) from the different perspectives of academia, industrial R&D, product development, and plant owner. Next steps are the international standardization activities at IEC level. The new work item proposal has been accepted recently.

During the project, the basic automation for modular plants has been developed. This includes operation and supervisory control. In order to have the same capabilities (or even more) like in conventional plants, further aspects of modular automation system have to be investigated. This includes, for example, alarm management, history management, advanced process control, inter-module communication, change management, and simulation and testing of modular plants.

Besides those topics, the plant lifecycle management requires deeper consideration when having flexible and changing modular plant structures. Further research is required how to systematically distinguish which part of the information should remain in the plant and which in the module when a module is taken out of service. Additionally, a concept for plant-wide module and plant management, containing several modules and several POLs, is required.

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