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Automation architecture for harnessing the demand response potential of aqueous parts cleaning machines

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Abstract
To reduce global greenhouse gas emissions, numerous new renewable power plants are installed and integrated in the power grid. Due to the volatile generation of renewable power plants large storage capacity has to be installed and electrical consumer must adapt to periods with more or less electrical generation. Industry, as one of the largest global consumers of electrical energy, can help by adjusting its electricity consumption to renewable production (demand response). Industrial aqueous parts cleaning machines offer a great potential for demand response as they often have inherent energy storage potential and their process can be adapted for energy-flexible operation. Therefore, this paper presents a method for implementing demand response measures to aqueous parts cleaning machines. We first determine the potential for shifting electrical consumption. Then, we adapt the automation program of the machine so that submodules and process steps with high potential can be energy-flexibly controlled. We apply the method to an aqueous parts cleaning machine in batch process at the ETA Research Factory.

Keywords Demand response architecture · Energy flexibility · Production machine · Cyber-physical production system · Industry 4.0 · Aqueous parts cleaning machine

Abbreviations

DR	Demand response
PLC	Programmable logic controller
OT	Operating technology
IT	Information technology
PC	Personal computer
CPPS	Cyber-physical production system
ERP	Enterprise resource planning
SCADA	Supervisory control and data acquisition
MES	Manufacturing execution system
OPC UA	Open Platform Communications Unified Architecture
TCP/IP	Transmission Control Protocol/Internet Protocol
IES	Inherent energy storage
MPC	Model predictive control
IoT	Internet of Things
VDI	Association of German Engineers e.V.
EF	Energy-flexibility
PID	Proportional-integral-derivative

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1 Introduction and motivation

The worldwide efforts to reduce CO_2 emissions lead to a massive expansion of renewable energies [1]. The fluctuating electrical energy supply of renewable power plants make a redesign of electricity distribution necessary. The previously valid principle of electricity generation following consumption is changing. Electricity consumers should intelligently shift their load with DR to adapt to volatile renewable generation [2]. Industrial consumers account for a large share of electricity consumption: for example in 2019, electricity consumption in the German industry sector accounted for over 43% of total consumption [3]. In comparison, the share for the European Union was about 36% [3] and for the USA

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about 26% [4]. Aqueous parts cleaning machines offer great potential for the use of DR due to their media tanks, which provide significant thermal inertia [2].

First approaches show that production machines can be used for DR. In [5] DR measures were implemented on a machine tool. Although initial research shows that cleaning machines have a high DR potential [2], these production machines have not yet been examined in detail. This examination is the subject of this paper.

Aqueous parts cleaning machines offer multiple options to shift their energy demand in time which can be used for different DR measures. First, the thermal inertia provided by built-in media tanks can be used as an inherent energy storage (IES) [6] allowing the implementation of the DR measure *store energy inherently* can be applied. Second, the process itself can be interrupted to apply the DR measure *interrupt process* or the process start can be shifted by the 'DR measure *shift start of job* [6]. Studies have shown that postponing the cleaning start has no influence on the cleaning result [7]. Initial research has investigated the use of cleaning machines for DR. In [2] the authors focus on bang-bang controlled actuators and analyse the tank heating system of a cleaning machine as an IES. More studies look at the electrical potential for DR of entire factories [8–10] or provide analyses for production machines such as machine tools [11–13] but do not focus on cleaning machines. In this paper we take a look at the IES capacity of cleaning machines as well as the cleaning process itself. Therefore we adapt methods used on other kinds of machines to aqueous parts cleaning machines.

The paper is structured as follows: After the introduction, we develop a method to determine the cleaning machine's potential for DR based on existing methods in Sect. 2. We first determine the DR potential of the individual machine modules (*store energy inherently*) and then analyse the cleaning process' potential (*interrupt process, shift start of job*). Second, we show how the machine's automation program can be adapted for executing DR measures in Sect. 3. In Sect. 4 we apply the method to an aqueous parts cleaning machine in the ETA Research Factory and validate the application in a field tests. Finally, we evaluate the method and give an outlook to future research in Sect. 5.

2 Analysis of the demand response potential of aqueous parts cleaning machines

In this section we describe our method for identifying the DR potential of aqueous parts cleaning machines at machine level. This is necessary to identify the modules that will be enabled for energy-flexible control in the next step. The ability of a machine to carry out DR measures is called energy-flexibility (EF) [14]. In some publications the terms EF potential and EF measures are used instead of DR potential and DR measures with equivalent meaning. In this work, we use the terms DR potential and DR measure. In our literature review, we consider potential analysis methods with both terms.

In the following we describe the main requirements for our potential analysis in Sect. 2.1. Then, we present a brief review of existing DR potential analysis for other machines and systems in Sect. 2.2. Finally, we use these methods, adapt them to our requirements and develop our method for the DR potential analyses on aqueous parts cleaning machines in Sect. 2.3.

2.1 Requirements for the analysis of the demand response potential of aqueous parts cleaning machines

We define our requirements for analysing industrial DR potential in order to evaluate how existing methods can be applied to aqueous parts cleaning machines:

- The potential analysis must be applicable or transferable to aqueous parts cleaning machines.
- The method's focus should be on electricity consumers so that consumers are identified that can adapt their electricity consumption to renewable production [10].
- The result of the analysis must be quantifiable to allow a comparison of different machines' DR potential [9].
- The analysis is exclusively carried out at machine level and is limited to module and process-related parameters of the machine. This is necessary since the manufacturing environment of the machine may differ and cannot be anticipated.
- The analysis should take little time and be feasible with known data and few energy measurements to provide a preselection among the machine modules and processes which should be used for DR measures.
- The DR analysis must analyse the impact of DR measures on the process and estimate their criticality, since a negative impact on productivity and quality must be avoided to ensure the reliable operation of the entire production.

We use these requirements to analyse existing methods for potential analysis.

2.2 State of the art: methods to estimate the industrial demand response potential

In the following, we present a brief literature review of existing methods to determine the DR potential in the industry sector. We sort the methods into two main categories: Determination of the potential of the factory as a whole and of individual production machines. As far as we know, there are no methods for the analysis of cleaning machines' DR potential in particular.

Most research focuses on evaluating the entire factory: One method is to map the factory as a simulation model and estimate the DR potential using simulation [15–17]. Other research attempts to assesses the DR potential based on DR measures [18, 19]. A different approach to examine factories is the evaluation via key figures and estimation of the potential based on axioms and the energy flows of the production site [8, 9]. Furthermore, a comprehensive method of analysing the whole factory and its processes is presented in [10]. The procedure includes an analysis at module level as well as the systematic development and characterisation of suitable DR measures. Another easier-to-use method is described in an industrial guideline by the Association of German Engineers e.V. [20]. Here, the suitability of entire machines is estimated and compared with that of individual machine modules. After an initial evaluation, more detailed energy measurements have to be carried out subsequently.

In contrast to the previously mentioned studies, the following research focuses exclusively on the machine level. [11] shows a method for the preselection of relevant modules regarding their suitability for defined measures which results in EF characteristic diagrams. In [12], the EF of machine tools in the production state is investigated. The approach is based on individual estimations for each module. [13] extends the approach of [12] with the methods from [8, 11] and also applies it to machine tools. This method does not require the prior definition of specific measures and results in a quantified value for the existing technical energy potential.

In addition to the above-mentioned methods for analysing the industrial DR potential, the VDI guideline 5207 *Energy-flexible factory - Fundamentals* should be mentioned. Here the authors define common DR measures for the whole production site including the machine level in detail [6].

2.3 Method for estimating the demand response potential of aqueous parts cleaning machines

To estimate the DR potential of aqueous parts cleaning machines we adapt existing findings to aqueous parts cleaning machines and extend them where necessary. We use the VDI list of common DR measures as a basis for the selection of suitable DR measures for aqueous parts cleaning machines. Then, we select suitable methods for calculating the DR potential of these measures.

The VDI 5207 guideline presents an overview of DR measures in production sites. The measures are divided according to the automation hierarchy into manufacturing level, manufacturing control level and enterprise control level. Due to the aforementioned requirements, only the following measures on the manufacturing level are relevant [6]:

- Interrupt process
- Change processing sequence
- Adjust process parameters
- Operate with bivalent energy
- Store energy (inherently)

As the first process step could be interrupted before its start, we also consider the measure *shift start of job*, even though it is located on manufacturing control level. In the following, we analyse it as part of *interrupt process*.

Not all DR measures are applicable to cleaning machines. The energetically relevant cleaning processes, which usually have the highest energy consumption, are cleaning and drying. Logically, the order of these cannot be changed, excluding the measure *change process sequence* from further consideration. In principle, it would be possible to adjust the process parameters of a cleaning machine. This could, however, affect the cleanliness and/or dryness of the part as a result, which is why we don't consider the measure *adjust process parameters*. We also omit the measure *operate with bivalent energy*, since we restrict ourselves to an electrically supplied cleaning machine. Therefore, we only consider *interrupt process*, including *shift start of job* if the interruption is before the first process step, and *store energy (inherently)* as DR measures in the case of an electrically supplied cleaning machine. The selected measures require potential analyses at machine component and at process level. For this purpose, we examine the existing methods for potential analysis.

Since we want to estimate the DR potential in order to have a preselection of the modules to be used for DR measures, in our case simulations are unsuitable due to the high effort needed for modelling. Furthermore, most of the approaches presented in Sect. 2.2 that take into account the factory as a whole [8, 9] are unsuitable, as we focus on the machine level. In other approaches [10, 18], specific DR measures have to be defined in detail prior to the potential estimation, including exact specification of lead time and call-off duration. This requires detailed knowledge about the use case and is too extensive for a preselection. Therefore, we choose the method for machine tools presented in [13] as a basic approach for potential analysis of the modules and the process. This approach is located at machine level and includes aspects for analysing machines from [12] and [19]. It is also partly similar to the VDI guideline [20]. However, only machine modules are considered instead of the whole factory. Thus, the evaluation criteria are more suitable for the analysis of machine modules.

The potential analysis is divided into two parts: First, the machine is analysed with a focus on its electrical consumers in Sect. 2.3.1. In this step, we identify the inherent technical DR potential. Second, we examine the cleaning process as a whole as well as its individual process steps with regard to their suitability for an interruption of a running process step in Sect. 2.3.2. Both steps combined form our method for the DR potential analysis of aqueous parts cleaning machines. An overview of the approach is depicted in Fig. 1.

2.3.1 Potential estimation for storing energy inherently

In accordance with [13], our analysis consists of three steps. The first step is the prioritisation of energetically relevant modules. We identify the nominal load $P_{n,i}$ of the i-th electrical consumer and its energy demand during the entire cleaning process W_i. The energy demand is calculated by

$$W_i = \sum_{s=1}^{k} P_{n,i} t_{s,i}, \tag{1}$$

where $t_{s,i}$ is the time a module is switched on during the process step s and k is the total number of process steps. If the machine consists of separate process chambers, as in case of throughput parts cleaning machines, the individual process steps are considered in the given order with their respective duration or throughput times. To compare the individual modules, we calculate the proportional share of energy demand ϕ_i for every module by

$$\phi_i = \frac{W_i}{\sum_{i=1}^{I} W_i}, \tag{2}$$

where I is the total number of modules.

As a result, we obtain two dimensions that we can use for further assessments of the modules' suitability for energy-flexible operation. Modules with a nominal load and a share of energy demand above specific thresholds, one for each feature, are considered in the further steps. These two thresholds are set by the user. We advise to choose the threshold values such that all modules with an energy consumption above a certain percentage of the maximum nominal load and of the total energy demand are selected.

The second step is to asses the suitability for DR measures during production. Here we determine how well a module can be made energy-flexible without affecting the cleaning process. For this purpose, we consider two criteria for determining the energy-process-independence of each module [12]:

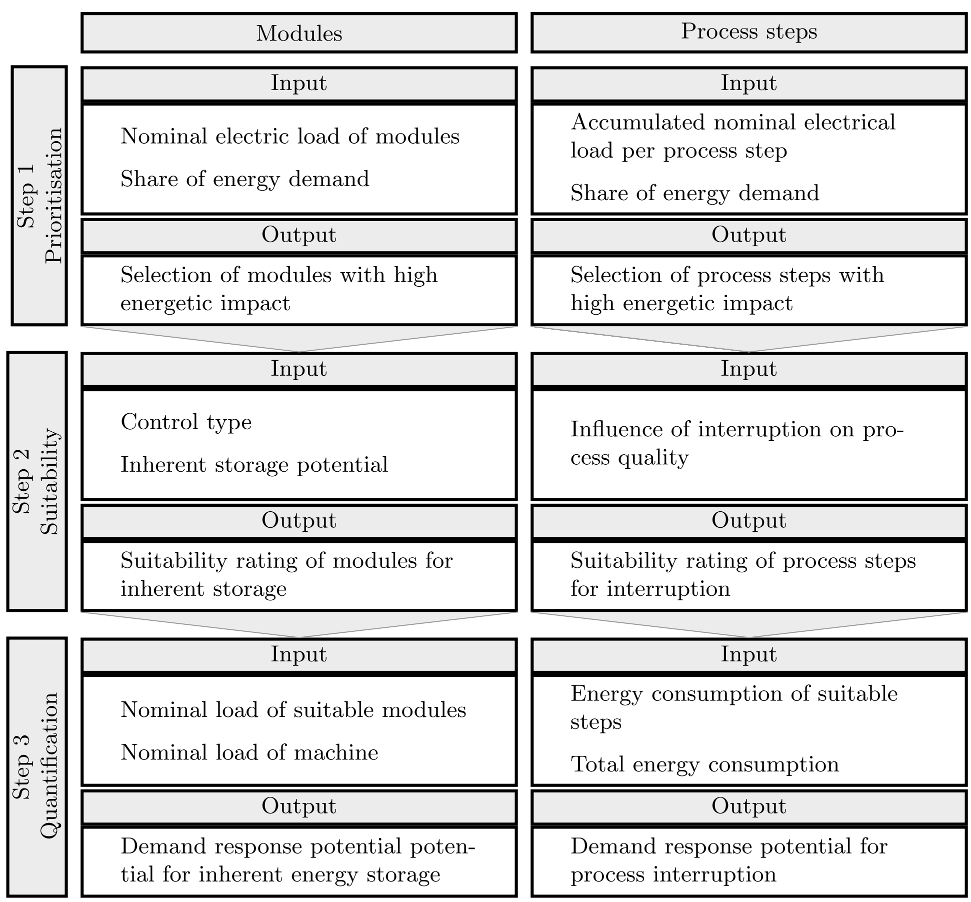


Fig. 1 Steps for determining the DR potential of aqueous parts cleaning machines divided into the analysis of machine modules and process steps, based on [13]

The *control mode* describes the dependency of the module's control on the actual state of the cleaning process. Modules can be controlled without any process or time dependence, for example infrequently switched on or off, making them nearly uncontrolled (C.1). They could also be switched at time intervals without any direct correlation to the cleaning process (C.2), for example temperature controlled tank-heating system, or in time intervals that depend on process-cycle states (C.3), for example a pulsing fan during drying. Finally, modules can be fully controlled in time and quantity (C.4), for example a frequency-controlled motor with varying speed that is controlled by a proportional-integral-derivative (PID) controller.

The *inherent energy storage (IES) capacity* determines the ability to store energy of the system a module is operating in. An example is a heating system consisting of a water tank as storage and the module tank heater. The capacity of a module system can be so large that it does not need extra energy input during one process cycle. Then, the module must not be switched on during the production process and can still perform its function if it is sufficiently charged prior to the process start (I.1). On the other extreme the capacity can be zero if electric energy is converted in real-time (I.4), for example a fan during a drying process. If a storage capacity is not big enough to cover the whole cleaning process it might be uncritical for the process (I.2) or it can be critical for the process (I.3). We determine the resulting energy-process-independence in a matrix based traffic light system, which is shown in Fig. 2.

In the last step the DR potential is quantified. We define

$$\mathcal{M} := \{i \mid i\text{-th module is green or yellow}\} \quad (3)$$

as the index set of all modules considered for energy-flexible operation, i.e., with green or yellow rating for their degree of energy-process-independence according to Fig. 2. Summing up their nominal loads $P_{n,i}$ the absolute achievable energy-flexible load

$$P_{\text{flex}} = \sum_{i \in \mathcal{M}} P_{n,i} \quad (4)$$

is determined [13]. Depending on the total rated power of the machine P_c, the ratio of power that can be used as energy-flexible load

$$R_P = \frac{P_{\text{flex}}}{P_c} \quad (5)$$

can be calculated [13]. In summary, the method leads to the technical DR potential to shift electrical load using inherent storage of the cleaning machine.

2.3.2 Potential estimation for interrupt process

The first step of the approach is carried out similarly to the module analysis. We calculate the accumulated nominal load and share of the total energy demand for every process step. Therefore, we first define

$$\mathcal{A}_s := \{i \mid i\text{-th module is active in the process step } s\} \quad (6)$$

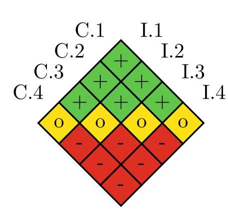
as the index set of all modules active in the process step s. To calculate the accumulated nominal load $P_{n,s}$ for the step s, we sum up the nominal load $P_{n,i}$ of all modules active in the process step to

$$P_{n,s} = \sum_{i \in \mathcal{A}_s} P_{n,i}. \quad (7)$$

To estimate the energy consumption W_s per process step s we have to consider the nominal load $P_{n,i}$ of the modules active in the process step and their programmed control time $t_{s,i}$. We calculate the energy consumption by

$$W_s = \sum_{i \in \mathcal{A}_s} P_{n,i} t_{s,i}. \quad (8)$$

Control mode
C.1: Nearly uncontrolled
C.2: Process-independent control in time
C.3: Process-dependent control in time
C.4: Entirely controlled in time and quantity



Inherent energy storage capacity
I.1: Capacity covers more than one cycle
I.2: Capacity covers less than one cycle but uncritical process
I.3: Capacity covers less than one cycle and critical process
I.4: Direct energy conversion in real-time

Energy-process-independence

+	High degree of energy-process-independence	→	highly suitable for energy-flexibility
o	Marginal degree of energy-process-independence	→	case specific suitability for energy-flexibility
-	Low degree of energy-process-independence	→	not suitable for energy-flexibility

Fig. 2 Assessment of the energy-process-independence based on [12, 13]

To compare the process steps with each other, we calculate the proportional share of energy demand ϕ_s for every step similar to (2) by

$$\phi_s = \frac{W_s}{\sum_{s=1}^{S} W_s}, \tag{9}$$

where S is the total number of steps. Next, we select the process steps with a proportional energy consumption above a defined threshold. These process steps are regarded for further consideration as they might be promising for an interruption of a running process step.

Second, we assess the possibility to interrupt the process. As pointed out before, only an interruption of a running process step of the process on machine level is considered. The interruption can occur at different points in the process. Consequently, the measure *interrupt process* [6] can be expressed as

- shift start of job (interruption before the first process step)
- interruption between process steps
- interrupt a running process step

We summarise the first two measures as an interruption before the process step begins.

An important requirement for implementing DR measures is to avoid compromising the process quality. Therefore, the evaluation of suitability should be either based on case-by-case assessments by experts or on scientific findings. According to [7], a delayed start of the cleaning process has no negative influence on the cleanliness of the part surface. Consequently, an interruption before the first step is usually feasible. As far as we know there is no research that determines if the interruption between two steps or during a running step of a cleaning machine influences the cleanliness of the product. Consequently an individual analysis of how an interruption influences the cleanliness must be made on a case-by-case basis. If the cleaning machine is operated in a continuous process, it is more difficult to interrupt individual cleaning steps than in a batch process. If one process is interrupted in continuous operation, other processes can also be influenced if they are not decoupled by intermediate storage where the components can be stored before passing through the next process step.

The assessment of the suitability is carried out by a traffic light system, as described in Fig. 3. If a running process step can be interrupted, it achieves a green rating. The possibility to interrupt before the start of a process step leads to a yellow rating. A red rating is given to steps for which none of the above measures is possible.

The third step, in which we quantify the DR potential of the process, is similar to the analysis of the modules, as we

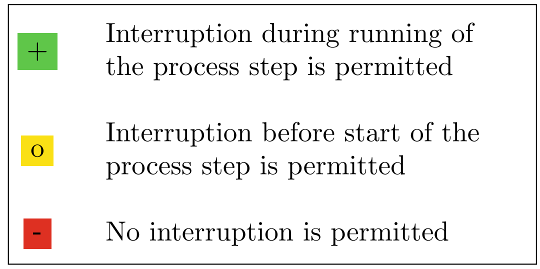


Fig. 3 The DR suitability of a process step is described by three levels indicating whether and when the cleaning step may be interrupted

consider all process steps with green and yellow rating. We define

$$\mathcal{S} := \{s \mid s\text{-th step is green or yellow}\} \tag{10}$$

as the index set of all steps with green or yellow rating according to Fig. 3. We calculate the absolute energy DR potential

$$W_{\text{flex}} = \sum_{s \in \mathcal{S}} W_s \tag{11}$$

and the ratio of our process we can use for DR

$$R_W = \frac{W_{\text{flex}}}{W_{\text{c}}}, \tag{12}$$

where the total energy consumption W_{c} is defined by

$$W_{\text{c}} = \sum_{s=1}^{k} W_s. \tag{13}$$

The overall result of the analysis is a total and relative load and energy amount for the measures *store energy (inherently)* and *interrupt process*. This expresses the technical DR potential and allows comparing the potential of different aqueous parts cleaning machines. However, this is only a best-case estimation, since the full potential for achievable energy-flexible load P_{flex} can only be reached if all selected modules are used for DR at the same time. Whether that is possible depends on the individual cleaning process. In the case of batch cleaning for example, the absolute DR potential W_{flex} represents the potential only before the first energy-flexible process step is carried out. After the first flexible process step is executed, only the potential of the remaining flexible steps is available. Furthermore, the machine's exact load profile and electrical consumption need to be measured to determine the exact amount of power and energy that can be used for DR.

Our approach fulfils the requirements defined in Sect. 2.1 and is appropriate for the preselection of modules that could be considered for energy-flexible control. However, to calculate and execute DR measures, information about the temporal availability of the machine is required. These information have to be provided by external energy control systems, which have information regarding characteristics of the machine's application context at the production site. The preselected modules and process must be enabled for external control so that the external control systems can execute DR measures. This can be done by adapting the machine's automation system.

3 Automation architecture for demand response on aqueous parts cleaning machines

Now that we have identified the potential of the cleaning machine for DR, the next step is to make this potential available. In order to control the modules and to interrupt the process, different approaches can be imagined. One idea could be installing additional relays to control the modules electrically. Though, we consider adapting the automation architecture as the best solution since it doesn't need additional hardware installation and can be provided by the machine's manufacturer ex works in the future. We first illustrate the shift of automation architectures from a hierarchical to a service-oriented system in Sect. 3.1. Then, we develop our concept for an automation architecture for DR on aqueous parts cleaning machines in Sect. 3.2.

3.1 Adapting the automation architecture from a hierarchical to a service-oriented design for demand response services

Up to now the, industrial automation architecture has been structured according to the automation pyramid defined in IEC 62264 [21], see Fig. 4. Production machines and their modules are part of the field and the control levels. The machines' sensors and actuators are located at the field level. They are connected to and controlled by programmable logic controllers (PLCs) at the control level. The control level is connected to high level systems such as supervisory control and data acquisition (SCADA) systems, manufacturing execution systems (MESs) and enterprise resource planning (ERP) systems which are located on higher levels. The automation pyramid ends at the company boundary and is not designed to communicate with entities outside the company such as a DR market [22]. In [22] the automation pyramid is extended by three additional levels to include the energy market. However, for the energy-flexible usage of production machines it is inconvenient to use the proposed automation architecture that consists of multiple levels: As requests from outside the business unit are brought in via the ERP system, all

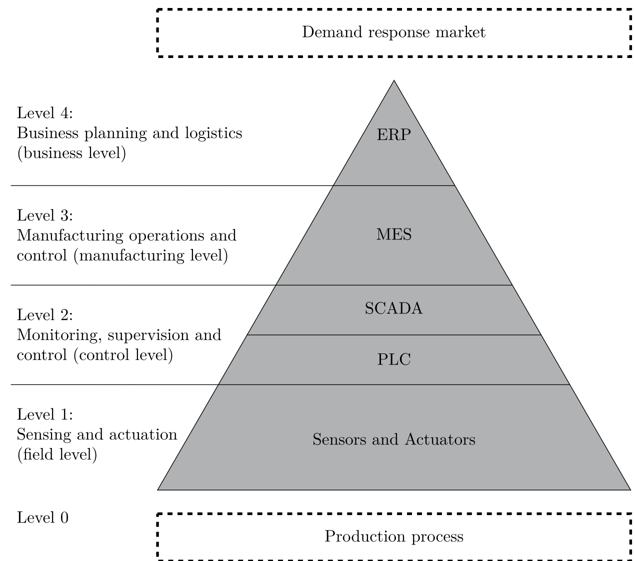


Fig. 4 Classical hierarchical automation pyramid with five levels based on [21]

other levels of the pyramid must then be traversed. This can lead to a very slow and complicated processing of DR measures. Therefore, we present an alternative concept in this paper.

To calculate DR measures, often complex optimisation procedures are used [23, 24]. These optimisation algorithms are usually provided in high-level languages such as C++, Java or Python and are executed on personal computers (PCs) on the information technology (IT) level [25]. PLCs which execute the DR measures are located on the operating technology (OT) level and their automation program is usually written in IEC 61131-3 languages [26]. The PLC automation programs on OT level are designed for fast and simple automation tasks that are executed in real-time but have limited capabilities for the implementation of complex algorithms. Optimisation algorithms often need a few seconds for their calculations whereas typical PLC tasks are executed in a guaranteed fixed cycle time of a few milliseconds. Therefore, the algorithms have to be deployed on the IT level separate from the automation program on the OT level.

We identified different approaches for the coordination of DR measures: First, the single machine can be part of an external electricity market or is controlled directly by the grid operator. Here, systems outside the company compute DR measures and the machine is connected directly to these external systems [22]. Second, the DR measures are calculated and executed for single machines or the whole factory by a central system that is located inside the company [27, 28]. Third, the cleaning machine can be part of a decentralised multi agent system where machines interact with each other to find a global solution near the global optimum [29, 30]. The traditional automation architecture is not designed for any of these machine interactions.

Due to the aforementioned factors, we believe that a new automation architecture design is needed for applications such as the energy-flexible operation of machines. One possible solution is to model the automation as a cyber-physical production system (CPPS). Cyber-physical systems are defined as computer systems which interact with other computational entities and are connected to the physical, mechanical world [31]. When applied to production and automation systems they are called CPPS [32]. This concept breaks the rigid automation hierarchy as CPPSs mainly consist of two main functional components: one high level area where more complex functions are implemented and a low level area with functions responsible for real-time data processing and control of the physical machine [32]. Both levels are connected by a third communication component that enables the link between the digital (cyber) elements and the physical elements of the CPPS.

In [33], a CPPS design called *automation diabolo* is proposed. It consists of three parts:

- the management and organisation level at the top,
- the communication layer in the middle and
- the field and control level at the bottom,

as shown in Fig. 5. In this design, the classical management systems classical management systems SCADA, MES and ERP are located at the top level and connected directly to the field and control level via a new communication layer at the centre. This has the advantage that management functions can address control functions simultaneously and without intermediate steps, thus enabling faster data flow and process execution.

Also, new services, including a DR service, can easily be added to the management functions. The services at the management level are usually executed in classic IT systems. These can be installed externally in the network or they can be part of the cleaning machine as an embedded or industrial PC. The services at the field and control level are usually executed in OT systems such as PLCs.

For the implementation of the communication layer, communication standards that can be understood by IT and OT systems must be used. In OT systems, simple electric binary or analog signals and fieldbus communication protocols such as Modbus or Profibus are used for the interaction between sensors, actors and the PLC. Communication between different IT systems is widely based on the Transmission Control Protocol/Internet Protocol (TCP/IP).

The usage of a service-oriented automation architecture for DR measures is already discussed in literature. In one concept, DR services are included in two interacting IT platforms [27, 28]:

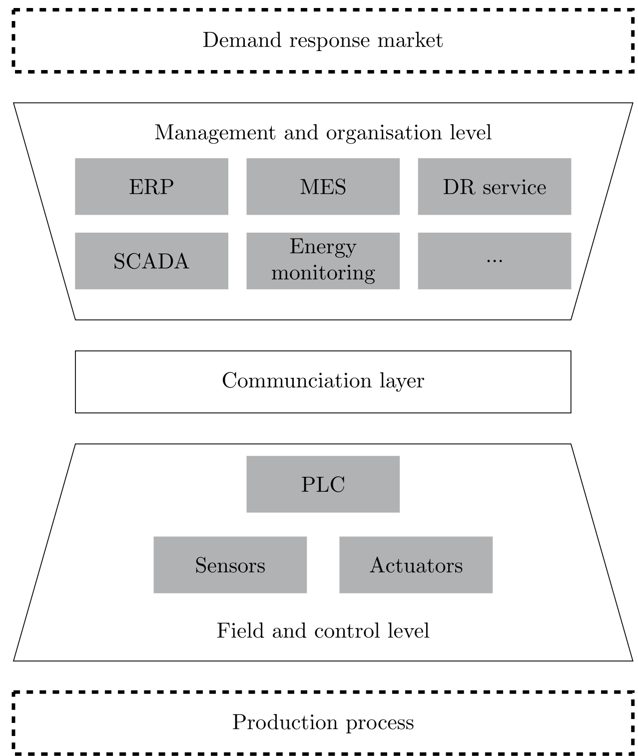


Fig. 5 Service-oriented automation diabolo designed for Industry 4.0 services such as DR Service, based on [33]

- On the consumer side, a company-side platform is connected to the factory and its machines. The platform's DR service coordinates the machines to carry out DR measures.
- The DR potential of the machine is pooled on the company-side platform and offered to a market-side platform managed by the grid operator. The pooled potential can be sold to a DR market on the market-side platform. If another market party buys the offered DR flexibility, the market-side platform demands a DR measure of the company-side platform that is carried out by the DR service.
- The company-side platform interacts with the market-side platform using the generic data model proposed in [34]. This data model describes industrial DR flexibility in a standardised way so that it can be traded by the grid operator. The model can be widely used for energy-flexible loads and storages in the industry sector.
- The company-side platform is connected to the machines control via the *Smart Connector* interface which is located on the communication layer of the automation diabolo.

Most of the interaction and calculation is carried out at the management level. This is only possible by using a service-oriented automation architecture.

The usage of a service-oriented automation architecture for DR measures in building automation is shown in [35]: Here, the authors focus on the modular object-based structure of the OT automation program that creates a hierarchical automation data model in the communication layer using Open Platform Communications Unified Architecture (OPC UA). The building automation program can communicate with a DR service located at the IT management level via the communication layer. The DR service optimises the operation of the industrial supply system controlled by the building automation based on a changing energy price. The authors emphasise the importance of guaranteeing safe operation of the supply system when it is controlled by DR services. Therefore, they include a safety function that interrupts control by DR services if safety limits are exceeded and activates the standard process control at the field and control level instead. The standard control controls the supply system until a safe state is reached, then it returns the control to the DR services again. An example is to keep the temperature in a thermal hot water storage within the safety limits and to prohibit external access in case the limits are exceeded.

In [2], the authors present a DR service that calculates the IES potential of hysteresis controlled production systems. The service is executed on an IT system at the management level. To calculate the potential, detailed information from the field level, such as the power demand or the current operating point of the machine, is required. Therefore, a connection to the field level is necessary.

In the following, we describe our CPPS approach focusing on the interaction between services at the management and field levels and the communication layer used for this use case.

3.2 Cyber-physical production system energy-flexible aqueous parts cleaning machine

For the energy-flexible operation of aqueous parts cleaning machines we define the following requirements for our CPPS:

1. IT-OT-interaction: DR services have to be deployed on IT systems separate from the OT automation program. The IT system can be included in the machine itself if we install an industrial PC that combines PLC functionality (OT) with a non-real time operating system such as Windows or Linux (IT). The IT system can also be located on a separate computer that communicates with the PLC. For both solutions, the communication layer must allow easy data exchange between OT and IT.
2. Inter-plant-communication: As stated above, the DR service can be located on the machine's IT system but it can also be located outside of the machine. The latter requires IT-OT-communication with other systems outside the cleaning machine. Therefore, the communication layer has to be modelled in a manner that enables this kind of inter-plant communication.
3. Scalability and transferability: The DR potential of an individual cleaning machines is limited. Therefore, it is reasonable to design the automation architecture such that it is as easily transferable to other machines and scalable for systems of different sizes. This way, a larger DR potential can be made available quickly and easily.
4. Process safety: Finally, the machine itself and humans interacting with the machine should not be harmed by the influence of external DR algorithms. Also, the quality of the cleaning process should not be compromised.

We propose a CPPS based on the automation diabolo [33] that takes all described requirements into account, visualised in Fig. 6. For energy-flexible production we add the DR services to the management level. The DR service decides if, when and how a DR measure is to be carried out. In the management level, additional services could be included for example a SCADA service that visualises actual machine states or an energy monitoring service that stores historic energy data in a database.

The communication layer connects the DR service at the management level to the cleaning machine and enables IT-OT-interaction and inter-plant-communication. Here, the information that is needed for energy-flexible operation of the cleaning machine is transmitted. Also, additional data points could be included here depending on the specific application, for example to provide information for additional services such as condition and energy monitoring. For the interaction between the DR service and the machine, we propose using an automation data model that includes information for the energy-flexible control of individual machine modules (*store energy inherently*) and the interruption of the cleaning process (*interrupt process*). In the following, we describe the data points that should be included in the automation data model for the interaction with DR services.

Direct control of individual machine modules for storing energy inherently requires information about the current status of these modules. Also, access to the module's control commands has to be established. Therefore, we include the following information for every module that can be used for storing energy inherently:

- *Nominal load*: The machine module's nominal load $P_{n,i}$ should be integrated. The value can be used to calculate the possible power or energy available for the DR measure. This information is also needed to offer the DR flexibility to a market [34]. The information is static and only changes if a module is physically replaced.

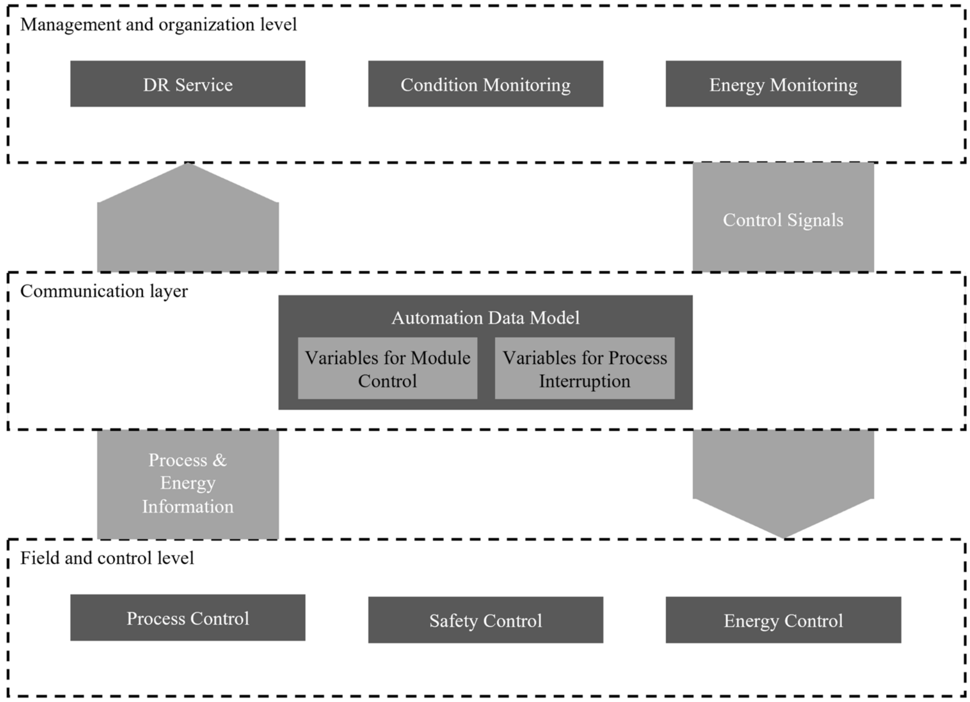


Fig. 6 Design of the cyber-physical production system for DR on aqueous parts cleaning machines with three levels based on the automation diabolo [33]. The process and energy information is communicated from field and control level to management and organizational level via the communication layer. The control signals are communicated in the opposite direction

- *Machine state correlation*: The machine states in which the module can be used as IES are described. We use the machine states *off*, *standby*, *operational* and *working* based on [36]. Most of the modules are only active and therefore can only be controlled while the machine is in the *working* state. However, a tank heating system can also be used during *standby*, for example. The correlation is static because it is determined by the machine manufacturer in the automation system.
- *Process step correlation*: The process steps in which the module is active are included. A module can only be controlled during specific process steps. For example, the air heater used for drying can only be controlled if drying is active. Like the machine state correlation the process step correlation is also static because it is specified by the machine manufacturer.
- *Power consumption*: The current power consumption of the module is needed as feedback if a DR measure is executed successfully. It can also be used as a parameter to predict the machine's future energy consumption. If the module's power consumption is not measured individually the machine's total power consumption can be used as feedback instead.
- *Operating point*: This can be the current switching state if it is a module that can only be turned on and off or the operating point as a percentage if it is a module working in continuous mode. The mandatory value is the basis to determine if the module can be used for load reduction or load increase at the moment. Also it is a feedback if the DR service is successfully controlling the module.
- *Process value*: By controlling the module the controller influences the process value. If for example the module is a heater that is keeping the tank temperature at a desired value, the process value is the current tank temperature. The current process value is needed to predict future machine behavior. For example the DR service may predict future tank temperatures depending on the control decisions to turn the tank heater on or off.
- *Flexibility limits*: This data point includes the upper and lower limits in which the energy-flexible module may operate, for example the temperature limits of a heating system. This information is used to determine the constraints in which the DR service can operate. It also may be used to calculate the possible DR measure duration a part of the characterisation as IES [2]. The flexibility limits can vary dynamically depending on the active machine state and process step. Also, a machine user can define specific flexibility limits that should be respected, for example to guarantee the cleanliness of the product.
- *DR set point*: The DR set point is the variable that controls the module directly. It is either the switching command (on and off) or the set point in percent or an absolute value for the module depending on whether it is operated in discontinuous or continuous mode. The value enables the control of the module by DR services.

Some of this information is static and does not change during machine operation and other data points may vary dynamically. Most of the data is accessed in read-only mode except for the DR set point which is written by the

DR service. An overview of the data points for storing energy inherently, their static or dynamic type and access mode is shown in Table 1

For *interrupt process*, information about the process status and the entire machine must be exchanged:

- *Step energy consumption*: The value shows the total energy consumption W_s per step for all steps that can be interrupted. It can be used to calculate the possible amount of power or energy of the DR measure. The step energy consumption varies depending on the step duration set by the user of the cleaning machine. It is constant during the cleaning process.
- *Machine power consumption*: Similar to *store energy inherently*, the current power consumption of the whole machine is the feedback if a DR measure is executed successfully.
- *Machine state*: The value shows the current machine state: *off*, *standby*, *operational* or *working* [36]. An interruption is only possible if the machine is in *working* state and the process is running.
- *Interruption countdown*: The value shows the duration until the next position for process interruption is reached. With this value the DR service can calculate the next possible moment for execution of a process interruption and consequently the DR measure.
- *Interruption command*: This variable is set to true to interrupt the process or between process steps. The process continues if the variable is set back to false. It enables the process interruption for DR services.

All these data points show dynamic machine information. As in the measure *store energy inherently*, most of the data is accessed in read only mode except for the interruption command. The overview of the data points for *interrupt process*, their static or dynamic type and access mode is shown in Table 2.

The cleaning machine's automation program is located at the control level. We suggest to use a modular object-based design when implementing the automation program since it enables easy extensibility and transferability. We include the functionalities *process control*, *energy control* and *safety control*:

- In *process control* the standard non-energy-flexible machine operation is monitored and controlled. This includes controllers for the individual machine modules and for the process flow. Each module of the cleaning machine should be represented by one object that includes its controllers.
- *Energy control* is an extension of the *process control* for energy-flexible production of the cleaning machine. The *energy control* functionalities can either be integrated in

Table 1 Variables included in the automation data model for the energy-flexible operation of machine modules

Variable	Use for DR service	Type*	Access*
Nominal load	DR measure's power or energy value	s	r
Machine state correlation	DR measure only when active	s	r
Process step correlation	DR measure only when active	s	r
Power consumption	Feedback of DR measure execution	d	r
Operating point	Load reduction or load increase	d	r
Process value	Prediction of machine behaviour	d	r
Flexibility limits	DR measure constraints	d	r
DR set point	Direct control of the module	d	w

For each variable its use, static or dynamic type and access mode are described

*s—static, d—dynamic, r—read, w—write

Table 2 Variables included in the automation data model for the energy-flexible process interruption of the cleaning machine

Variable	Use for DR service	Type*	Access*
Step energy consumption	DR measure's energy value	d	r
Machine power consumption	Feedback of DR measure execution	d	r
Machine state	Availability for interruption	d	r
Interruption countdown	Next moment for DR measure	d	r
Interruption command	Enable process interruption	d	w

For each variable its use, static or dynamic type and access mode are described

*s—static, d—dynamic, r—read, w—write

the *process control* objects or implemented separately. If the *energy control* is integrated in the *process control* it replaces the standard non-energy-flexible controllers with energy-flexible controllers. If it is implemented separately from the *process control*, the *energy control* object sets the set points for the standard controllers. Therefore, communication between *process control* and *energy control* has to be implemented. The PLC variables for the automation data model are included in the *energy control* objects in order to communicate with the DR service

- If we connect the field and control level to the management level, errors generated by management services can directly affect the control devices at the field level. A *safety control* designed especially for access by management services is needed since standard *process control* is not designed for this kind of interaction. The *safety control* guarantees a safe operation while executing DR measures. One approach presents a system which restricts the access for the DR service to the machine controllers as presented in [35]. In this case, however, the *safety control* is implemented in objects separate from the *process control* and interacts with them. *Safety control* can also be included in the *process control* object by limiting the output control values of machine module controllers. *Safety control* ensures that no humans are harmed, the cleaning machine is not damaged and no unintentional change to the process takes place while the machine is controlled by DR services.

After presenting our automation architecture for the CPPS cleaning machine we apply it to an exemplary cleaning machine in the following.

4 Exemplary application of the method to an industrial cleaning machine

In this section we apply our method to the cleaning machine model MAFAC KEA, an aqueous parts cleaning machine for batch cleaning. First, we describe the considered machine and its cleaning process in Sect. 4.1. Next, we analyse the DR potential for storing energy inherently in Sect. 4.2 and for process interruption in Sect. 4.3. Finally, we show the adjusted automation architecture in Sect. 4.4.

4.1 Description of the examined machine and cleaning process

The examined machine, MAFAC KEA, is an aqueous parts cleaning machine with a closed cleaning chamber. The central units are the cleaning chamber with its holding basket and spray nozzle system and a 320 ls tank filled with aqueous detergent. Loading and unloading with parts is done manually. The tank temperature control and the air heating are carried out by electric heaters. The cleaning pump supplies the cleaning chamber with detergent from the tank. An oil separation system separates oil residue from the detergent. Air can be supplied or extracted from the chamber via two fans. The holding basket and the spraying frame are driven by electric motors. The total rated power of the machine P_c is 20.7 kVA. The installed power analyser, Janitza UMG 96 RM-P, measures the machine's total power consumption.

The examined process takes 12 min in total. The process steps and the involved modules are presented in Table 3. The first process step *spray cleaning* is the main cleaning process which lasts for 600 s. Here, the detergent is pressurised by the cleaning pump and sprayed onto the parts. Furthermore, the holding basket and spraying frame counterrotate. The three modules, cleaning pump and the two motors for spraying frame and holding basket, are active during the whole step. In the next step, *impulse blowing*, the detergent residues which are now contaminated with soil are removed by *impulse blowing*. For this purpose, compressed air alternately passes through the nozzle system for 10 s. This is followed by a 10 s pause and then another 10 s of compressed air. The basket rotates for the entire 30 s. In addition, the moist air inside the cleaning chamber is extracted by the exhaust fan throughout the whole duration of this step. Finally, components are dried with hot air during *convection drying*. The air is heated using temperature-controlled electric heaters, which are switched on and off according to a temperature control. On average over multiple process cycles, they are switched on five to six times in the process step, resulting in a total activation time of 57 s. The supply fan is active during the entire process step. In addition, the

Table 3 Reference process of the MAFAC KEA cleaning machine with a total duration of 12 min

Process step	t_s (s)	Modules activated	$t_{s,i}$ (s)
Spray cleaning	600	Cleaning pump	600
		Basket rotation	600
		Nozzle rotation	600
Impulse blowing	30	Exhaust fan	30
		Basket rotation	30
		Nozzle rotation	20
Convection drying	90	Exhaust fan	90
		Drying fan	90
		Basket rotation	90
		Air heating	57*

The process consists of the three process steps *spray cleaning*, *impulse blowing* and *convection drying*. Step duration t_s, active modules in the respective process steps and their activation time per process step $t_{s,i}$ are shown

*Temperature-controlled, average value over multiple process cycles exhaust fan continues to extract moist air. This last step takes 90 s until the basket finally turns to its starting position and the chamber door opens. During the whole cleaning process the temperature of the aqueous detergent must be kept around 60 °C and the tank heater is controlled in a hysteresis between 58 °C and 62 °C. Thus, he tank heater's activation time is not constant in every process cycle, in some cycles it is not activated at all. We estimated an average activation time of 152 s over multiple cleaning process cycles. The oil separation system is also operating independent of the process steps. It is turned on and off depending on the measured level of oil residue in the detergent. The average activation time is 100 s.

4.2 Identification of demand response potential for storing energy inherently

We start with the examination of the modules by looking up the respective nominal power $P_{n,i}$ of the electrical consumers from the machine's data sheets and determining the running time of the individual modules, see Table 4. The running time of the modules is defined in the machine control program. Exceptions are tank heater and air heater which are both temperature-controlled. For these modules, we record the activation time over several cleanings and calculate the average activation time. Using the running times, we calculate the energy demand W_i and share of energy demand ϕ_s for each electrical consumer i for the whole cleaning process using (1) and (2). We only consider controllable consumers that can be used for DR, therefore parts such as the machine's PLC or the control cabinet cooling are excluded. The results are shown in Table 4.

Based on the nominal load $P_{n,i}$ and the share of energy demand ϕ_i, modules with high energy relevance are selected using two thresholds. As we want to avoid the exclusion of promising modules we choose low thresholds: Only modules with nominal power below 1 kW and share of energy demand below 5% are excluded. The flexibility potential of modules with nominal power and energy demand below these thresholds appears to be too small to be considered for DR measures. Electrical consumers that are at least above one of these thresholds will be considered. The energy demand and share of energy demand of all modules and the thresholds are shown in Fig. 7. The areas below one threshold are coloured in yellow. The area below both thresholds is coloured in red.

The tank heater and the air heater have the highest nominal loads. The cleaning pump accounts for the largest share of energy demand. Exhaust fan, drying fan, oil separation and the motors for basket and nozzle rotation are below both

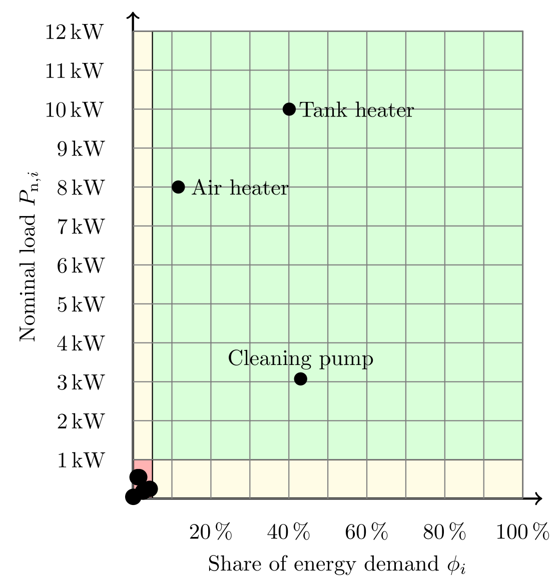


Fig. 7 Nominal load $P_{n,i}$ and share of energy demand ϕ_i of all modules for the selection of modules relevant for further examination. The thresholds are set to 1 kW for $P_{n,i}$ and 5% for ϕ_i. Only three modules with values above one threshold, in green and yellow sections, are examined further. The data values are shown in Table 4 (color figure online)

Table 4 The table shows nominal load $P_{n,i}$, total activation time per cleaning cycle t_i, absolute energy demand W_i and share of energy demand ϕ_i fore every module

Module	$P_{n,i}$ (kW)	t_i (s)	W_i (Wh)	ϕ_i (%)	Ctrl. mode	IES capacity	Rating
Tank heater	10	152*	422.22	36.3	C.1	I.1	Green
Air heater	8	57*	126.66	10.9	C.3	I.2	Yellow
Cleaning pump	3	600	500	43	C.3	I.4	red
Exhaust fan	0.55	120	18.33	1.6	–	–	–
Drying fan	0.55	90	13.75	1.2	–	–	–
Basket rotation	0.25	720	50	4.3	–	–	–
Nozzle rotation	0.18	620	31	2.6	–	–	–
Oil separation	0.045	100*	1.25	0.1	–	–	–

It also shows the results of the energy-process-independence analysis of the selected modules: control mode (Ctrl. mode), the IES capacity and the resulting overall rating

*Temperature- or level-controlled, average value over multiple process cycles thresholds. Consequently, we do not consider them further, as their impact is too low.

The second step is to asses the energy-process-independence. For this purpose, we evaluate the control mode and the IES capacity for the tank heater, the air heater and the cleaning pump: as mentioned before, the temperature-controlled tank heater is independent of the cleaning process. There is no control of the quantity of electrical load demand and neither temporal nor process related control commands are used. Hence, the control mode is C.1. The task of the tank heater is to guarantee at least the minimum temperature of the cleaning detergent during *spray cleaning*. As stated above, there are process cycles in which the tank heater is not activated. Therefore we assume that the IES capacity is high enough to cover more than one process cycle, leading to the rating I.1.

The air heater is only active during the step *convection drying* and therefore process-dependent. It can only be switched on and off and is consequently not controlled in quantity, leading to the rating C.3 as control mode. The air heater has a small buffer capacity, as the thermal behaviour during heating and cooling down is characterised by a hysteresis. This is not sufficient to cover the function. To determine if the process is critical we must distinguish between two cases. If the cleaning machine is used for the parts final cleaning and corrosion can be excluded, a slight undershoot of the nominal temperature during drying is not critical for the process as the parts can subsequently air-dry. If the machine is used in a process chain preparing the parts for sensitive following processes, such as hardening or coating, drying is critical. As we use the potential analysis for a preselection of modules that can be used for DR and cannot anticipate the following processes we choose to rate the air heater with I.2. If the cleaning machine is used for preparing the parts for sensitive following processes, the air heater's flexibility limits can be set such that DR measures cannot be executed on this system.

The cleaning pump is only switched on during the step *spray cleaning*. This corresponds to a process-related control. There is no control of the quantity. Accordingly, the control mode of the cleaning pump is C.3. The cleaning pump supplies the spray nozzles and is directly related to the functionality of the *spray cleaning*. This is a real-time energy conversion without buffer capacities, which corresponds to mode I.4. The evaluation of energy-process-independence is summarised in Table 4.

Finally, using (4), we estimate the DR potential $P_{\text{flex}} = 18\,\text{kW}$ including all consumers that have achieved a green or yellow rating and the relative potential $R_P = 87.0\%$ according to (5). This potential can only be reached if the tank and air heaters are used for DR at the same time. As the air heater is only active for 57 s during the process step *convection drying* the full potential can only be activated during this short period of time. Since the air heater is averagely switched on six times for 10 s, the full potential is only available for very short-term DR measures such as internal peak load shifting.

Table 5 Nominal load $P_{\text{n},s}$, absolute energy demand W_s, share of energy demand ϕ_s and result of the analysis of criticality for every process step

Process step	$P_{\text{n},s}$ (kW)	W_s (Wh)	ϕ_s (%)	Rating
Convection drying	9.35	160.42	21.7	Yellow
Spray cleaning	3.43	571.67	77.3	Yellow
Impulse blowing	0.98	7.67	1	–

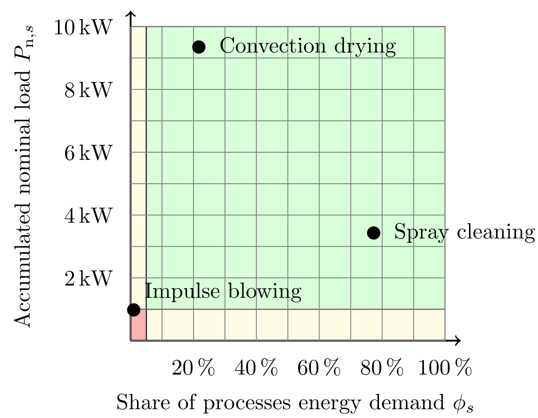


Fig. 8 Accumulated nominal load $P_{\text{n},s}$ and share of process energy demand ϕ_s of all three process steps. Only process steps with values above one threshold, in green and yellow sections, are examined further. The data values are shown in Table 5 (color figure online)

4.3 Identification of the demand response potential for interrupt process

After estimating the inherent storage potential, we now consider the potential for interrupting the process. First, for each process step s we examine the relevance for DR by calculating the accumulated nominal power $P_{\text{n},s}$ of all active consumers using (7) as well as the proportional energy demand W_s using (8), see Table 5. To cal%culate these values, we use the activation time $t_{s,i}$ from Table 3 and the respective nominal load $P_{n,i}$ from Table 4. Equivalently, the limits are set to 1 kW accumulated load and 5% of the total energy demand. The results are shown in Fig. 8. It turns out that *spray cleaning* accounts for the largest share of the energy demand, while the step *convection drying* requires the highest nominal power. Impulse blowing is energetically unimportant and therefore not considered further. The total energy consumption of the described cleaning process is $W_c = 739.75\,\text{Wh}$. It is important to note that the largest consumer, the tank heater, is independent of the process and therefore not considered.

In the next step, we evaluate whether an interruption of a running process step is technically permissible without negative influence on the process quality. Statements are either based on scientific findings or case-by-case assessment. As already mentioned, a delayed start of the cleaning process has no negative effect on the cleaning result [7]. Accordingly, an interruption before the first step, *spray cleaning*, is feasible. The second considered step is *convection drying*. The purpose of the drying process is to remove the remaining detergent from the parts' surface to prevent corrosion and prepare the parts for sensitive following processes such as hardening or coating. This process is performed after most aqueous cleaning processes and is generally done via evaporation [37]. As far as we know, there is no research on the influence of delayed drying for the cleanliness of the parts. For now, we assume that corrosion is prevented if the interruption is only for a few minutes, making an interruption before the process step *convection drying* permissible. Regarding the interruption of a running process, we currently cannot evaluate the influence to the cleanliness of the parts. Accordingly, this is avoided until the influence of an interruption on the cleaning quality is known. The evaluation results in a yellow rating for the steps *spray cleaning* as well as for the *convection drying*, shown in Table 5.

For the quantification of the DR potential, all process steps with a green or yellow rating are considered. Now we use the energy demand to calculate the absolute and relative DR potential, see (11) and (12). For the KEA this results in $W_{\text{flex}} = 0.732\,\text{kWh}$ and a relative potential $R_W = 99\%$.

The potential analysis shows that a direct control of the tank and air heater as well as interruptions before *spray cleaning* and *convection drying* have a high DR potential and should be considered for DR measures. We now adapt the control system to enable the machine for executing these DR measures.

4.4 Implementation of the automation design

In order to implement the CPPS design presented in Sect. 3.2, we have to adapt the existing automation program of the MAFAC KEA located on its PLC. The *process control* including the field level communication to the machine modules already exists in an object-based structure. We integrate the *energy control* and the *safety control* in the existing *process control* objects. For this, we first partly replace the standard non-energy-flexible controllers that control the machine modules so that the cleaning machine is able to carry out DR measures. Second, we extend the standard process flow control to enable an interruption of the process. Third, we add a separate control function to control the global machine state. In order to prevent negative influences on the process quality and to ensure a safe operation during DR measures, we finally implement *safety control* functions. In the following, we describe the four steps in detail.

Every machine module is represented by a module-object in the existing process control. For the *energy control* of the two modules that were selected for DR, we modify the existing controllers and add Boolean control variables for the DR set points (on and off) to their module-objects. This enables direct control by the DR service.

To interrupt the process we add the Boolean variable *interrupt* and the step *interruption* to the process flow control function which is part of the process control. If the variable *interrupt* is true, the program will step into the step *interruption* until the variable is set back to false. This is only possible at the two decision points marked in Fig. 9.

In addition to including *energy control* in the module-objects and the process flow control function we add a separate function to the *process control* that controls the global machine state. Following [36] we define four online states:

- *Working*: This state is automatically set during process execution. A start of a cycle is only permitted if the machine is previously in *operational* state and the tank temperature is within the temperature limits. The tank heater can be used for DR inside these limits.

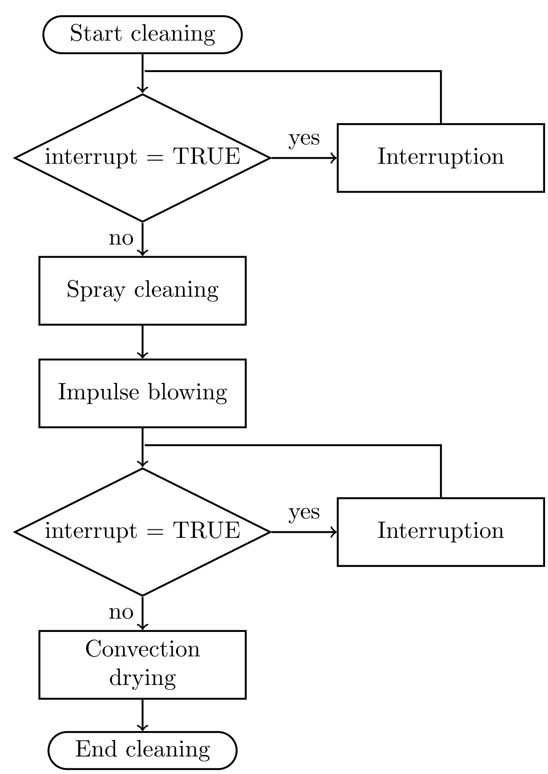


Fig. 9 Program flow chart of the cleaning process

- *Operational*: This state is set between cleaning cycles and during process interruption. All modules are controlled such that the machine can change to *working* at any time. The tank heater can be used for DR within the temperature limits equal to the *working* state.
- *Standby*: This mode can be set if no cleaning is to be performed for a longer period of time, but cleaning is still expected and the machine cannot be switched off for this reason. In this mode, all modules are switched off and the tank heater can be used for DR measures more flexibly as the temperature limits are set to a wider temperature range than in the *working* and *operational* state. It is impossible to start a cleaning cycle directly from *standby*. First the machine has to be set to *powering up* and then to *operational* in order to guarantee safe process execution.
- *Powering up*: This mode is set to prepare the machine for a cleaning process. The temperature limits for the tank temperature are set to the same limits as in the *operational* state. Therefore the tank heater is activated or deactivated until the tank temperature is within the temperature limits and the state is set to *operational*. The tank heater cannot be used for DR.

Depending on the machine state, DR measures can be executed more or less flexibly. In the machine state *off*, the machine and its PLC are turned off. Therefore, this state is not represented in the process flow control.

We integrate the *safety control* in the *process control* module-objects. To ensure safe operation, the direct control of the tank and air heaters is limited to specific temperature limits. The limits for the tank heater depend on the current global machine state. In the states *working*, *operational* and *powering up*, the operating limit is between 55 °C and 65 °C. The tank heater can be used for DR measures more flexibly during *standby*. In this case the lower boundary is removed and the higher boundary is set to 85 °C. If the current tank temperature exceeds the acceptable temperature range, the standard *process control* takes over until a safe temperature is restored.

We develop an OPC UA data model as an implementation for the automation data model in the communication layer. The data model is created using the presented object-based automation program. For the energy-flexible operation of the machine modules, we add the current state and the switching command for the tank heater and the air heater to their module-objects and publish them as OPC UA variables. For process interruption we integrate the current machine state in the machine-state-function and the command for interruption in the flow control. We include the machine's power consumption in the *process control* to get a feedback for our field test. The power demand of the individual modules is not measured.

At the management and organisation level, we implement two exemplary DR algorithms in Python as DR services. The algorithms aim to take advantage of low electricity prices. The first algorithm activates the energy-flexible modules if the electricity price is below a defined threshold. The second algorithm interrupts the cleaning process if the price is over a second defined threshold.

4.5 Field test

After identifying modules and process steps with a high potential for DR measures for the MAFAC KEA cleaning machine and enabling the machine for energy-flexible control, we now run two field tests to demonstrate the execution of DR measures. As described in Sect. 4.4, the machines automation system is linked to the management level via OPC UA over Ethernet IP. The DR algorithm is executed on a PC that is connected to the same local network as the cleaning machine's PLC. The PC is a Lenovo Thinkpad T460s with Intel Core i5-6300U 2.40 GHz dual core processor, 16 GB DDR4-RAM and Microsoft Windows 10 Pro 64 bit. First, we execute the DR measure *store energy inherently* by controlling the machine's tank heater and second we perform the *interrupt process* measure by interrupting the cleaning process. For *store energy inherently* we only consider the tank heater as the energy prices are updated every five minutes and the air heater is only suitable for DR measures with a duration of a few seconds.

The results for *store energy inherently* are shown in Fig. 10. We run the full cleaning process five times over the duration of two hours. The beginning and end of every cleaning process are marked with dotted lines. The electricity price falls below the defined threshold of 100€/MWh three times, activating the tank heater, as shown in the upper two diagrams of the figure. The three time intervals in which the price is below the threshold are highlighted in gray in all four diagrams. The third interval exhibited a communication problem where the tank heater was switched on with a delay of 70 s.

The third diagram shows the cleaning machine's power consumption. The total machine power demand rises significantly when the tank heater is activated as it is the machine module with the highest electrical load. When the tank heater is active the first time, the power consumption rises from 2.0 to 10.3 kW, during the second and third time from 2.0 to 12.1 kW. The first activation is during *convection drying* characterised by its rapidly changing load curve. The cleaning pump is deactivated in this step. The second and third activation occurs in process step *spray cleaning* where the cleaning pump is active. Therefore, the changes in the power consumption differ between first and second or third activation. The measurement also shows that the actual power consumption

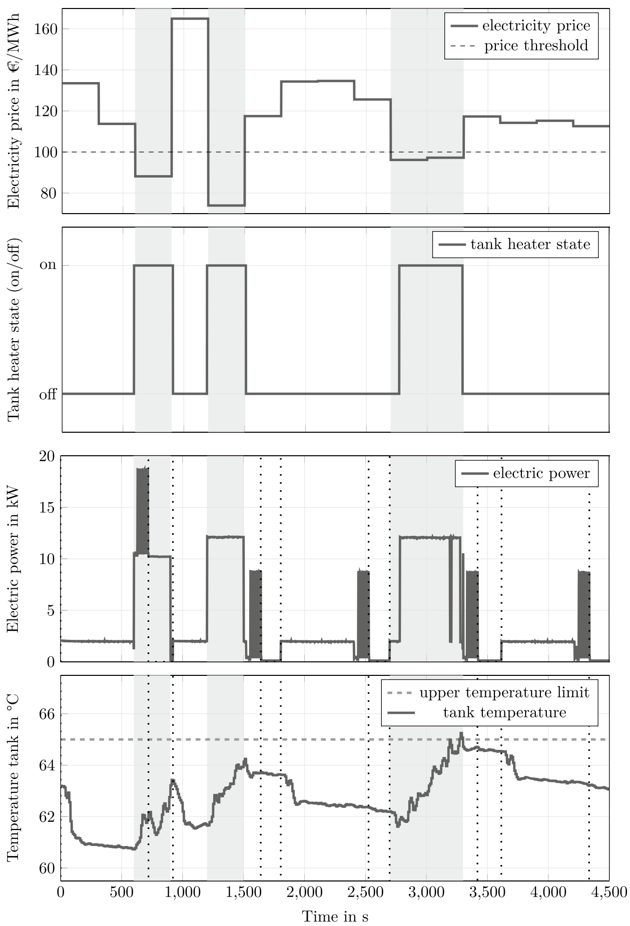


Fig. 10 From top to bottom: energy price, tank heater state, electric power and tank temperature during the field test for storing energy inherently. The three time intervals when the electricity price is below the threshold and the DR measure is executed are highlighted in gray. The five cleaning process are marked with dotted lines

of the modules is slightly lower than their nominal load $P_{n,s}$. The average power consumption of the tank and air heaters are approximately 8 kW each whereas the cleaning pump requires 2 kW. The total power consumption during *standby* is approximately 0.1 kW.

The diagram at the bottom of Fig. 10 shows the tank temperature during the cleaning processes. The temperature drops by 1–2 °C each time when the cleaning process is started. The temperature drops become smaller during the experiment. Despite being cooled down in cold water in between process cycles, the cooling seems to be insufficient by the end of the field test. Therefore, future more realistic field tests require more parts to ensure that the machine is loaded with parts at room temperature for each process cycle. During most of the field test, the temperature stays within the safety limits of 55 °C and 65 °C. Only at the end of the third tank heater activation period, exceeds the upper limit, causing the safety service to intervene.

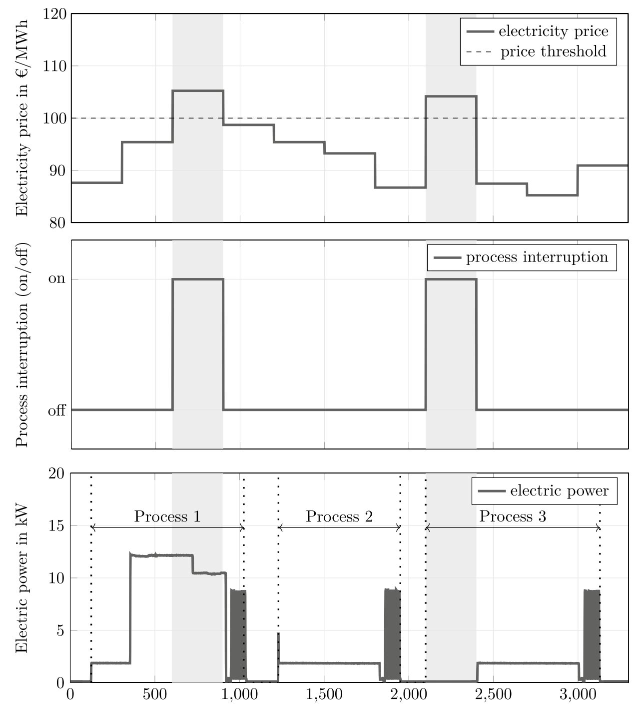


Fig. 11 From top to bottom: energy price, process interruption and electric power during the field test for *interrupt process*. Two time intervals when the electricity price exceeds the threshold and the cleaning process is interrupted are highlighted in grey. The three cleaning processes are marked with dotted lines

We execute *interrupt process* in a second field test, shown in Fig. 11, where we run three cleaning processes. The beginning and end of every cleaning process are marked with dotted lines in the bottom diagram. The electricity price, shown in the top diagram, rises above the threshold of 100 €/MWh twice, triggering a process interruption during these periods, which are highlighted in grey. The process interruption is displayed in the middle diagram.

The bottom diagram shows the total electric power demand of the cleaning machine. The tank heater is active during the first cleaning process and leads to a rise of the power consumption to 12 kW. The process step *spray cleaning* is running when the process interruption is activated for the first time after 600 s. Since an active process step can not be interrupted, the process is interrupted after 723 s, before the *convection drying* step. The second interruption is triggered after 2100 s during the third process cycle, postponing its start by 300 s.

5 Summary and conclusion

In this paper we presented a method for applying DR measures to aqueous parts cleaning machines. Previous research indicated that aqueous parts cleaning machines could have a high DR potential but yet no structured method for analysing their DR potential existed. Therefore, we developed a DR potential analysis for aqueous parts cleaning machines. We first identified the DR potential of aqueous parts cleaning machines, focusing on the potential of machine modules for storing energy inherently and the potential created by interrupting the cleaning process. After identifying the DR potential, we depicted the automation infrastructure that must be set up to use the cleaning machine for DR measures. The automation infrastructure consists of three parts, forming a cyber-physical production system (CPPS): the machine automation including process, safety and energy control at the field and control level, the automation data model at communication layer and the DR service at the management and organisation level. The automation data model connects the DR service to the machine automation using Open Platform Communications Unified Architecture (OPC UA).

We applied the method to an aqueous parts cleaning machine at the ETA Research Factory, TU Darmstadt. We examined the DR potential of the machine, implemented the automation infrastructure on-site and executed two field tests to demonstrate the successful application of the method. The field tests show that aqueous parts cleaning machines allow energy-flexible operation by storing energy inherently or shifting electrical loads by interrupting the cleaning process. The method should be transferred to other kind of production machines in the future.

The developed method could be used by manufacturers of aqueous parts cleaning machines to identify the DR potential of their machines and provide DR functionalities in the machine for their customers. The automation data model should be integrated in a standardised data structure, for example an OPC UA companion specification, to guarantee that the interfaces between the DR service and the automation system are the same for different machines from different manufacturers. It must be guaranteed that the interface is also standardised for the DR service. If the DR service is executed on an industrial Internet of Things (IoT) system or cloud platform, these systems must support this interface accordingly.

The developed automation architecture can be used for more complex DR services. For example, a model predictive control (MPC) algorithm could be used to control the tank heating system. The algorithm could forecast the tank temperature based on the current actions and aim to minimise electricity costs by switching the tank heater on in times of low energy prices while keeping the tank temperature inside a safe temperature range. Furthermore, the use of DR services based on artificial intelligence could be examined in future research.

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Declarations

Conflict of interest The authors declare that they have no competing interests.

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