

Chapter 6

Cyber-physical Approach for Integrated Energy and Maintenance Management



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Abstract Because of nowadays complex and highly automated industrial production lines, every stoppage involves the danger of a massive economic harm. That's why companies use already various production, quality and maintenance methods to reduce—or at least to handle—unforeseen stoppages. This paper presents a novel approach to improve the reliability of production fields by supporting predictive maintenance under the combination of systems from energy and maintenance management. Wireless sensor networks and mobile devices are integrated into a cyber-physical system to gain real-time transparency of energy demands within production environments. Being aware of challenges introducing cyber-physical systems into the brownfield, the proposed solution considers needs of data standardisations, IT security, staff participation, big data handling, long-term technical risk and cost-benefit estimations. The developed methods are considered by user-oriented design principles to deliver role-specific information. Therefore, the derivation of these informational requirements is based on production unique job activities. Allocating time and component-based energy demands whilst taking machine and environmental conditions into account enables a basis of comparison and a continuous improvement process of energy efficiency and maintenance. These demands are fulfilled by the methods of a continuous energy value stream mapping, an energy efficiency tracker and an integrating energy and maintenance monitoring. This proposed approach is based on the ESIMA project funded by the German Federal Ministry of Education and Research. The project aims for “Optimised resource efficiency in production through energy autarkic sensors and interaction with mobile users”.

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6.1 Introduction

Apart from the enhancement of conventional production-related objectives like cycle time and quality, the improvement of the efficient use of energy is becoming one of the most relevant industrial developments. This is mainly driven by the European ambitions to reduce energy demand as well as carbon dioxide emissions by 20% compared to 1990 until 2020 (European Commission 2018). With a share of around 30% of Germany's energy demand, the industry (Umweltbundesamt 2018) is forced to contribute by improving their own energy utilisation. In addition to legal requirements the rising energy demand, rising energy prices and sophisticated environmental requirements of the consumer enforce the enterprises to develop.

One leading movement in factories is the increasing digitalisation and interconnection between machines, which allow a higher transparency, performance and flexibility of production processes. This progress is initiated as a part of the high-tech strategy proclaimed by the German federal government in 2011 (Bundesministerium für Bildung und Forschung 2018). The vision of the fourth industrial "revolution" is essentially impelled by the technological concepts of cyber-physical systems and the Internet of things (Hermann et al. 2015). The consolidation of both is supposed to enable real-time communication between human-machine and machine-machine.

Expecting to benefit from the assumed potentials, new fields of research are coined, for example in order to identify synergies between energy management and predictive maintenance. The subsequent approach combines the aspects of machine condition and energy monitoring under consideration of a minimally invasive integration into the brownfield.

Thereby, this paper describes efforts to design and develop software-assisted methods for the analysis and visualisation of energy and machine data. A particular focus is being placed on an approach for predictive maintenance and also in order to provide an energy monitoring and management system. Concrete ambitions are for example:

- To support a continuous improvement process, a certain concept for evaluating measures of improving energy efficiency and to support maintenance activities was developed.
- By visualising and overlaying the machine data and the energy demand, a higher transparency is provided concerning the correlation between the operating modes and the energy demand.
- By energy value stream mapping, productive and unproductive rates of produced components can be revealed.

However, due to their high variety of action, the sense of responsibility and the individual reaction ability, humans in the production environment will continue to be the master control instance of the system within the cyber-physical casual network (Bauernhansl et al. 2014a, b). As shown in Fig. 6.1, the human (employee) is centred between the physical and the virtual components. System behaviour of the physical components becomes more transparent and replicable for the employee by the compound and information exchange of software elements within the cyber (virtual and

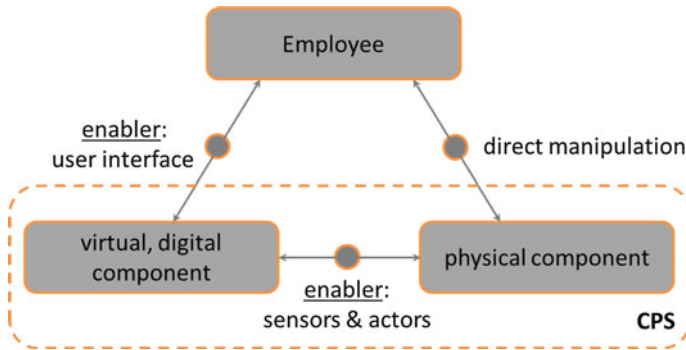


Fig. 6.1 Cyber-physical system casual network (Gorecky and Loskyll 2014)

digital components) and physical components. Gorecky et al. describe that either direct interaction takes place between the employee and the physical component or indirect manipulation of the physical components takes place across the virtual, digital component (Gorecky and Loskyll 2014).

Thus, the software-based visualisation and interaction of the developed methods were compiled with regard to human centred designed principles (DIN EN ISO 9241-210 2011). Therefore, the users of these approaches were placed at the centre of the development process to reach a high usability (Chamberlain et al. 2006). Production workers, energy managers, maintainers, team leaders, operating engineers and managers have been identified as beneficiaries of the above-mentioned solutions, since they will be enabled to assess energy efficiency measurements and to facilitate condition-based maintenance strategies.

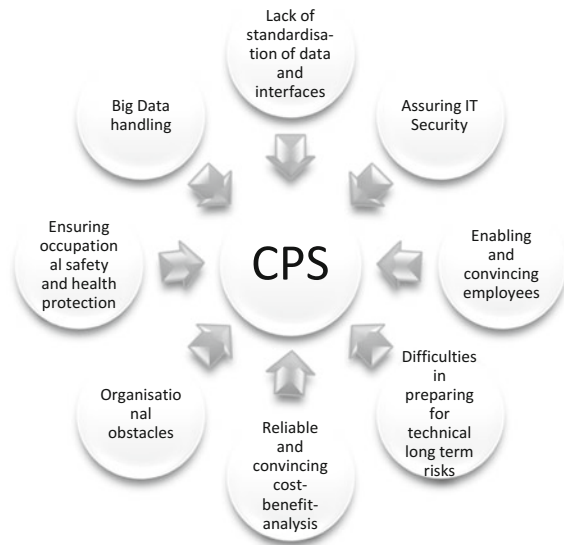
6.2 Challenges by Introducing CPS into Brownfield

Apart from these potentials, enterprises are facing various obstacles, regarding Fig. 6.2, when introducing cyber-physical systems into brownfield environments. The following listing gives an overview of challenges that are arising while creating an increasing interoperability of different systems by merging production and information technologies (DFKI 2014):

- **Lack of standardisation of data and interfaces**

In addition to the known difficulties, such as underdeveloped standards for data interfaces and communication protocols, a practical realisation rises to following challenges: on the one hand, for the implementation of interfaces in consisting systems, experts with knowledge of often outdated programming languages are needed. On the other hand, bureaucratic obstacles have to be overcome in order to gain access to a running and established system. The inability in mastering

Fig. 6.2 Challenges for cyber-physical systems



the system complexity as well as the common stable opinion of “never change a running system” substantially impedes progress.

- **Assuring IT security**

The development of cyber-security and data protection is of particular importance for the industry (Ziesemer 2015). Especially, frequently arising issues concerning topics like the Internet of things and cloud computing cause distrust towards IT applications.

Due to the increasing interconnectedness of systems, the production and business IT have to face higher requirements for security technologies, such as anti-virus protection, firewalls, virtual private networks and user authentication (Fallenbeck and Eckert 2014). According to Fallenbeck and Eckert, security gaps pose tremendous risks even potentially for the physical world, e.g. real physical harm can originate from hacked production equipment. High standards and real-time conditions of industrial systems need to be fulfilled here. In order to obviate or at least reduce these risks, it is necessary to implement innovative security solutions, which is particularly difficult in brownfields, as they were once designed for a long-term use (>20 years) and in no case dimensioned for the safety aspects of today (Ganschar et al. 2013). Especially, the implementation of cryptographically protected network interfaces and a comprehensive authorisation management is affected, because user authentication, encryption and decryption of data need to be done in a minimum of time (Fallenbeck and Eckert 2014).

- **Enabling and convincing employees**

On the one hand, introducing new technologies causes insecurity due to a lack of knowledge and overextension of some employees. On the other hand, it leads to

distrust and resistance of employees, who consider their knowledge of their personal property and assume their jobs being endangered by an increasing automation. While a lack of knowledge can be addressed by qualification and training measures, a lack of acceptance is very difficult to overcome. The technological development from an exclusive data preparation to a self-organising and decision-making system is often construed as an ethically critical development in which the employee, the former controller of the system, becomes a system-controlled production good. In order to avoid or at least slow down this process, some employees eschew to feed in their knowledge into the system.

- **Difficulties in preparing for technical long-term risks**

Due to insufficient possibilities of technical testing, a risk estimation of industry 4.0 technologies is yet rather challenging, especially in the long term. Therefore, the constant availability of infrastructure and system components (e.g. WLAN by the use of new wireless communication technologies; keyword: denial of service) as well as the compatibility with existing highly diverse components and systems within brownfields cannot be assured adequately.

- **Reliable and convincing cost-benefit analysis**

At present, cost-benefit analysis of industry 4.0 technologies either cannot be made adequately due to a lack of experience or cause caution because of an insufficient calculated profitability. In particular, concerning energy costs, high investments often do not simultaneously imply high savings. Especially for companies that are mainly driven by short-term goals, the payback period of energy-saving models is too long.

- **Organisational obstacles**

From an organizational point of view, a lack of responsibilities and inadequate management support are the main barriers for the adoption of industry 4.0. The cross-department cooperation is indispensable for a successful implementation of complex systems and applications with widespread information demands.

- **Ensuring occupational safety and health protection**

At times, implementing new technologies could affect occupational safety and health protection notelessly. For instance, the long-term effects of using data eye-glasses are yet not investigated adequately. Conceivably, they could distract the employee or even cause fear of surveillance, which could possibly endanger their safety and health.

- **Big Data handling**

Filtering and aggregation of a various big data volume for a comprehensive, close to real-time and reliable use (Tole 2013) are a relevant challenge of industry 4.0. Nevertheless, large companies already reached a high level of data acquisition in comparison to small and medium-sized enterprises, which has been proven by established systems like monitoring and management of power screwdriver data, pick to light and laser-based commissioning.

6.3 Concept Development

Based on the rapid developments in Information and Communication Technology (ICT), new opportunities open up, as well in manufacturing environments. Cyber-physical systems (CPSs) offer direct interaction possibilities between virtual software-based systems (“cyber-world”) and physical objects (“physical world”), e.g. manufacturing equipment. Interaction between different components of a CPS is provided due to wired or wireless communication networks. In conjunction with an energy management system, assistance to achieve energy objectives and policies by interrelated or interacting elements is provided. By monitoring of energy demands and key performance indicators (KPIs), organisations are able to save resources and to obtain a financial benefit (Posselt et al. 2014). By incorporating process and PLC data an integrated maintenance management system supports advanced scheduling activities and reduces machine failures.

Figure 6.3 shows a framework of cyber-physical (production) systems with the four subsystems (I–IV), their single elements and the necessary interfaces (a–h). Information transfer between the physical and the cyber-world is done within a closed control loop including different means for data acquisition and storage, appropriate models and decision support or even automated control schemes. Data acquisition on physical level could be realised by energy self-sufficient sensor nodes placed beside or in a machine’s electric cabinet and additionally in the environment to monitor production conditions. To reduce costs and expenses for wiring, data acquisition on field level could take place with energy-autonomous sensor nodes and wireless data transfer (Neef et al. 2017).

The human stays in the centre of attention, as the operational instance in the real world and the beneficiary of the provided methods and tools provided by the

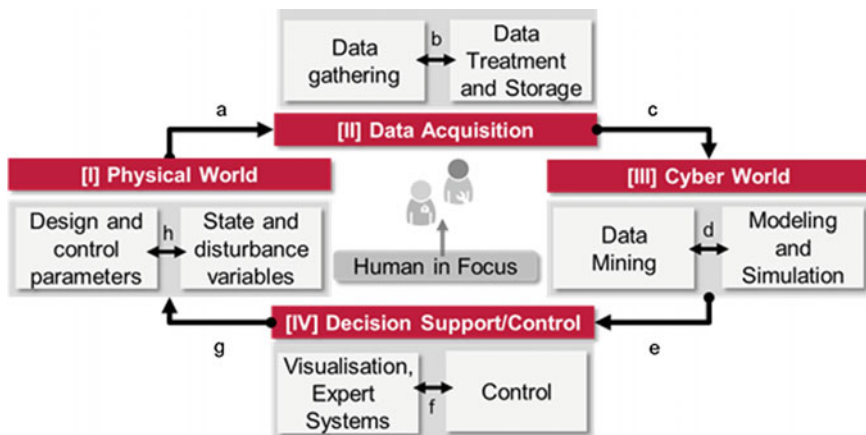


Fig. 6.3 Functional diagram of a physical production system and mapping into a virtual environment (Thiede 2018)

cyber-layer. Hence, within a factory environment, different user roles have to be distinguished since they incorporate different tasks, responsibilities and qualifications. Thus, in context of the envisioned integrated energy and maintenance management, they need to be addressed through different means. Those roles are derived and described in the following section.

6.4 User Roles and Derivation of Information Requirements

Production-related roles can be found in almost every large manufacturing enterprise. In general, these user roles differ in the amount of strategic and operative tasks they have to fulfil. While management positions also have strategic tasks, executive roles mostly fulfil operative tasks. Staff responsibilities and the authority to make strategic decisions are the main characteristics for management positions. The energy manager as a staff position gives support for strategic decisions along all hierarchy levels while also executing management decisions concerning energy efficiency.

The higher a role is classified within the hierarchy, the higher is the amount of his strategic tasks and the more aggregated the information need to be for him. Vice versa, the more operative the daily work, the higher is the employee's demand for detailed information concerning his specific tasks.

Therefore, the information demand of a specific role depends on their positions and activities. Some identified professional activities of these user roles and the derived informational requirements of an integrated energy monitoring and maintenance approach are shown in the following tables. Table 6.1 displays some main activities and informational requirements of management positions. In order to plan operational and strategic measures under consideration of their personal and financial resources, these leadership members need aggregate information and figures on the current situation and expected developments with regard to energy and maintenance issues. Meanwhile, the CEO and managers focus on corporate objectives; team leaders and foreman are measured on achievements of specific production domains. All of these management members can delegate tasks to their subordinated employees, e.g. operators.

Table 6.2 have their high operative activities and mostly immediate influence on production in common. The operating engineer has a more future oriented planning focus in comparison to the maintenance employee and the machine operator, which both have a more day-to-day driven business.

Table 6.1 Management positions, activities and informational requirements

	Activities	Informational requirements
CEO	<ul style="list-style-type: none"> Defining corporate goals for energy and maintenance issues 	<ul style="list-style-type: none"> Corporate energy demand and CO₂ emissions
Manager	<ul style="list-style-type: none"> Planning and decision-making of strategic targets in consideration of corporate goals Providing production forecasts Initiating and executing change processes 	<ul style="list-style-type: none"> Aggregated key figures (energy demand development, maintenance activities) of specific department Graphical preparation of trends
Team leader	<ul style="list-style-type: none"> Fulfilling operative targets Developing, coordinating and implementing of maintenance concepts Qualify and promote his employees for maintenance and energy issues 	<ul style="list-style-type: none"> Aggregated key figures Energy value stream of assembly lines Environmental conditions (illumination, temperature, etc.)
Foreman	<ul style="list-style-type: none"> Coordinate repair orders and employees Define measurements of manufacturing, assembly and maintenance plans Adhere deadlines of maintenance Problem analysis and forward of recommendations for process improvements Evaluate maintenance measures 	<ul style="list-style-type: none"> Assembly line energy demand Energy value stream of assembly line Individual KPI for energy efficiency and maintenance-based failure safety

Table 6.3 exemplifies the abundance of the activities of an energy manager. As an expert for energy efficiency, his informational demand focuses on energy issues.

6.5 Introducing Methods and Tools

Figure 6.4 depicts the identified user roles with the derived specific informational requirements. Depending on the hierarchical position of a user role, varying demands concerning the granularity of information must be considered. Consequently, user role depending aggregation of data and information is requested and provided by customisable key figures and meaningful charts. The user-specific informational requirements are drawn on methods and tools that will be presented in the further sections. An essential enabler to apply the derived methods and tools is the aspiration to allocate reproducible time and component-based energy demands (compressed air and electricity) during processing while taking machine and environmental conditions (e.g. temperature, humidity, luminous flux, carbon dioxide and airflow) into

Table 6.2 Executive positions, activities and informational requirements

	Activities	Informational requirements
Operating engineer	<ul style="list-style-type: none"> • Achieve manufacturing and maintenance targets under strategic guidelines • Analyse and identify effects of assembly lines and possible weaknesses • Realise optimisation measures • Create service specification for utilities and machines 	<ul style="list-style-type: none"> • Energy value stream of assembly lines and machines • State surveys of machines and assembly lines • Flexible demand measurements and documentation
Maintenance employee	<ul style="list-style-type: none"> • Ensure machine uptime • Maintenance (shutdown, inspection, servicing, repair, optimisation, recommissioning) • Supervise condition monitoring and maintenance management system • Analyse and remedy error and weak points • Optimise utilities and machines • Document and track performed measures 	<ul style="list-style-type: none"> • Graphics of assembly lines and machines structures • Customisable key figures and trends • Measurement data overview • Sensor infrastructures • Machine state-based energy demand (also after maintenance activities) • Machine control data
Machine operator	<ul style="list-style-type: none"> • Analyse work pieces and machine faults • Remedy by low complexity and ordering maintenance by serious faults/failures/errors • Partially preventive maintenance and repairing • Documenting of faults and failures 	<ul style="list-style-type: none"> • Machine and energy states

account. The presentation of method and tool-based computational outcomes can be provided on mobile devices, e.g. a tablet pc or smart phone.

6.5.1 Allocation of Specific Energy Demand as an Enabler

Energy demand of a machine tool is highly dynamic and depends on the interaction of different machine components which results in distinctive machine states. Assignment of energy demand to components or an allocation to the originator is highly dependent on clear and meaningful data sets, particularly to assign energy or auxiliary demand to products. The United States Environmental Protection Agency (US EPA) firstly introduced the allocation of energy use to products as an extension to

Table 6.3 Energy manager, activities and informational requirements

Activities	Informational requirements
<ul style="list-style-type: none"> • Achieve corporate energy objectives by energy efficiency optimisation and CO₂ reduction measures • Supervise energy monitoring and management system • Review current state energy situation • Identify and analyse energetic wastage and derive optimisation measurements • Consult management for planning and realisation of energy objectives • Develop and implement an optimal resource usage • Accomplish economic feasibility studies of machines and processes • Evaluate possible invests in energy optimisation • Benchmark machines and processes 	<ul style="list-style-type: none"> • Key figures and trends • State-based demand of machines and assembly lines • Energy demand and CO₂ emissions of departments and whole company • Track of energy efficiency measures and energy optimisation process

The informational requirements of these user roles need to be fulfilled by the methods and tools presented in the following sections

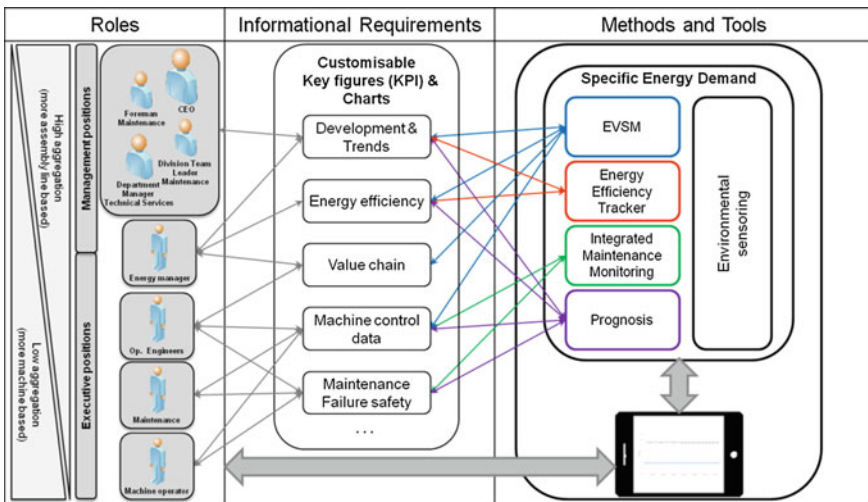


Fig. 6.4 Linkage of user roles, informational requirements and methods and tools to achieve requested requirements

the existing value stream mapping methodology. By adding energy aspects to value stream mapping, energy costs can be reduced and the productivity can be improved (US EPA 2011).

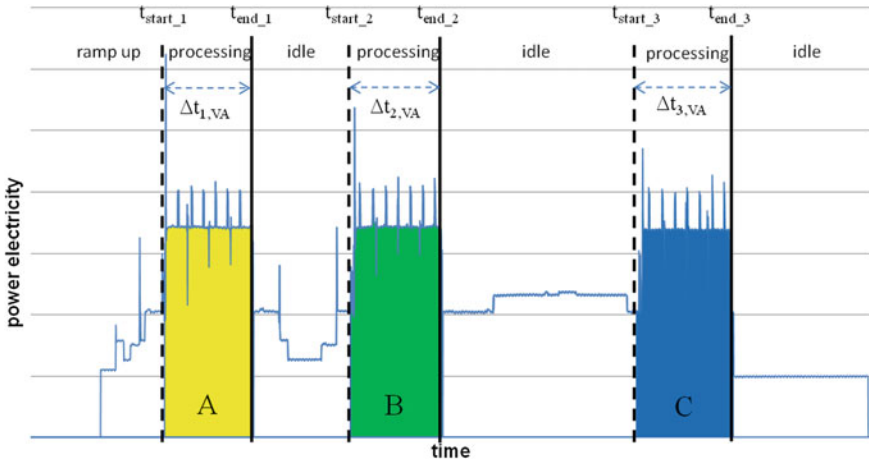


Fig. 6.5 Schematic allocation of electricity demand for identical products

As stated above, production processes in general require different energy carriers and auxiliary supplies to create value. The demand and type of media to operate the production process vary over time. The production cycle can be principally distinguished into value-adding and non-value-adding times (Erlach and Westkämper 2009). If the supply of the production process is not disconnected, there is typically a certain amount of energy and periphery media needed to keep the process in ready for operation state. This time is called non-value-adding time that can take place in different machine states, e.g. during standby (e.g. machine idling while waiting for parts), maintenance or failure.

The use of real-time machine data combined with metering data of energy and auxiliary flows to allocate energy and auxiliary demands to discrete products is the key in deriving meaningful performance figures and characterise industrial processes. The unique assignment of energy use to certain products during the value-adding time makes the process itself comparable. Figure 6.1 Cyber-physical system casual network (Gorecky and Loskyll 2014)

Figure 6.5 depicts an exemplary load profile and indicates graphically how the allocation of the value-adding electricity demand can be performed. The dashed vertical line represents the starting time of the value-adding process (processing). The solid line represents the end time of the value-adding process (and start time of the non-value-adding process time during machine’s idle mode). Both events can be read from machine’s programmable logical controller (PLC) or production planning systems. The energy (e.g. electricity and compressed air) and auxiliary (e.g. lubrication, water) demands for identical products (e.g. area A, B and C) are reproducible within specified tolerances. Therefore, the part-specific measured demands are suitable for energy efficiency monitoring and tracking of energy efficiency measures.

To reduce internal costs of energy for the manufacturing industry, the implementation and tracking of energy efficiency measures as a part of a continuous improvement

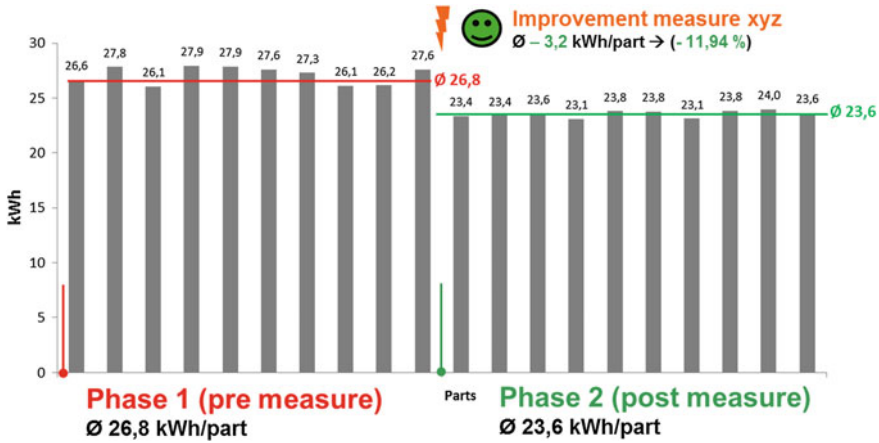


Fig. 6.6 Monitoring for an energy efficiency measurement with part-specific energy demand

process are an indispensable part. To establish a continuous improvement process, the possibility to evaluate implemented energy efficiency measures is a fundamental condition (May et al. 2015) Adequate reproducible key performance indicators should be periodically reviewed to conform to the requirements of a continuous improvement process, e.g. within the framework of ISO 50 001 energy management (DIN EN ISO 50001 2011–12).

To support this systematic approach, different interactions and evaluation possibilities drawn of the collaborative data pool were implemented. According to the causative principle, the distinction between different energy carriers and the examination by different machine states is an important aspect. To achieve intended energy efficiency goals, the user can set milestones with information concerning time, type (e.g. compressed air or electricity), reference quantity and tracing of the applied energy efficiency measurement. By the use of steadily monitored mean values, the user can spot the achievement of target values and acting up to the ISO 50 001 procedure “plan, do, check, act” will be simplified.

Figure 6.6 shows exemplarily the layout of a monitoring view for energy efficiency measures. The view includes the mean value of part-specific value-adding energy demand. The essential outcome is indicated in the row “optimising measure xyz” and shows the decrease in value-adding part-specific energy demand.

6.5.2 Dynamic Energy Value Stream Mapping

Energy value stream mapping (EVSM) evolved out of value stream mapping methods developed for lean manufacturing purposes. The extension by the energy dimension allows the designing of time and energy-efficient production systems simultaneously.

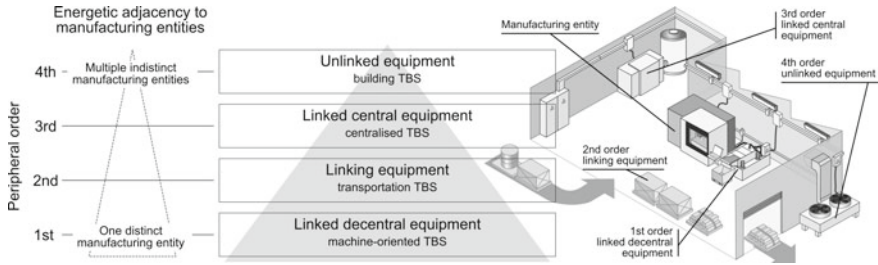


Fig. 6.7 Energetic adjacency of TBS to manufacturing entities (Posselt 2015)

A wide range of possible approaches can be found in the current state of research (US EPA 2011; Erlach and Westkämper 2009), mainly addressing the same basic set of key performance indicators extended by their specific performance indicators to ensure a more holistic perspective on energy flow transparency. Bogdanski et al. introduced an extended energy value stream approach that includes the technical building service (TBS) dimension (Posselt et al. 2014; Bogdanski et al. 2013). As shown in Fig. 6.7, Posselt further distinguishes the energetic adjacency of TBS providing equipment in relation to the value-adding manufacturing entity (Posselt 2015).

The comprehensive assessment regards energy shares demanded by direct value-adding core processes of production machines up to unlinked equipment with lowest possible adjacency to the core process as, for example, floor heating systems. The used energy for the value-adding process time of the core process E_{VA} can be determined as a function of the arithmetically averaged power during value-adding \bar{P}_{VA} and the sum of the work piece-specific value-adding time $\Delta t_{w,VA}$:

$$E_{VA} = \bar{P}_{VA} \cdot \sum_{w=1}^k \Delta t_{w,VA} \tag{6.1}$$

Further information about calculation for non-value energy and consumers on higher peripheral order can be found in (Posselt et al. 2014). Figure 6.8 depicts the considered elements up to the fourth order in an energy value stream box (Posselt et al. 2014). With this holistic assessment perspective, a true cause and effect analysis can be achieved through creating energy value stream maps in a reoccurring, comparative manner.

So far, the methodology of EVSM was widely applied in a pen and paper-based manner, representing only a temporal snapshot of a current condition which comes with an evident pair of disadvantages as shown in Table 6.4.

The concept introduced in Fig. 6.9 now offers the possibility to implement the EVSM methodology within a dynamic data stream that is based on a collaborative data pool within the cyber-layer. The new cyber-physical approach allows having a total process chain perspective and hence preventing the phenomenon of problem shifting caused by local improvement activities.

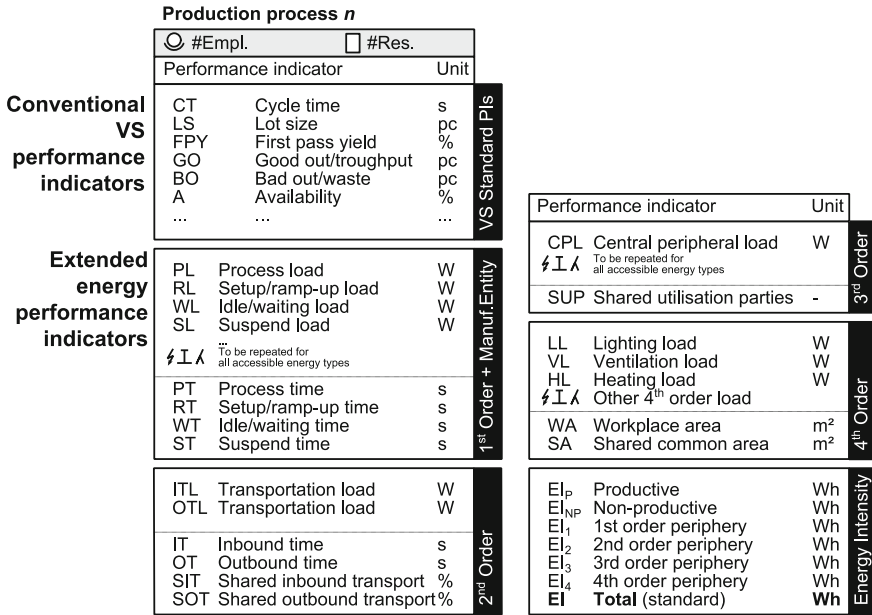


Fig. 6.8 Energy value stream box (May et al. 2015)

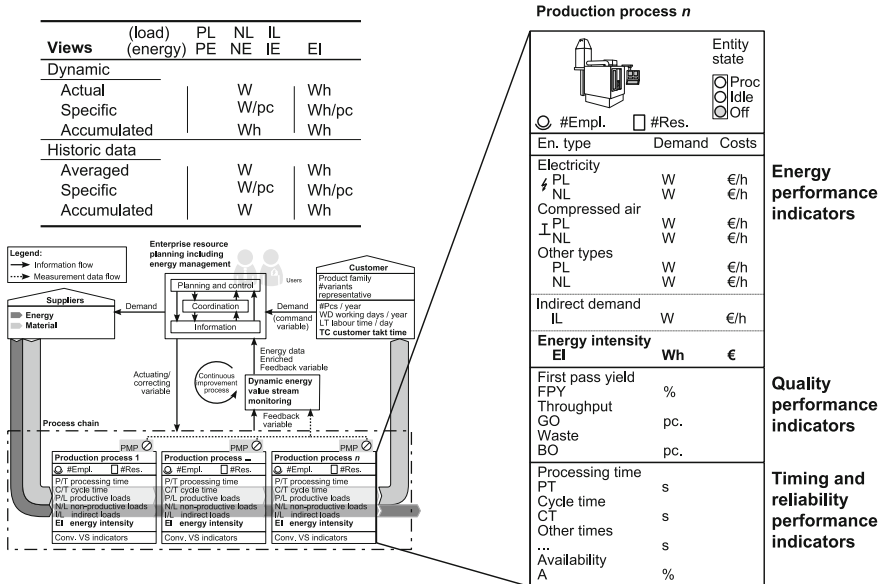


Fig. 6.9 Visualization of energy and conventional value stream KPIs (Posselt 2015)

Table 6.4 Disadvantages of the static pen and paper-based approach and new specifications of the dynamic approach eliminating these drawbacks

Disadvantages of static pen and paper EVS mapping	Specifications of new dynamic EVS monitoring
No differentiation of productive and non-productive time shares	Application of intelligent PMPs (IPMP) to automatically detect entity states
Before and after acquisition of EVS maps requires a repetitive, time-intensive measurement	Low effort to create EVS maps from dynamic data streams
Improvements in the system need yet another temporary measurement to evaluate possible benefits	Immediate indication of differences between two EVS maps, in an accumulated and process quantity view
Interdependency effects between entities in the linked process chain are not intuitively identifiable	Intuitive visualisation to identify interdependencies
Different aggregation periods rely on extrapolation of temporary short-term measurements	Reliable, full-term, parallel monitoring of actual power demands and calculatory integration (tool supported)
Support of a continuous improvement process is cumbersome	Easy to use and quick to apply approach to support continuous improvement actions and reporting

The dynamic energy value stream mapping procedure has to follow a standard set of calculation rules for the desired performance indicators in order to obtain reproducibility. All entities monitored have to be describable with a consistent set of entity states in order to allocate productive and non-productive energy states (energy effectiveness). To estimate the energetic and economic effect of measures on longer periods of time, simple extrapolation functions must be incorporated. To consider peripheral entities of different orders, the metering strategy has to be extended accordingly. In order to ensure quick implementation and later extension, common industrial interfaces of energy flow sensor shall be considered (e.g. standard interfaces for three-phase electric power, analogue inputs for non-electrical energy flows). To support the intuitive understanding of the KPI evaluation, a dynamic visualisation with the already present layout and design of the material-oriented value stream must be realised.

The energy performance indicators in the category below give detailed information about any of the utilised energy types (external and internal ones). The values and units displayed vary, depending on the selected view. The user can decide on a dynamic view showing actual values (process quantities), specific process quantities in a reference unit of one piece of processed goods or the accumulated values since the beginning of the accumulation period (e.g. start of a test series). The user can, at any time, save the set of specific and accumulated views to a database for later comparison. The accumulated productive energy PE is calculated for each energy type as $PE = PL \cdot PT \cdot GO = [\text{Wh}]$.

The accumulated unproductive energy NE is calculated for each energy type as

$$NE = NL \cdot (CT - PT - OT) \cdot (GO + BO) = [\text{Wh}],$$

with OT being the off time share within the CT of a resource. The indirect energy IE for the case of the fourth peripheral order is calculated as

$$IE = IL \cdot CT \cdot GO = [\text{Wh}].$$

Correspondingly, the key energy performance indicator of a process EI is calculated as the sum of productive- and unproductive- and also indirect energy shares:

$$EI = PE + NE + IE[\text{Wh}],$$

and the specific key performance indicator as

$$EI_{\text{spec}} = (PE + NE + IE)/GO[\text{Wh}].$$

Saved data is regarded as historic data. It serves as a basis for a series of EVS map comparisons to accompany the start of production of new products, or for the implementation of energetic or conventional improvement measures. The saved historic views can be printed or directly compared by difference indication to allow the identification of bottleneck processes, energetic drivers and different types of lean and energetic wastes (e.g. idle times, high idle loads, uneven levelling of process performances, overproduction, unproductive energy demands and ineffective utilisation of energy types).

For the utilisation of the dynamic EVS monitoring, a metering strategy is to be applied by means as described by Posselt (Seera et al. 2014). The focus can be narrowed down to the entities of the desired process chain, but to be able to incorporate the indirect energy demands (IL), peripheral entities are recommended to be included by making sure to define the source–sink relationships as well as the energetic adjacencies of each manufacturing entity.

Hence, the capability to interact with real EVSM live data is given. Computation results and consequential recommendations for action are displayed target-oriented as a control strategy or as a recommendation for a specific action within e.g. a mobile application. As a result, energy value stream mapping becomes easier when using a consolidated ICT system as introduced. The presented ICT system covers the relevant data path from shop floor level to the specific user. Three stages of data transfer can be distinguished:

- **Data acquisition on field level:**

To meet the requirements of the presented methodology, data acquisition on field level is necessary. Power measurement of the actual power of the core process and the attached peripheral units with an update frequency of one second and as well event based process information read from a machine execution system

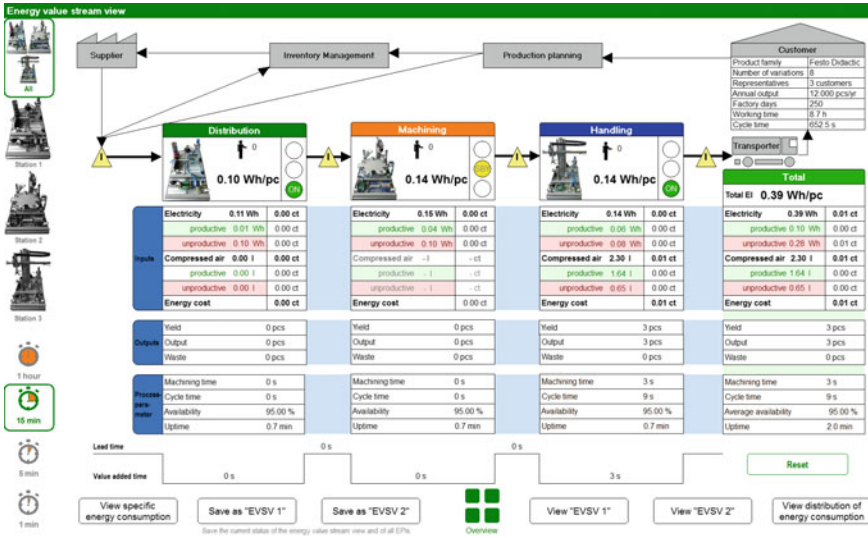


Fig. 6.10 Dynamic energy value stream monitoring applied on a Festo Didactic modular production system for educational purposes (Posselt 2015)

(MES) or from the machine’s programmable logical controller (PLC) represent the collaborative data basis for computation.

- Preprocessing and computational analysis within the cyber-layer:**
 The cyber-layer represents the unit to synchronize and perform syntactic analysis of raw process and measurement data. Depending on the available prepared data from field level, several methodologies—besides EVSM—could be provided within the cyber-layer to satisfy the informational requirements of the user. Calculation algorithms, e.g. Eq. 6.1, are implemented within a backend unit.
- (Mobile) presentation within value stream boxes:**
 The mobile presentation represents the interface to the user, e.g. the mobile maintainer. Target-oriented indicators to evaluate manufacturing processes (calculated within the cyber-layer) are graphically prepared and displayed. Figure 6.10 depicts schematically a structure outline to display EVSM specific performance indicators.

The implementation of the methodology and dynamic performance indicator calculation is realised on the PLC of the energy transparent machine hardware concept, but with a higher performing processor for the operating system of the IPC operating the PLC. The main view of the developed frontend is shown in Fig. 6.10, depicting the typical value stream map and the new energy-aware performance indicators.

As soon as the application is started, the status indication of the three stations comes up. Upon the activation and initialisation of the stations, the idle signal indicates ready for production. The idle load is indicated, and for the aggregated indicator view, the non-productive energy share integrates the load for each station, differentiated into its supplied energy types. As soon as the first work pieces are processed

and throughput is generated, the resulting OK parts are accounted as yield. At this point, the specific energy indicator set can be called up, as shown in Fig. 6.10. The energy intensity per part is accounted in the header of each station. At the bottom, the productive and idle time shares are indicated.

On this basis, the users can make test runs with a representative number of work pieces to create a benchmark and save it as a static energy value stream map in the history data. Now technical alterations by changing the compressed air pressure at the air preparation unit, changes in the machine control, smart local controls of the vacuum gripper or new electrical components can be tested. The influence on the whole process chain can be evaluated at an instance through higher or lower actual loads and changes in the processing times. Most suitable configurations can be tested again for the benchmark number for yield, and a secondary static energy value stream map can be saved and compared directly to the historic benchmark.

It has been proven in the experimental demonstration that the dynamic and instantaneous feedback of energy performance indicators is highly important for a continuous improvement process. Furthermore, the effect of a single parameter on the whole picture (in this case the process chain, in the real case the whole factory) is important to understand. Without instant informational feedback, a cause and effect relationship can hardly be generated by the involved persons. Especially, when it comes to more complex setups, it is recommendable to also include the direct energy in the dynamic monitoring system, as it helps to integrate facility and production domains with one tool (Posselt 2015).

6.5.3 Integrated Energy and Maintenance Monitoring

The German Institute for Standardisation defines maintenance as the “combination of all technical, administrative and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function” (DIN EN 13306 2010–12).

From an economic point of view, a fundamental goal in maintenance is to keep the reliability of a facility at a high level while simultaneously optimising the overall costs consisting of maintenance and downtime costs as depicted in Fig. 6.11 (Herrmann 2010). The left side represents breakdown maintenance strategies. Breakdown maintenance ensures the functional integrity of production machines by intervention in case of breakdown. In contrast, preventive maintenance follows the strategy of scheduled preventive replacement of abrasion-prone parts before a breakdown occurs (Reichel et al. 2009). This approach is located on the right section of Fig. 6.11 and is characterised by minimal downtime costs.

The optimal maintenance strategy tagged with the black dashed line is based on the knowledge when a maintenance action should be performed and represents the most economically reasonable solution. To operate a maintenance workforce at this optimal point, either real-time information about the condition of a component achievable by ad hoc monitoring is required or an integrated system can be set up.

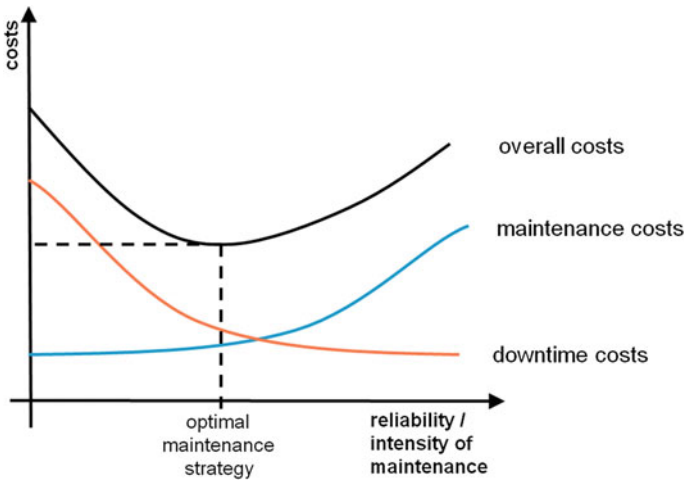


Fig. 6.11 Optimal maintenance strategy (US EPA 2011)

By setting up an integrated system, a collaborative data pool to obtain necessary information can be used. The information provided by this data pool forms the basis for several methodologies. In this manner, the necessary data is already existent within the cyber-layer and is part of the closed-loop system introduced in Fig. 6.2. Additional measurement technology or equipment is no longer required. Nowadays, computational performance of an embedded system is sufficient to use data of simple measurement technology, e.g. electricity measurement to gain further information about the condition of a component or a machine.

In this context, the correlation between current signature and wear out of machinery and components is scientifically proven by several authors. Seera et al. detected three different common induction motor faults by using real current signals (Seera et al. 2014). Anwar K. Sheikh et al. experimentally state the correlation between drill wear out and increased power demand of a milling machine (Sheikh et al. 2005). Sami Kara et al. demonstrated the correlation between operating time of electric drives (for the case of washing machines) and several state variables. He could prove that the rotational motor speed, the power demand, vibrations and temperature of the motor were reasonably related to the age of the motor (Kara et al. 2005).

Assume that the specific demands of electricity, compressed air and lubrication per produced part follow a normal distribution $N(\mu, \sigma)$ with mean μ and standard derivation σ over the time as shown in Fig. 6.12. The mean will be calculated by a finite set of time independent measurements of energy or auxiliary demand. As a result, a discrete sequence of mean values will be achieved. Occurring systematic measurement errors will be equalised. Derivations of this mean values can be detected automatically. The abnormal change of the mean energy demand per part (e.g. as a result of machine wear out over time) is indicated by the dashed vertical red line.

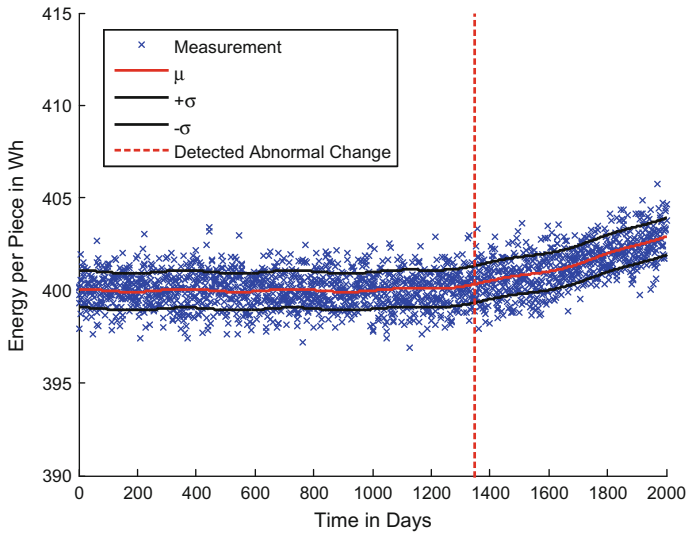


Fig. 6.12 Change in energy demand per part over time and detected abnormal threshold

6.5.4 Prognosis

A reliable estimation of a components condition is naturally a necessary but also not sufficient condition to improve maintenance activities. Additionally, the prediction of possible future states of a component and its overlying system is crucial. Studies indicate that for the estimation the actual operating time of a component, different state variables (e.g. vibrations, temperature, voltage or electrical power demand) in combination with methods like regression analysis or artificial neural networks can be used (Kara et al. 2005). Based on these values, also an estimation of the remaining lifetime and, thus, potential maintenance demand can be given. However, this mainly relates to the exchange of components as maintenance strategy and also neglects the stochastic nature of the problem. Simulation, and more specifically Monte Carlo simulation, is an appropriate approach here. Based on values like mean time between failure (MTBF) that can be derived from the above-mentioned data analysis, failure rates and failure probabilities can be calculated and used for the simulation. To achieve the necessary statistical robustness, a sufficient quantity of simulation runs needs to be conducted which results in a distribution of result values. Figure 6.13 shows the example of an industrial robot with four different drives. In this case, the total cost of ownership (TCO, includes maintenance, failure and energy costs) was used to compare the effect of different maintenance strategies—breakdown, periodic and condition-based maintenance with varying intervals were analysed (Herrmann 2010). For decision support, the average value over all simulation runs (here 385 runs per scenario) but also the spread of the values as measure for the risk of a strategy is of importance. It gets quite clear that maintenance strategies significantly differ in

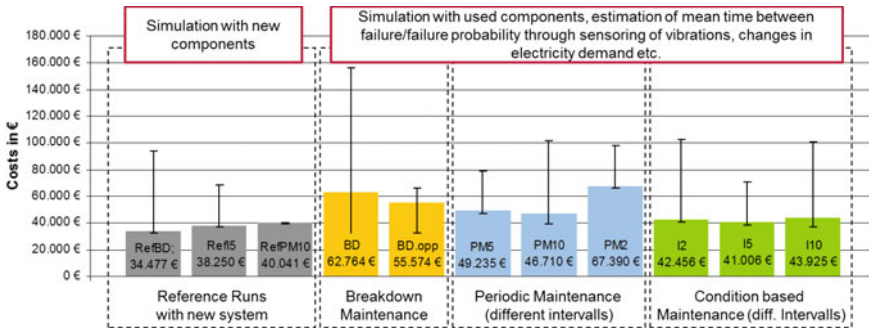


Fig. 6.13 Exemplary results of Monte Carlo simulation of different maintenance strategies (case study for an industrial robot) (Herrmann 2010)

terms of their impact on component behaviour and, thus, related TCO. The example also underlines the necessity to consider the specific circumstances of the situation; for example, a new system should be maintained different compared to an operating system where all components show varying conditions.

Data-based analysis and prognosis functionalities can give distinctive decision support for maintenance. On the one hand, the example underlines the potentials, but on the other hand, the inherent complexity and simulation efforts are certainly a barrier for industrial application on a continuous base. However, being clearly related to current developments in context of cyber-physical systems, increasing IT performance and intuitive applications will allow to conduct those simulations in daily work and even decentralized on smart devices.

6.6 Critical Review and Outlook

The described solution gives reason to expect synergies for predictive maintenance and energy management, as the integrated energy and condition monitoring system achieve a high transparency of the machines energy demand and support an optimised maintenance strategy. The use of a collaborative data pool provides sufficient information to cover a wide range of profitable methods and tools. The software implemented methods and tools enable users with mobile devices opportunities for analysing, controlling and improvement of machine-specific energy demands and maintenance issues on the basis of the same hardware. Further categories of smart environment sensors like rel. humidity, brightness, carbon dioxide, airflow and motion will be introduced.

The distinction between different user roles and their specific information requirements is important to prepare and provide custom-tailored information.

Nevertheless, the introduction of such a system into brownfield requires the consideration of a wide range of subjects. Therefore, it is necessary to achieve acceptance

of the employees for the system by supporting their daily work and not to sense that they might get replaced by the machines. Furthermore, topics for IT and security are important, like standardisation of data and interfaces, an extensive authentication management and the encryption and decryption of data. Also, the lack of reliable cost-benefit analysis and difficulties in estimating long-term risks for technical and occupational safety does impede the introduction of the suggested system.

It can be noted that due to a high number of different machine controls and production planning systems, the application of such an approach becomes highly complex.

Next work of the authors will be to extend the methodology to more advanced data mining methods relying on the examination of high-resolution load profiles. Figure 6.2 opens up further possibilities for the analysis of production equipment and the derivation of decision rules. The application of effective feature extraction strategies and the use of proper evaluation models pave the way for reliable prediction on wear out of manufacturing machines and facilities.

The presented approach will be proved within research and industry demonstrators. Hence, a wide range of different manufacturing systems can be considered.

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References

- Bauernhansl T, Ten Hompel M, Vogel-Heuser B (2014a) Industrie 4.0 in produktion, automatisierung und logistik: anwendung technologien migration. Springer, Berlin, Heidelberg, New York, p 399
- Bauernhansl T, Ten Hompel M, Vogel-Heuser B (2014b) Industrie 4.0 in produktion, automatisierung und logistik: anwendung technologien migration. Springer, Berlin, Heidelberg, New York, p 525f
- Bogdanski G, Schönemann M, Thiede S, Andrew S, Herrmann C (2013) An extended energy value stream approach applied on the electronics industry. In: Emmanouilidis C, Taisch M, Kiritsis D (eds) Advances in production management systems. Competitive manufacturing for innovative products and services. APMS 2012. IFIP advances in information and communication technology, vol 397. Springer, Berlin, Heidelberg
- Bundesministerium für Bildung und Forschung (2018). <http://www.bmbf.de/de/9072.php>
- Chamberlain S, Sharp H, Maiden N (2006) Towards a framework for integrating agile development and user-centred design. In: Marchesi M, Abrahamsson P, Succi G (eds) Extreme programming and agile processes in software engineering. 7th International Conference, XP 2006, Oulu, Finland, 17–22 June 2006. Proceedings 2006. Aufl. Springer, Berlin, Heidelberg, p 143f
- DFKI (2014) 6th innovation day of the SmartFactoryKL
- DIN EN 13306 (2010–12) Maintenance—Maintenance terminology
- DIN EN ISO 9241-210 (2011) p 19
- DIN EN ISO 50001 (2011–12) Energy management systems—requirements with guidance for use

- Erlach K, Westkämper E (2009) *Energiewertstrom – Der Weg zur energieeffizienten Fabrik*. Fraunhofer Verlag, Stuttgart. ISBN 978-3-8396-0010-8
- European Commission (2018). https://ec.europa.eu/clima/policies/strategies_en
- Fallenbeck N, Eckert C (2014) IT-Sicherheit und cloud computing; Bauernhansl T, Ten Hompel M, Vogel-Heuser B. *Industrie 4.0 in produktion, automatisierung und logistik: anwendung technologien migration*. Springer, Berlin, Heidelberg, New York, p 398f
- Ganschar O, Gerlach S, Hämmerle M, Krause T, Schlund S (2013) *Produktionsarbeit der Zukunft - Industrie 4.0*. In: Spath D (ed) IAO, Stuttgart, Fraunhofer, p 56f
- Gorecky D, Loskyll M (2014) Mensch-maschine-interaktion im industrie 4.0-zeitalter. In: Bauernhansl T, Ten Hompel M, Vogel-Heuser B (eds) *Industrie 4.0 in produktion, automatisierung und logistik: anwendung technologien migration*. Springer, Berlin, Heidelberg, New York, p 525; Zamfirescu CB, Pirvu BC, Schlick J, Zühlke D (2013) Preliminary insides for an anthropocentric cyber-physical reference architecture of the smart factory. *Stud Inform Control* 22(3)
- Hermann M, Pentek T, Otto B (2015) Design principles for industrie 4.0 scenarios: a literature review. Dortmund, Technische Universität Dortmund, p 4f
- Herrmann Christoph (2010) *Ganzheitliches life cycle management, nachhaltigkei t und lebenszyklusorientierung in unternehmen*. Springer, Berlin, Heidelberg, New York, p 360f
- Kara Sami, Mazhar Muhammad, Kaebernick Hartmut, Ahmed Noor-E-Alam (2005) Determining the reuse potential of components based on life cycle data. *CIRP Ann Manuf Technol* 54(1):1–4
- May G et al (2015) Energy management in production: a novel method to develop key performance indicators for improving energy efficiency. *J Appl Energy* 149:46–61
- Neef B, Schulze C, Herrmann C, Thiede S (2017) Integriertes Energie- und Instandhaltungsmanagement im Kontext Industrie 4.0—Verbesserte Energieeffizienz und Instandhaltung durch Smart Devices und energieautarke kabellose Sensoren, in: *Industrie Management 4.0, Ausgabe 1/2017, Energie- und Ressourceneffiziente Produktion*
- Posselt G et al (2014) Extending energy value stream models by the TBS dimension—applied on a multi product process chain in the railway industry. In: *Proceedings of 21st CIRP conference on life cycle engineering 2014*, pp 80–85
- Posselt G (2015) *Towards energy transparent factories*. Springer. ISBN 978-3-329-20868-8
- Reichel J, Müller G, Mandelartz J (2009) *Betriebliche instandhaltung*. Springer, Berlin, Heidelberg, New York, p 137f
- Seera M, Lim CP, Nahavandi S, Loo CK (2014) Condition monitoring of induction motors: a review and an application of an ensemble of hybrid intelligent models. *J Expert Syst Appl* 41:4891–4903
- Sheikh AK, Al-Sulaiman FA, Baseer MA (2005) Use of electrical power for online monitoring of tool condition. *J Mater Process Technol* 166:364–371
- Thiede S (2018) Environmental sustainability of cyber physical production systems. *Procedia CIRP* 69:644–649
- Tole A (2013) Big data challenges. *Database Syst J* IV:3:31ff
- Umweltbundesamt (2018). https://www.umweltbundesamt.de/daten/energie/energie_verbrauch-nach-energetraegerern-sektoren
- US EPA (2011) *Lean, energy & climate toolkit*. EPA-100-K-07-003
- Ziesemer M (2015) So sieht Industrie 4.0 aus - ZVEI stellt, Referenzarchitektur Industrie 4.0 (RAMI) vor und definiert die, Industrie 4.0 Komponente, in: *Technik und Wirtschaft für die deutsche Industrie—Produktion, Nr. 13*, p 17