Context-Aware Analysis Approach to Enhance Industrial Smart Metering

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Abstract

With consideration of the increasing relevance of energy consumption and rising energy costs, strategies to improve energy efficiency in manufacturing environments have to be developed. As the energy consumption results from the temporal accumulation of individual power demands of subordinate devices, energy metering enables to capture these demands and display the dynamic behaviour. A fundamental precondition for the identification and implementation of improvement measures is nevertheless transparency about energy demands as well as related couplings and interdependencies. In this paper, the context-aware analysis approach is proposed to provide additional information supporting the understanding of energy consumption in manufacturing environments.

Keywords:

Manufacturing System; Energy Efficiency; Context Awareness

1 INTRODUCTION

In manufacturing systems energy and resources are used in order to obtain operational readiness (e.g. through compressed air provision or heating) and conduct transformation processes for value creation. Hence, manufacturing is simultaneously value creating and resource-consuming. Due to increasing electricity and raw material costs, the usage of energy and resources is increasingly exerting pressure on the management of manufacturing companies. Industrial operations have consumed about 29 % of the final energy in Germany in 2007 [1]. Considering the electrical energy proportion, more than 556 PJ are used in industrial application areas. This corresponds to 23 % of the total industrial final energy consumption [2]. In the Republic of Korea the industrial sector is even responsible for 56 % of the final energy consumption in 2006. When calculating the share of the electrical energy consumption, the industrial sector accounts for more than 50 %, representing about 598 PJ [3]. Assuming 3500 kWh yearly electricity consumption per 4-member household, this equals to more than 92 million households.

With regard to the increasing relevance of energy consumption in manufacturing systems and the related costs, strategies to improve energy efficiency have to be developed. In accordance with the principles of a sustainable development, these strategies have instantly to consider economic, ecological and social aspects from a life cycle perspective in order to avoid problem shifts from one life cycle phase to other life cycle phases [4].

'Organizations of all kinds are increasingly concerned to achieve and demonstrate sound environmental performance by controlling the impact of their activities, products or services on the environment […].' (Introduction of DIN EN ISO 14001 [5]). In this statement the aspect of control, as an enabler to improve sustainability, is highlighted. In order to realize a sustainable development through control, management systems have to be enabled to define objectives and derive strategies to efficiently design, plan and operate all elements in manufacturing systems [6]. An important precondition for this is the availability of adequate and prompt information about the energy and resource demands and resulting consumption patterns of all elements in manufacturing systems in order to facilitate optimal decision making of improvement measures [7][8].

2 INDUSTRIAL SMART METERING

2.1 Energy consumption of manufacturing processes

Manufacturing processes transform semi-finished inputs into value-added outputs. Energy consumption becomes a physical necessity to perform that transformation. Theoretical calculations can be performed to estimate minimum energy expenditures of energy to perform processes (for example metal cutting or metal forming), but due to several losses in forms of mechanical friction, plastic and elastic deformation as well as the resulting heat losses a fairly higher amount of necessary energy expenditures is needed to perform the actual transformation process. Gutowski et al. have shown in early studies of manufacturing processes that the actual consumed energy for machining processes is overwhelmed by over five times as much energy needed for auxiliary processes like coolant pumps, lubrication supply and technical air ventilation [9]. To draw that conclusion Gutowski et al. had to meter the actual power demand of all *subordinate devices* in regard to the overall demand of the process related to the number of produced units.

Another study concerning the energy efficiency of manufacturing processes was performed by Devoldere et al., showing that the regarded hydraulic press brake's actual processing time, used for discrete work piece bending added up for a time share of less than 13 % of the total active time of the machine, resulting in a unproductive time share of over 87 %, consuming a high amount of unnecessary energy expenditures [10]. In this study Devoldere et al. have clearly indicated the need to approach an analysis of energy consumption behaviour by *considering the aspect of time*. Consumed energy is the integrated demand of electrical power over a certain period of time and is usually not considered as being static in its behaviour.

In order to gain a better understanding of energy consumption of manufacturing processes a metering strategy has to be applied

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taking the aspect of time-dynamic behaviour and of subordinate devices into consideration.

2.2 Metering of energy consumption

To gain an understanding of the energy and resource consumption behaviour of manufacturing processes a time-related measurement of the power demand of a selected system is to be applied initially. The electrical power actually demanded by a process is imposed indirectly from the metering values of voltage and current of all active electrical supply lines of the system. Figure 1 shows the power profile *P(t)* of an exemplary production machine.

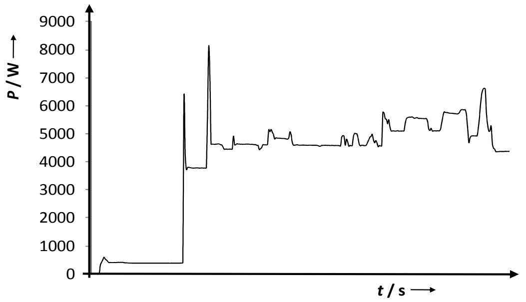

Figure 1: Power profile *P(t)* of a production process.

The amount of informational degree that can be derived from the given metering data is highly dependent of the granularity of a measurement in time and in amplitude [11]. This granularity is a result from the metering system's sampling rate, metering signal resolution and the capacity of the digital processing system in the measurement chain. Analysing Figure 1 under the aspects of a better energetic system understanding, one can define maximum power demands and draw a conclusion about the dynamic behaviour of the process by estimating the variance of the profile, but can hardly allocate any power demand level to any operation mode. Neither can one tell which amount of consumed energy was related to value adding and which to non-value adding operation modes. In order to gain a better understanding of the power profile the lack of information has to be compensated with expert knowledge of operators or engineers or further informational sources.

The selection, dimensioning and operation of the metering system as well as the realisation of a metering data acquisition, data processing and the provision of the pre-processed metering data is what we have related to in this paper as *Industrial Smart Metering*. The emphasis on 'smart' is related to the coupling to an integrated data pre-processing and communication interface.

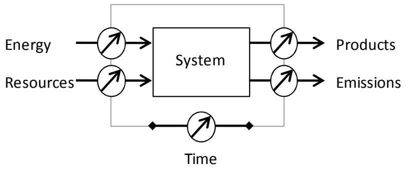

Figure 2: Generic metering model for better energy and resource aware system understanding (adapted from [7]).

Industrial smart metering adopts the generic model of energy and resource metering of industrial manufacturing processes as depicted in Figure 2, in order to create a foundation for a better system understanding by taking all inputs and outputs as well as the time aspect into consideration. When applying also expert knowledge to the gained metered data, a certain degree of allocation of power demands and time shares is possible by either logging process observations or known events to the metered data.

Figure 3 shows exemplarily how the linkage of expert knowledge to the power profile from Figure 1 can be applied. The grey horizontal and vertical lines indicate a rough division of power demand ranges of different operation modes of the processes observed by the process engineer from the operation of the selected grinding machine.

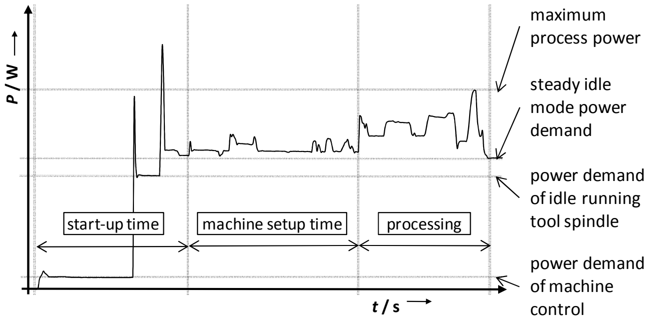

Figure 3: Power (*P*) demand of a grinding process over time (*t*).

The higher informational degree of Figure 3 in relation to Figure 1 is determined by the allocation of time-spans to events like start-up, machine setup and processing. Each time-span contains a specific field of individual power demand behaviour. But nevertheless, a true allocation of subordinate power demands is hardly possible on the given informational background not mentioning the time and effort to manually allocate visual observations to the time axis of the metered power profile.

Today's market provides smart meters known from the applications in private households, implemented with the focus to enable a certain level of transparency of the energy consumption of a household. By giving the user a visual feedback through various means of information ranging from power profiles over different time periods or accumulated energy counts or even calculated performance indicators. The provided information is generated in order to overcome the consumer's habitual consumption behaviour by raising his awareness for the energetic impact of his behaviour [12]. The new awareness is ideally causing a motivation in the consumer to rethink his routine behaviour and finding a more optimal solution while taking energy as a new optimization criterion into consideration.

The concept of *Industrial Smart Metering* is trying to adapt the same approach as smart metering in private households and is applying it to the requirements of a manufacturing environment [11]. Obviously, the requirements of a manufacturing environment are a lot more ambitious. The target group of the provided energy-related information does not only consist of one or two persons with quite the same interest, skill, and competence level as in a private household, but is rather divers, ranging from the shop floor operator and facility manager up to the process engineer and management staff. Each single target person has a different expert knowledge and a separate range of operational competency which leads ideally to a very case specific information provision for each receiver of the information.

Against this background the use of context related information to enhance the analysis and evaluation of power demand profiles in terms of industrial smart metering by integrating additional already existing informational sources from the manufacturing environment is proposed. Such additional informational sources can be simply the human logging the operation modes or rather complex, the machine's programmable logic controllers (PLC) as proposed by Vijayaraghavan and Dornfeld [13], external sensors, and historical metering data from databases. The following chapter introduces the context-aware approach and introduces a general model that can be applied to manufacturing environments.

3 CONTEXT AWARE APPROACH

3.1 Context-awareness

Currently, ubiquitous computing technologies are receiving an increasing attention as a means to realize a more sustainable manufacturing [14][15][16]. Especially, among the technologies, context-awareness can be used to increase the understanding of energy consumption in manufacturing environments. This section describes a basic introduction into the contents of context-awareness and explains the major elements of technology. In general, context-awareness is the ability to provide suitable services to a user by analyzing the context of the user. The context can be any information characterizing the situation of an entity. The entity can be person, place, or object relevant to the interaction between the user and a context-aware application [17]. The context is diverse from situation to situation. In case of the energy related situation, the energy profile, historic consumption data, operational data from PLC and ERP can be considered as some of the available context. A system can be understood as context-aware if it uses context to provide relevant information and/or services to the user, where relevancy depends on the user's task. In order to realize a context-aware integration of the additional contextual informational sources, the following major elements of technology are required as shown in Figure 4.

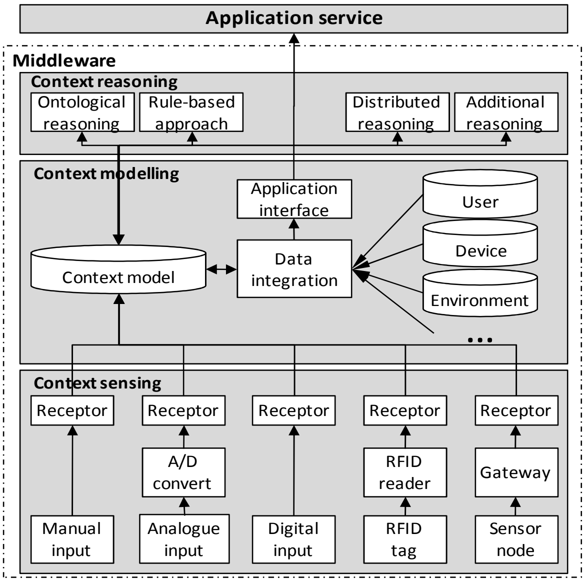

Figure 4: Generic architecture of context-awareness middleware.

Context sensing

Sensing the context is the start of context-awareness. The context could be collected via manual input of an operator, analogue or digital input of sensors (such as smart energy meters), RFID readers and sensor network nodes. Then the receptors process the information with additional treatments such as signal processing, feature extraction, and profile generation. The sensed context is stored according to a context model and is used for reasoning [18].

Context modelling

The context model provides a basis on which the context-aware application is developed and executed. The model is used to express and store the dynamic and uncertain information sensed while the application is running. The model should be easy to maintain ensuring the integrity, consistency and validity of the context and to apply reasoning techniques. Many modelling approaches are available such as mark-up scheme models, graphical models and ontology based models [19]. The model is required when incorporating external databases from users, devices, environments, etc.

Context reasoning

Reasoning the context is to infer logical consequence from existing information and decision rules. The aim of context reasoning is to deduce new knowledge, based on the available context information. To do so, the reasoning engine checks the context model database for consistency, classifies new information and applies decision rules. Based on the collected information, and on the decision rules provided by the experts, the system can adapt itself to the changes which are detected. There are various techniques such as ontological reasoning, rule-based approach, distributed reasoning, and additional reasoning including probabilistic logic, fuzzy logic, and Bayesian networks [20][21][22].

Middleware

The middleware intermediates between the low-level measuring devices and the high-level context-aware application. The middleware consists of sub-modules which support context sensing, modelling, and reasoning. It collects the sensed context, processes the context, and provides suitable services to the application via the application programming interface.

3.2 Holistic factory model adopting context-awareness

In the field of sustainable manufacturing, the context-awareness approach for fostering energy and resource efficiency has not been seen yet. It aims towards enabling operators to make a decision, based on a systemic system understanding derived from real-time sensed context of the factory, instead of a decision based on a fragmentary system view derived from single energy profiles and a limited expert knowledge.

Figure 5 shows a context aware information handling model implemented into a holistic factory view including the technical building services (TBS), machines, the factory environment, the energy and resource distribution network and the factory shell as possible context sources. The rather holistic perspective of the manufacturing environment implies the informational complexity indicated by many metering points and various decentralised data storage devices.

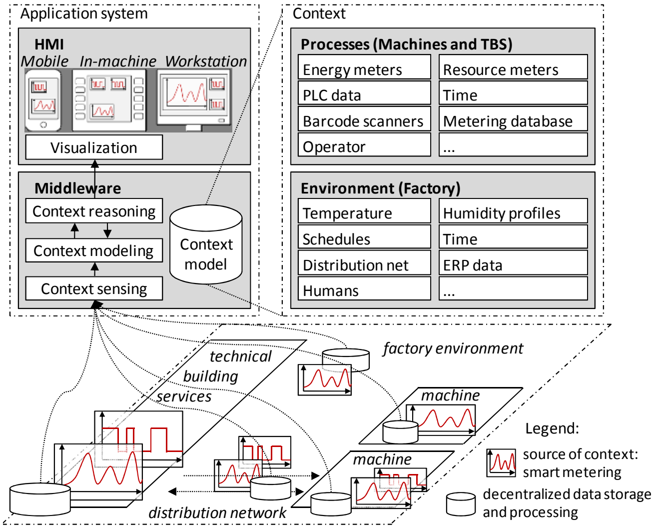

Figure 5: Concept of the context aware information handling.

The presented context-aware approach is aiming to extend the users understanding of the energy and resource flows by providing a better transparency of the system behaviour of single consumers and their related processes as well as in relation to the whole manufacturing environment. The amount of informational degree provided to the user is targeted to extend his already existing expert knowledge.

In order to derive a higher informational degree from industrial smart metering data the available context around the entity has to be sensed and aggregated in context models. This task is performed by the middleware as depicted in Figure 5. The proposed context used for extending the informational degree is divided into two categories consisting of context information from processes, including machines and TBS as well as context information from the environment, represented by the surrounding factory. The various informational sources inside these two categories range from visual observations from operators in forms of digital process protocols to real-time sensor data from subordinate processes or interlinked processes. The middleware fulfils the role of aggregating this context information as well as interpreting the individual informational sources in terms of indicating their relation to the metering data that is to be analysed (e.g. a graph like Figure 1). The interpreted data is handed on to the reasoning unit which is interlinking the informational sources and is providing the higher informational content to the user through visualisation elements. The relative context that is taken into consideration is case specific and can consists of informational sources directly related to the process, like energy meters or position sensors or speed sensors as well as indirectly related informational sources like, ERP-data, barcode scanners and RFID-readers. The superposition of smart metered data and context-aware information is aiming to provide the user a higher degree of information as he himself would be capable of deriving by using solely his expert knowledge as a single source of information.

The individual receiver of the context aware information is not restricted by the context-aware application in any way to use his expert knowledge and competence level to draw further conclusions and to tap the derivable efficiency potentials by changing his usage behaviour or by taking direct actions.

4 CASE STUDIES

4.1 Technical building services

Compressed air is one of the most commonly used pre-processed secondary energy forms in industrial manufacturing processes. Around 10 % of the total electrical energy consumed by the industry sector can be allocated to compressed air usage [23]. In defiance to the low efficiency of compressed air production, the energy carrier compressed air is in high favour of the manufacturing industry because of its universal applicability. It is used in machine tools for clamping, air-lubricated bearings, in handling processes for grippers and sorting and in control applications even as an information carrier.

To the human, compressed air is invisible, has no harming effect if being exposed to it, is only sensible through its impulse or by its acoustic noise when passing from high pressure to low pressure environments and is often taken for granted because no separate cost units exist. These facts lead to the matter why compressed air is mostly treated unaware of its actual impact to the overall energy consumption. In most manufacturing companies the actual compressed air consumption of single processes or whole distribution systems is unknown. The degree of transparency is therefore very low, which makes it an ideal application field for the presented approach. This case study shows how industrial smart metering is applied at an exemplary compressed air distribution network with the use of context sensing on one producer (PP) and three consumers (CP A, CP B and CP C). The sensed context is derived from electrical power metering on the four devices. The main metering point is deployed by means of installing an industrial volumetric flow sensor in the distribution network between the producer (with buffer) and the three consumers.

Graph *a)* of Figure 6 shows the metered volumetric flow profile *Q(t)* of the compressed air flowing from the producer side to the consumer side. Without further information a proper analysis of the volumetric flow profile cannot be executed sufficiently. Peak demands can be identified, but the much more important key figures like leakage flows or identification of consumption behaviour of single consumers is impossible without having more volumetric flow metering points at each single consumer at hand.

The approach of context-awareness allows us now to have a walk-around of installing new sensor elements by accessing already existing informational contexts. In this case study we present how already existing electrical energy meters installed in the three consuming processes used for industrial smart metering purposes can benefit the analysis of the *Q(t)* profile by applying the presented context-aware approach.

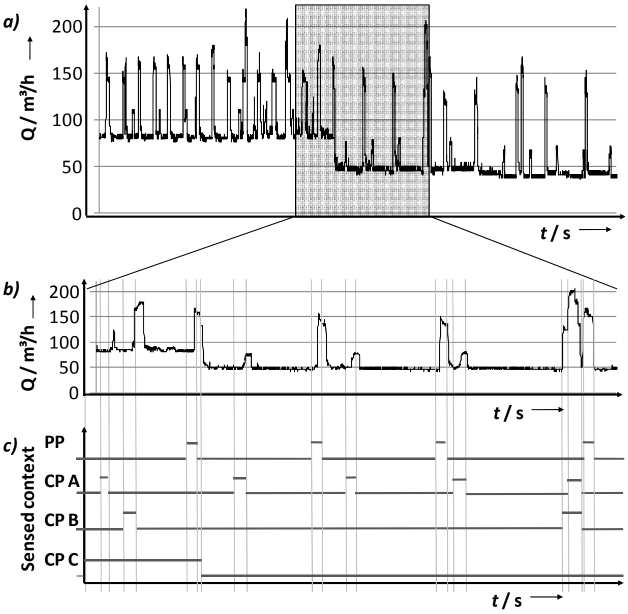

Figure 6: Context-aware analysis of a compressed air profile.

The sensed context information in graph *c)* consists simply of the duty cycles of the four devices derived from the change in state of the electrical energy consumption profiles (high state equals a power demand higher than zero, low state equals a power demand of the processes of zero watts), assuming that compressed air is consumed as soon as the machines are powered up. During context modelling, the change of the duty cycles from active to inactive and vice versa are synchronised in time axis with *Q(t)* and allocated to the enlarged section of the volumetric flow profile displayed in graph *b)* of Figure 6.

From graph *b)* and the allocated context-aware information of graph *c),* the user is now able to derive much more transparency of the compressed air distribution network through the application of context reasoning. During the time where no producer and no consuming devices are running, a constant leakage flow can be successfully identified. In the same way, peak demands can be allocated to single processes. The additional knowledge gained from the context-aware analysis can be transformed into immediate efficiency optimisation actions.

4.2 Integration of PLC data in power measurements of machine tools

Machine tools are primarily the centre of attention with regard to power measurements performed in manufacturing [10][24][25]. While it is simple to measure the temporal power demand of a manufacturing process, the analysis of the performed operations and the resulting behaviour demands additional information in order to derive optimal improvement measures and determine the saving potentials [26].

With regard to the energy-related optimization of machine tools from process and component perspective, a comprehensive understanding of the underlying processes and operating states of components during the operation of the machine tool is essential. Due to the complexity of performed processes and the time overlay of starting and stopping procedures, guidance is required providing data about the exact operation of each integrated device [13].

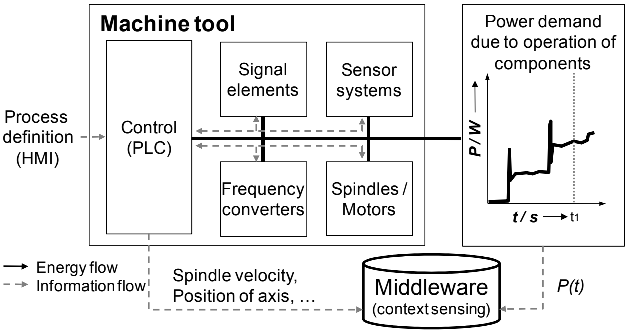

Figure 7: PLC as information source for energy-related analysis.

Programmable logic controllers (PLC) are applied in machine tools to realize the automated operation of machining processes. Hence, PLCs are controllers that capture data about the conditions and operating parameters of components in order to test, evaluate and resolve parameters to operate the process [27]. Thus, the PLC represents an important source of information which can support the analysis of power profiles in a context-aware application (see Figure 7).

Data from the PLC of a grinding machine tool was accessed using an OPC protocol and transferred for context sensing via middleware in a database system [28]. The considered test procedure includes the starting of the machine tool and the spindle as well as moving the axis. Due to the variety of available data, the spindle velocity and positions of the x- and z-axis were initially monitored. The resulting data from a power measurement as well as the PLC data is displayed in Figure 8 for the operation of the machine tool.

In context modelling, the superposition of data from the two sources is done through time index synchronisation. This enables to relate the increase of power demand with the operation of the spindle. Consequently, an energy-related analysis can be initiated improving the power demand of the spindle as well as the operating time by context reasoning. With regard to the movement of the axis, the power measurement revealed no significant increase of power. However, the measured data enables to identify and avoid non-value adding movements of the axis and can thus support the reduction of processing times to a necessary minimum.

The merging of PLC data with power demands supports the context-aware understanding of the process and performed motions of the integrated components and thus avoids manual monitoring and observation of the machine tool behaviour for an energy-related analysis. Hence, this represents the starting point to resolve highly detailed data about the energy demands and operation of components as a basis for energy-related improvements (e.g. process improvement) [13]. Although software applications provide access to the PLC of a machine tool, the interpretation of the data is yet time demanding in order to create a context model with consistent linking of the data sources to sub-component operations and modes.

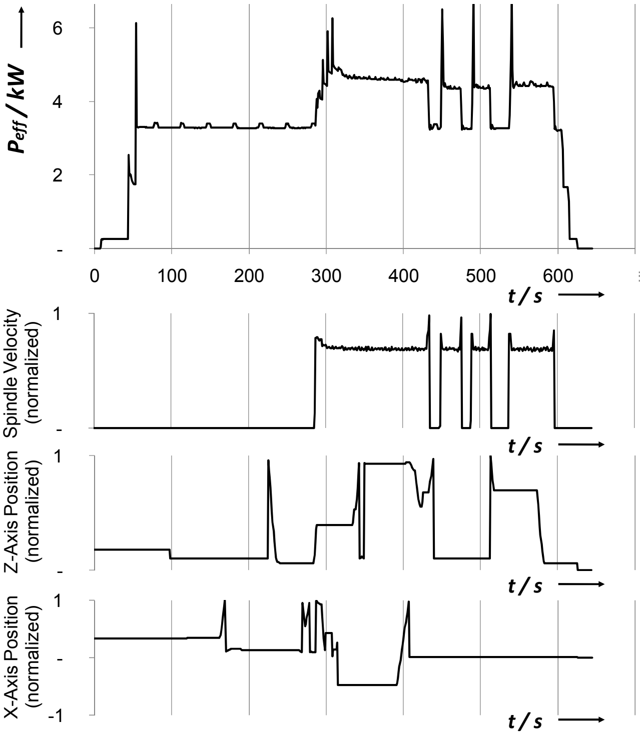

Figure 8: Example of merging data from power measurement and PLC information.

5 SUMMARY AND OUTLOOK

This paper has introduced a context-aware analysis approach to enhance industrial smart metering applications. It was shown that the manufacturing industry is getting sensitised to treat energy and resource consumption in manufacturing environments not simply as necessary cost factors to enable value-creation, but as a strategic investment just like time and material. Energy and resource aware manufacturing requires a high level of system understanding. The basis for this understanding is industrial smart metering. It has been shown that understanding metering data requires system knowledge that is unevenly distributed on various knowledge carriers inside the manufacturing environment. The introduced context-aware analysis approach is adapting methodologies known from context-aware applications on consumer-product level to the industrial manufacturing environment. Two case studies show exemplarily the application of the approach. It could be demonstrated how the different informational sources ranging from smart energy meters to machine PLCs could be used to enhance the analytical degree of information of the presented volumetric flow and power profiles.

While context-awareness is mostly applied to simple usage scenarios like houses, offices, etc. but rather seldom to complex usage scenarios like factory environments, the resulting challenges become quite obvious. The context in manufacturing environments is much more complex and has more dynamic contexts and events. Therefore, we see a wide field for more fundamental studies on context-awareness applications in manufacturing environments. The paper has shown the benefits that can be derived in the field of energy efficiency and is emphasizing the potentials in the field of a more sustainable manufacturing.

Future work will focus on the methodological aspects of the context-aware analysis approach to match specifically the manufacturing environment. Furthermore the studies on gaining energetic flow transparency of manufacturing processes will be broadened and intensified.

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