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The global threat of climate change as well as the quest for energy security reinforces the
necessity for a KPI system capable of measuring and evaluating eco-efficiency in a manufacturing
environment. This paper develops an implementation guideline for eco-efficiency performance
measurement in manufacturing according to a PDCA-logic.

1   INTRODUCTION

The threat of global climate change, environmental deterioration as well as the quest for energy and resource security leads to an increasing importance of the concept of eco-efficiency in society, politics and industry alike. From 1980 to 2007, for example, in contrast to a population growth of 52%, the total extraction of fossil fuels grew by 73% and the one of minerals by 78% (SERI 2011a, SERI 2011b). These figures show that today's resource consumption is unsustainable and prone to lead to a resource scarcity. Since manufacturing processes are responsible for almost one third of the world's energy consumption and 36% of global carbon dioxide (CO_2) emissions, their alignment to eco-efficiency criteria is particularly salient (IEA 2007). Through the publication of 'Changing Course' by the World Business Council on Sustainable Development (WBCSD) in 1992 the term 'eco-efficiency' has been coined to describe activities that create economic value while simultaneously reducing ecology impact and the use of resources (DeSimone and Popoff 1997). Consequently, for an eco-efficient configuration of manufacturing systems economic and environmental aspects have to be considered simultaneously.

As literature on performance measurement often emphasises, the impacts of goods, services or processes only become comparable and controllable, if they can be quantified (Neely et al. 1995). Hence, systems capable of collecting, processing and evaluating the relevant quantitative parameters have to be set up to achieve a concise assessment of eco-efficiency criteria. As far as the economic dimension is concerned, a quantified assessment of production costs has already been quite concisely researched and implemented in manufacturing facilities; master data related to production costs are exhaustively stored in databases and heuristics for the optimization for production workflows are well embedded in Enterprise-Resource-Planning-Systems (Kim 2009). Contrastingly, only in the last two decades has the measurement of environmental performance indicators (EPI) been moved into the scope of performance measurement systems. Although a plethora of approaches for the set-up of

Environmental Performance Measurement Systems (EPMS) exist today (e.g., ISO 14031, VDI 4070), none of these set a particular focus on the measurement of the eco-efficiency performance in manufacturing processes.

For that purpose, this paper strives to confer the more generalist approaches for eco-efficiency performance measurement to a manufacturing setting. This paper begins with presenting an overview on the most common methods for measuring eco-efficiency nowadays and highlight how these relate to production processes. Then an exemplary production system with an associated performance measurement infrastructure is introduced; this system has been specified in an EU-project currently under review. The overview on methods for measuring eco-efficiency has shown that an application of a Plan-Do-Check-Act-logic (PDCA) is quite common for the set-up of EPMS. Hence, this logic will be applied case-based on the exemplary production system. The result of this paper is the development of an implementation guideline for eco-efficiency performance measurement in manufacturing systems according to a PDCA-logic.

2 METHODS FOR MEASURING ECO-EFFICIENCY AND ASSESSMENT OF THEIR APPLICABILITY IN MANUFACTURING SYSTEMS

In this chapter, the authors introduce the most common methods for measuring eco-efficiency and assess the suitability of their application in manufacturing systems.

2.1 Research Background

In literature and practice, it is often not precisely distinguished between the terms environmental and eco-efficiency performance. Therefore, we begin with a conceptual distinction of the two terms. While environmental performance is only based on one variable (environmental performance), eco-efficiency can be defined as the ratio between two variables (environmental and economic performance) (Müller and Sturm 2001). An universally valid consensus on the indicators most suitable for describing environmental performance does not exist; environmental indicators used conventionally are, for instance, energy consumption, materials consumption, water consumption, greenhouse gas (GHG) emissions and ozone depleting substance (ODS) emissions (Verfaillie and Bidwell 2000). Quite commonly used indicators for expressing economic performance are financial or production values. Since this paper centers on eco-efficiency in production processes, the following definition of eco-efficiency will be used:

$$eco-efficiency = \frac{environmental\ performance}{units\ produced}.$$

It is the scope of the following sections to analyze and review leading approaches in the field of eco-efficiency performance measurement. In a first step, indicator frameworks will be assessed regarding their suitability for eco-efficiency measurement in production processes. In a second step, implementation methodologies for eco-efficiency performance measurement systems will be evaluated in regards to their applicability in a production context.

2.2 Indicator Frameworks

Leading standards for the set-up of indicator frameworks in the field of environmental assessment are the international standard ISO 14031 (Environmental management - Environmental performance evaluation – Guidelines) and the German standard VDI 4070 (Sustainable management in small and medium-sized enterprises - Guidance notes for sustainable management). In ISO 14031, environmental performance indicators (EPI) and environmental condition indicators (ECI) build the base for the set-up of a generic indicator framework. The scope of this standard does not include detailed recommendations concerning the set-up of an indicator framework particularly designed for production processes. VDI 4070 proposes to cluster indicators in the categories economical, ecological and social performance indicators. Furthermore, the standard distinguishes between recommended, additional and complementary indicators according to their degree of relevance for the assessment. Again, no references to production processes are made.

In addition to the standards, the publications 'Measuring eco-efficiency – a guide to reporting company performance' by the WBCSD and 'Sustainability Reporting Guidelines' by the Global Reporting Initiative (GRI) are globally known reference documents for the set-up of environmental performance measurement processes. The WBCSD distinguishes between general applicable and business specific indicators. The economic dimension is covered in the WBSCD indicator framework by the Product/ Service Value which is operationalized through the indicators 'quantity of goods or services produced or provided to customers' or 'net sales'. The environmental dimension is covered by the indicators energy consumption, material consumption, water consumption, greenhouse gas emissions and ozone depleting substance emissions. The GRI indicator framework sets an emphasis on a sustainability instead of an eco-efficiency perspective. Hence, the framework is based on economic, environmental, social, product responsibility and human rights indicators. And again, no references to production processes are made.

A review on academic literature has shown that the majority of research papers focusing on eco-efficiency assessments in production processes, e.g. the production of cheese, furniture or steel, are based on a Life-Cycle-Assessment-methodology (LCA) (Michelsen et al. 2006, Van Caneghem et al. 2010, Van Middelaar et al. 2011). Hence, the indicator systems developed in these papers are mainly derived from LCA-literature. The development of a generically applicable eco-efficiency indicator framework particularly designed for production processes is not included in the scope of any of the reviewed papers.

2.3   Implementation Logic

The standards ISO 14031 and VDI 4070 both recommend the application of a PDCA-logic for the implementation of an environmental performance measurement system. The PDCA management model adapted for the implementation of an EPMS by ISO 14031 is illustrated in Figure 1.
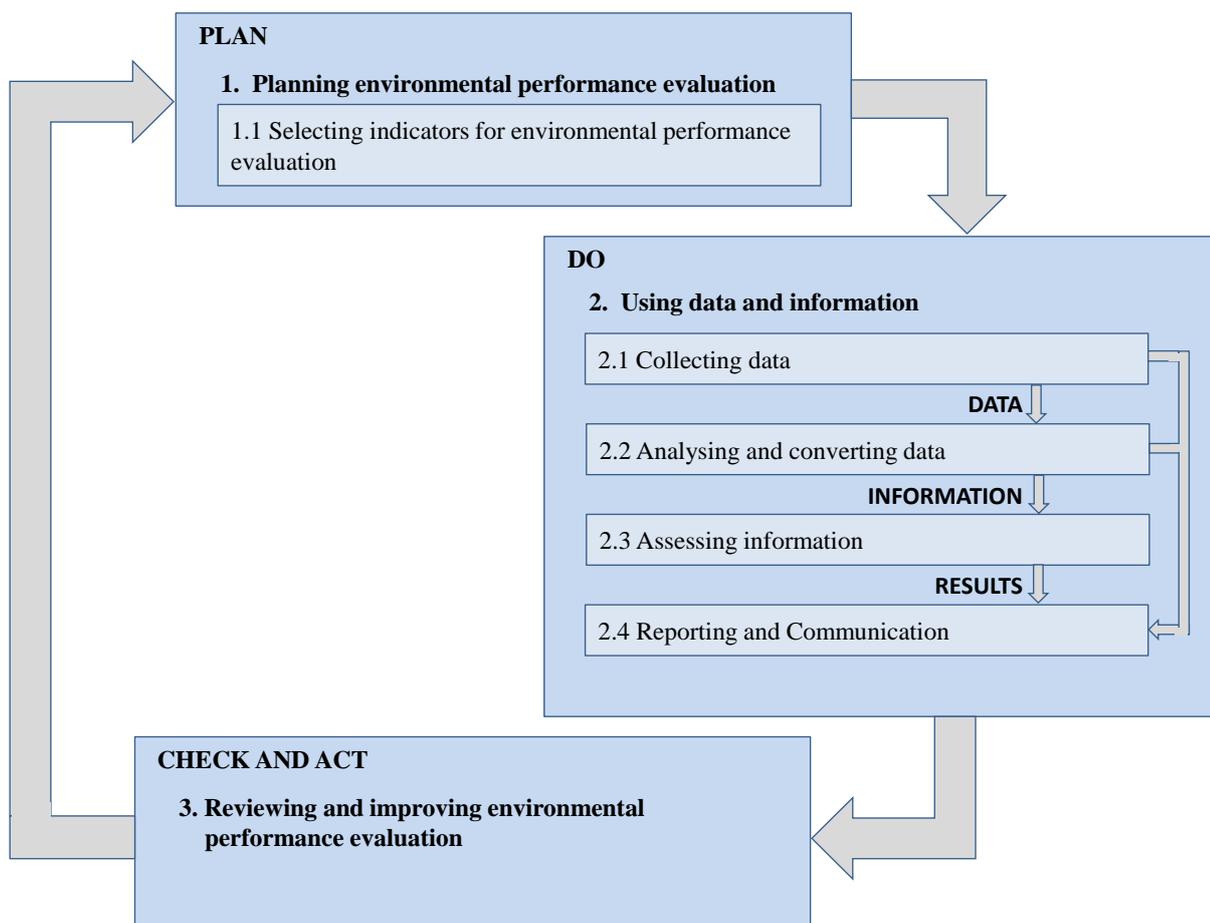
PLAN

1. **Planning environmental performance evaluation**

   1.1 Selecting indicators for environmental performance evaluation

DO

2. **Using data and information**

   2.1 Collecting data

   DATA

   2.2 Analysing and converting data

   INFORMATION

   2.3 Assessing information

   RESULTS

   2.4 Reporting and Communication

CHECK AND ACT

3. **Reviewing and improving environmental performance evaluation**

Figure 1: PDCA-model (ISO 14031)

In the first phase of the PDCA-model, the Plan-Phase, the environmental performance assessment is planned. In this context the EPIs are selected and the indicator framework is designed. In the Do-Phase, environmental raw data is collected, converted into information and then assessed. Besides, the environmental information is prepared in the form of reports for communication purposes. In the Check-and-Act-Phase, the environmental performance assessment system previously set-up is validated and improvements are made if necessary. The PDCA management model is a broadly applied methodology for the control and continuous improvement of processes and products. In ISO 14031 and VDI 4070 this methodology is adapted to fulfill the requirements for a set-up of environmental performance assessment. However, specific disciplines such as production, sales or marketing are not specifically considered.

The WBSCD- and GRI-guidelines both center on the set-up of a report structure, e.g. the development of eco-efficiency profiles. They do not contain a fully elaborated practical approach for implementation. As mentioned above, the academic papers reviewed accomplish eco-efficiency assessments based on a LCA-methodology (Michelsen et al. 2006, Van Caneghem et al. 2010, Van Middelaar et al. 2011). Instead of the development of a generic implementation guideline for eco-efficiency performance measurement systems, in these papers eco-efficiency assessment for pre-defined production processes are accomplished.

2.4   Summary of Literature Review

The literature review reveals that the today existing and renowned approaches for eco-efficiency performance measurement can be characterized by a high general applicability. A specific focus on individual target groups, for instance production managers, is seldom set. Hence, production and facility manager are still in need of frameworks, indicator systems and implementation guidelines in order to optimize their manufacturing processes with regard to eco-efficiency.

3 SYSTEM DESCRIPTION

This chapter introduces an exemplary production system with an associated performance measurement infrastructure; the system has been specified in an EU-project currently under review. In chapter 4, this system is used as object of study to develop the implementation guideline for eco-efficiency performance measurement.

3.1 Production System

According to Nyhuis et al. (2008) "a production system is a sociotechnical system which transforms input (e.g. know-how, methods, material, financial resources, energy) through value-creating processes (e.g. production or assembly) or associated processes (e.g. transportation) into output (products, costs, residues)". The production system used as object of study in this paper is a production facility typical for the mechanical engineering sector; e.g. machinery meant for welding, cutting or forming can be found on the shop-floor.

Production planning is defined as the sum of all spatial, temporal and quantitative planning and control processes relevant for a production system. It can be distinguished between strategic, tactical and operational production planning. The scope of Strategic Production Planning is based on the definition of the long term production strategy which includes the selection of the most favorable production locations, the set-up organizational structures within the production system as well as the development of operational production concepts. Tactical Production Planning focuses on the definition of the breadth and depth of the production program in addition to planning activities for human resources and operating equipment. Operational Production Planning and Control contains the planning of the short term production and sales program, including the calculation of the required resources, individual parts and components (Arnold 2008).

In the early 80s, Production Planning and Control (PPC) software solutions have been introduced to production facilities to ensure an IT-based planning of production processes. Traditionally they have

been programmed to ensure high service levels, a high and evenly distributed utilization of capacity, short lead times, low stock levels as well as a high degree in flexibility (Luczak and Eversheim 1998).

In the recent past, through the rise of concepts like sustainability and eco-efficiency, environmental aspects in production processes progressively moved into the center of attention. For the time being, these aspects are seldom represented in PPC systems. A major obstacle for an optimization of production processes according to environmental criteria is data availability. In the next section a performance measurement infrastructure capable of collecting, processing and interpreting environmental data for production planning processes is introduced.

3.2   Eco-efficiency Performance Measurement System

The core target of the presented Eco-Efficiency Performance Measurement System (EEMPS) consists of the following two aspects: (a) presentation of an overview in regards to the eco-efficiency of a production system and (b) contribution to an optimization of production processes. For reasons of comprehensiveness the EEMPS used as object of study in this paper distinguishes between the preparation of information for strategic, tactical and operational production processes. In Figure 2, the performance measurement infrastructure, centering on an EEMPS, used as object of study is presented. Production System and PPC are included in the system boundaries since they are relevant providers and receivers of input and output flows.
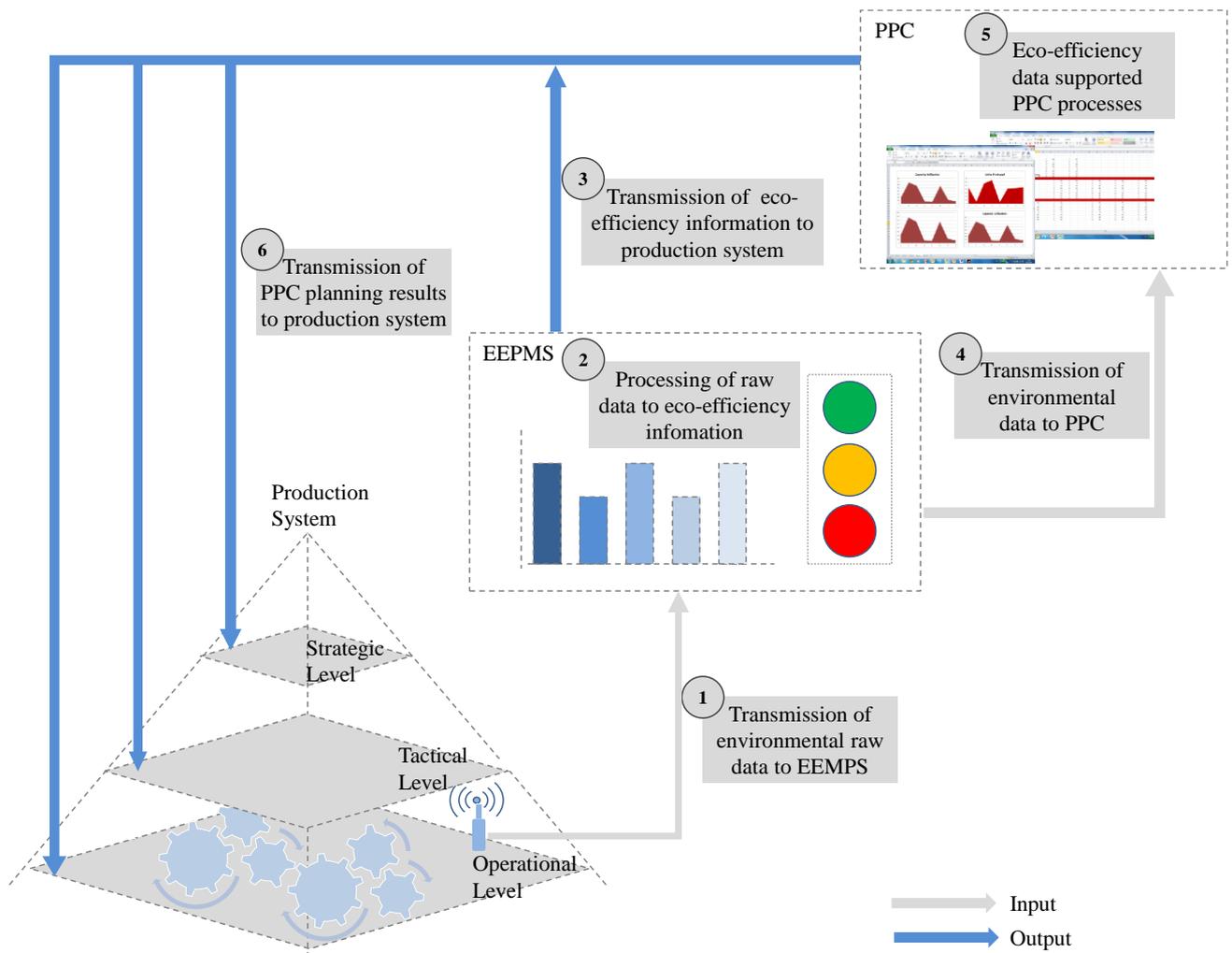
Figure 2: Eco-Efficiency Performance Measurement System

In the following, the core processes taking place in the performance measurement infrastructure are explained. (1) To begin with, environmental raw data is provided from the operational level of the production system to the EEPMS via process analysis and sensors. (2) Then, an algorithm-based aggregation of the environmental data takes place in the EEMPS. Furthermore, the environmental data is set into relation to the units produced. These two steps ensure a conversion of environmental data into eco-efficiency information. (3) Parts of the eco-efficiency information is then sent back to the production system to provide decision-support on the strategic, tactical or operational level. (4) The rest of the data is forwarded to the PPC via an electronic interface. (5) In the PPC, the data supports IT-based planning and control processes. (6) In a final step, the planning results of the PPC

are transmitted back to the production system where a direct implementation of the recommendations

follows.

4 IMPLEMENTATION GUIDELINE FOR ECO-EFFICIENCY PERFORMANCE MEASUREMENT IN MANUFACTURING SYSTEMS

In the following, it is described how an EEPMS can be implemented in a manufacturing environment by the application of a PDCA-logic. The PDCA-logic applied conforms to a large degree with the PDCA-model introduced in ISO 14031.

4.1 Planning Eco-efficiency Performance Evaluation

1. Selecting indicators for eco-efficiency performance evaluation

It is a quintessential prerequisite for the set-up of an EEPMS to determine the required performance indicators. There are a multitude of structural frameworks and approaches for an selection of indicators present in literature and practice (e.g. ISO 14031, VDI 4070, GRI indices). However, neither a consensus on a common standard has been achieved nor do well-known approaches feature indicators defined for production systems in particular. To close this research gap, Plehn et al. (2011) developed an indicator framework for production processes by filtering environmental performance indicators according to their relevance and applicability in production using the Supply Chain Operations Reference Model (SCOR). Hence, the authors of the paper at hand recommend using this indicator framework as a base for the selection of environmental performance indicators. For the specification of this framework to the requirements of a specific production company, they propose an execution of surveys and interviews with employees of the company and a subsequent adaption of the framework to the individual needs of that company. The surveyed group should include employees from various interest groups; this will ensure that requirements stemming from the shop-floor as well as management level are considered for the system set-up. A feedback loop from the second phase of the PDCA-circle, the Do-Phase, back to the Planning-Phase is required, since it has to be ensured that (a) the collection of the required data is feasible, (b) ambiguities in regards to the

information the collected data contains are clarified and (c) the collected data provides all relevant information for the evaluation.

4.2 Using Data and Information

2. Collecting data

This phase of the PDCA-circle defines in which manner the input data for the EEPMS is collected. According to ISO 14031, data collection should ensure reliability; depending on factors such as availability, adequacy, scientific and statistical validity and verifiability. Since it is the objective of the EEPMS to disclose the potential for optimization in regards to eco-efficiency criteria within the production system, input data has to be collected within system boundaries of the production system. Hence, data collection directly from production machinery will be the main source of input. The monitoring of machinery with the aid of sensory devices or smart meters is quite common in production operations. Since the consumption of energy and various other resources is often dependent on the operation currently performed, Vijayaraghavan and Dornfeld (2010) suggest to employ event stream techniques to monitor consumption patterns of machinery. Furthermore, they claim that automated monitoring systems help to attach contextual process-related information to raw data. Therefore, an automation of the data collection procedure will ensure an availability of data enriched with supplementary information.

The authors of the paper at hand recommend the set-up of a sensor network to ensure a provisioning of high-quality real-time data to the EEMPS. A transmission of the information deducted from the real-time data to a PPC later on, can particularly lead to substantial benefits in the eco-efficiency range. The recommendation to set-up a sensor network is particularly appropriate in a large enterprise setting. For data collection in a small or medium enterprise (SME) setting, the set-up of a sensor network is mostly likely to exceed budget restrictions. Hence, a less sophisticated case-based approach is recommended for SMEs.

3. *Analysing and converting data*

The raw data collected from the shop-floor is transmitted to the EEPMS where it is then converted into information. The authors suggest a data conversion according to a LCA-methodology; an approach also often applied in academic literature associated with eco-efficiency measurement in manufacturing environments (compare Chapter 2). In alignment with LCA-methodology, the first step in the set-up phase of an EEMPS is the selection of the generic environmental indicators most suitable for a specific manufacturing facility. Common generic environmental indicators are, for instance, greenhouse gas emissions, waste or water consumption (compare Chapter 2). To receive a more elaborative list of potential generic environmental indicators a consultation of standard literature for LCA (Baumann and Tillman 2009, Guinée 2002, Klöpffer and Grahl 2009) is recommended. When selecting the environmental indicators, it should be ascertained that the chosen indicators reflect the most predominant environmental impacts of the investigated production facility.

As preparation for the conversion process, the environmental raw data collected from the production system is sorted and allocated to generic environmental indicators. Afterwards, the raw data is converted into meaningful equivalent units (characterization), dependent on the generic environmental indicator it is assigned to. The standardization procedure just explained, paves the way for a quantitative comparison of time-, process- and product-dependent eco-efficiency data sets.

4. *Assessing information*

ISO 14031 distinguishes between two types of indicators, Environmental Condition Indicators (ECIs) and Environmental Performance Indicators (EPIs). Since the main purpose of ECIs is an evaluation on a macroeconomic level, they can be neglected in the case of an eco-efficiency assessment within a production facility. EPIs, then again, are divided into the two subcategories Management Performance Indicators (MPIs) and Operational Performance Indicators (OPIs). MPIs

provide decision support for long-term strategic planning processes. Referring to production processes, this signifies that MPIs deliver information for the strategic production planning (program planning, location planning, organizational development). OPIs back-up operational planning processes through quantifying the input and output flows of a system with reference to its boundaries. Applied to a production environment, this translates into a mapping of for production processes required input factors (e.g. resources, energy, water) and output factors (e.g. emissions, waste). For tactical production planning processes, a combination of OPIs and MPIs, dependent on the exact planning task, is required.

Since it is the scope of an EEPMS to perform an eco-efficiency assessment, the environmental indicators just described have to be set in relation to the units produced (compare chapter 2). Furthermore, external impacts have to be considered in the assessment phase to ensure a coherent result. For instance, process adjustments or the employment of new machinery on the shop-floor may require that additional data has to be collected. Changes in production volumes or lot sizes may influence the environmental performance of a process step considerably. Besides, climatic changes such as temperature, humidity etc. might also lead to distortions in measurement results.

The procedures just explained ascertain that a comparison between current and historical eco-efficiency data becomes possible, process optimization scenarios can be ranked or a benchmarking of production facilities can be achieved.

5. *Reporting and communication*

As previously illustrated, the EEPMS provides eco-efficiency performance data to all levels of a manufacturing system (operational, tactical and strategic level). The data is converted and aggregated into information taking the sometimes diverging requirements of the different levels into account. The information is visualized in the EEPMS according to a value stream mapping methodology (VSM). The visualization enhances the accessibility of the information. Furthermore, intelligent

warning functionalities call attention to situations in which prompt action is required. Through the direct transfer of information to the PPC system, adaptions in production planning and control processes can be performed in real-time.

4.3 Check and Act

6. Reviewing and improving eco-efficiency performance evaluation

A periodical review and improvement of an EEPMS is recommended to obtain accurate and meaningful results (ISO 14031). First of all, various aspects regarding the internal system set-up as well as the external business setting have to be regularly validated: Is all relevant data collected? Do the individual indicators still provide information required by the stakeholders? Does the indicator structure still serve its purpose? Are the environmental objectives still in alignment with the company strategy? Did the external legal situation change?

Secondly, there are peculiarities to be considered as a consequence of the fact that this paper focuses on the implementation of an EEPMS in a manufacturing environment. Especially since the EEPMS described in this paper continuously exchanges information with a PPC-system, even minor changes in production processes can require the readjustment of the EEPMS. Therefore, in a Check and Act-Phase designed for a manufacturing setting the following additional aspects have to be verified: Have there been any amendments made on the shop-floor which require a readjustment of the EEPMS? Are additional sensors required to distinguish between different process steps more precisely? Did machinery elements change their performance? Are all from the PPC-information required information still provided? Are the interfaces to the PPC fully available?

4.4   Summary of Results

The development of an implementation guideline for eco-efficiency performance measurement in manufacturing systems has disclosed to what extend generic guidelines have to be adjusted to the specific requirements of a production facility. Referring to a PDCA-logic (ISO 14031), Figure 3 illustrates which amendments are recommended to achieve the optimal measurement results and subsequently highest eco-efficiency gains in a production system.
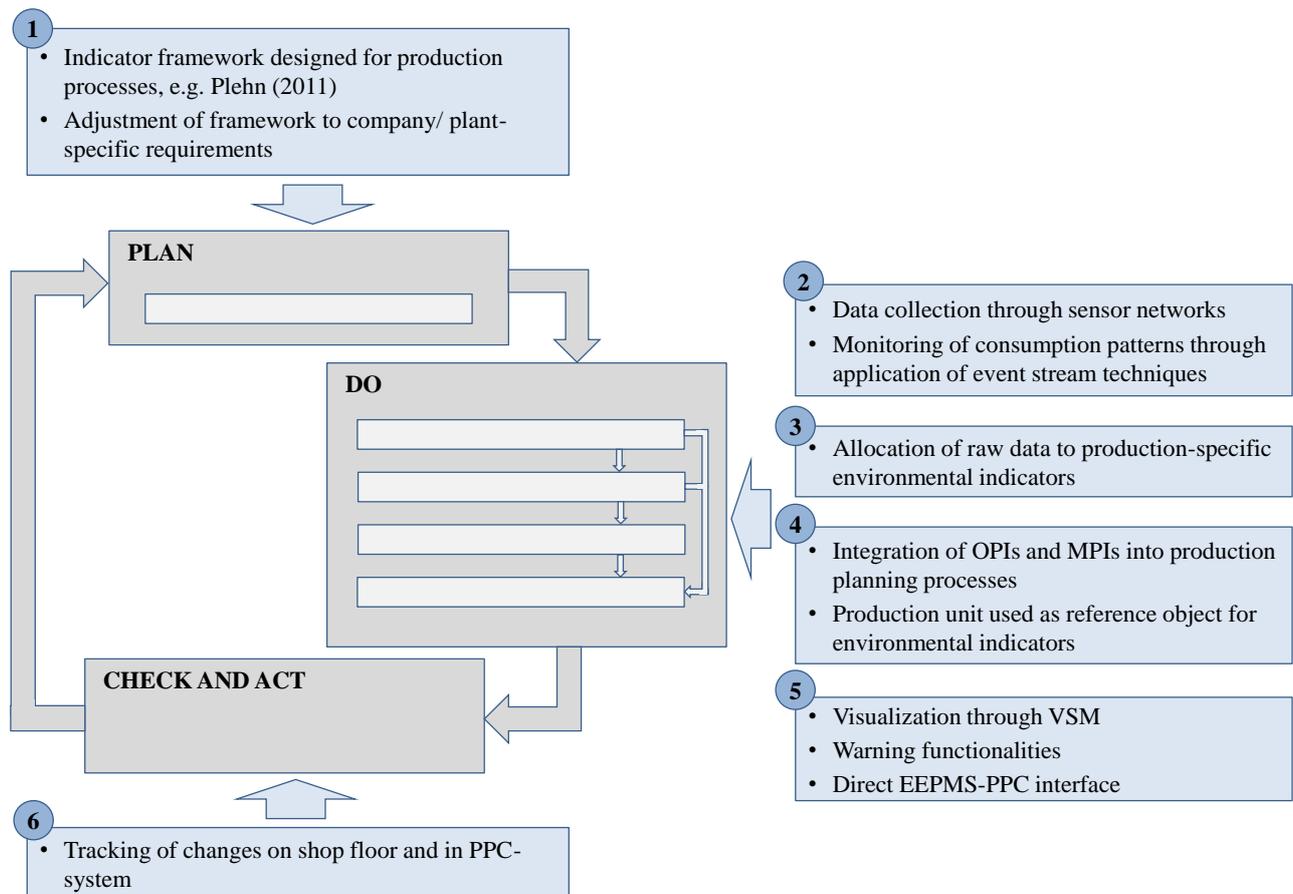
1
- Indicator framework designed for production processes, e.g. Plehn (2011)
- Adjustment of framework to company/ plant-specific requirements

PLAN

DO

2
- Data collection through sensor networks
- Monitoring of consumption patterns through application of event stream techniques

3
- Allocation of raw data to production-specific environmental indicators

4
- Integration of OPIs and MPIs into production planning processes
- Production unit used as reference object for environmental indicators

CHECK AND ACT

5
- Visualization through VSM
- Warning functionalities
- Direct EEPMS-PPC interface

6
- Tracking of changes on shop floor and in PPC-system

Figure 3: Amendment of PDCA-model to production processes

In the first phase of the PDCA-model 'Selecting indicators for eco-efficiency performance evaluation', the authors recommend the application of an indicator framework particularly designed for production processes. Furthermore, the framework might have to be adjusted to company- or plant-specific requirements. In the second phase 'Collecting Data', the set-up of a sensor network is most likely to lead to the highest availability of environmental production data. The resource

consumption of machineries can be attributed to certain production processes through the monitoring of consumption patterns. Hence, potential for optimization can be revealed. In the third phase 'Analysing and converting data', this paper suggests the allocation of raw data to production-specific environmental indicators. The authors emphasize that in the fourth phase 'Assessing information' information provided by OPIs and MPIs should be understood as decision-support for production planning processes. For the conversion on the environmental information provided by OPIs and EPIs into eco-efficiency information, the production unit is most suited to be used as reference object. In the fifth phase 'Reporting and Communication', a direct consideration of warning signals emitted by the EEMPS on the shop floor is recommended. Besides, a direct EEMPS-PPS interface is to be set-up. And in the final phase 'Reviewing and improving eco-efficiency performance evaluation', the tracking of amendments made to the shop-floor and PPC-system should allow their consideration in the evaluation of measurement results.

5   CONCLUSION AND OUTLOOK

This paper reveals that an implementation of systems capable of measuring eco-efficiency is a valid approach for mitigating the negative impacts of production systems on the environment. Since production processes are one of the key emitters of hazardous substances, their monitoring and optimization is particularly advisable. The most common methods for measuring eco-efficiency are introduced in this paper. A literature review confirms that currently no eco-efficiency measurement methodology particularly designed for production processes exists. To close this research gap, the authors apply the PDCA-model, frequently used for the implementation of Environmental Performance Measurement Systems, to a production setting. This leads to the development of an implementation guideline for eco-efficiency performance measurement in manufacturing systems.

During the process of developing the implementation guideline, it became apparent that a consideration of production-specific peculiarities is prone to increase the effectiveness of an Eco-efficiency Performance Measurement System. In this context, the set-up of a real-time connection between EEPMS and PPC can be particularly highlighted. Such an interface between EEPMS and PPC allows for potential process optimizations to be directly put into practice. Moreover, through a comparison of the eco-efficiency performance before and after the implementation of the optimization measures, the success of these measures becomes instantly assessable.

Today, academic literature and practical use cases illustrating such an integrated approach for measuring eco-efficiency in manufacturing systems are still rare. Both eco-efficiency indicator frameworks and implementation guidelines have to be further honed to achieve optimal interactions between the actual production system, production planning processes and eco-efficiency measurement activities.

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