Smart Manufacturing Execution System (SMES):
The Possibilities of Evaluating the Sustainability of a Production Process

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Abstract

Sustainability in production processes is mandatory in the manufacturing environment due to restrictions such as legislation. Conventional Manufacturing Execution Systems (MES) don't really support environmental sustainable goals but are actually the most suitable background for an extension towards sustainability monitoring, control and assessment. This paper introduces a new MES generation which is enhanced with interoperable data acquisition, analysis and optimization in line with sustainability goals.

A harmonization work on metrics and indicators, aligned with the Triple Bottom Line, is presented based on an analysis of industrial users' requirements within machining process context. Also, a framework for sustainability evaluation through a specific architecture is introduced.

Based on an industrial use case, the given approach is set in the context of the FoFdation project which also addresses the integration among manufacturing IT systems towards overall lifecycle management.

Keywords:

Data acquisition, Green manufacturing, Manufacturing Execution System (MES), Sustainability evaluation, Triple Bottom Line

1 INTRODUCTION

Sustainability in production processes is mandatory in the manufacturing environment due to constraints such as legislation, market and company goals. The market factor explains why there is a growing need for better monitoring and awareness of manufacturing processes to address both environmental and productivity optimization issues. Quality improvement, production cycle reduction must nowadays be managed while also taking into account new concurrent thresholds such as energy consumption and carbon footprint indicators.

Conventional Manufacturing Execution Systems (MES) don't really support environmental sustainable goals but are actually the most suitable background for an extension towards sustainability monitoring, control and assessment. This paper introduces a new generation of MES which is enhanced with interoperable data acquisition, analysis and optimization in line with sustainability goals.

A harmonization and clarification work on metrics and indicators, aligned with the Triple Bottom Line, is presented based on the analysis of industrial users' requirements and literature research within machining process context. Furthermore, a framework that suggests how to implement sustainability evaluation through a specific architecture and the required metrics description is introduced.

The given approach, based on an industrial use case, is set in the context of the FoFdation project (www.fofdation-project.eu) which also addresses the integration with PLM-ERP towards overall lifecycle management.

The paper introduces an analysis and proposal for a sustainability evaluation framework in which the IT solution is based. A comprehensive set of existing sustainability metrics and indicators have been considered and categorized according to different aspects such as the Triple Bottom Line definition. Out of such metrics and indicators, the framework was chosen to foster the implementation of sustainability improvements and support decision makers in assessing the impact and effects of these measures not only on the environmental requirements but also on the overall business performance.

After a review on existing commercial systems (dedicated data collection tools, MES like tools and specialized systems for energy management), the Smart Manufacturing Execution System (SMES) solution is presented. The conceptual idea for such a solution was based on a conventional MES, adapted and enhanced with new hardware architecture in order to directly collect information on resource consumption from the machines. The proposed architecture allows for the combining of information on the execution of the manufacturing operations and resource consumption data, leading to an improved awareness of the manufacturing operations performance. The data collection features are completed with an analysis through an Online Analytical Processing (OLAP) system which allows the investigation of sustainability parameters in a multidimensional space, and then the optimization of the production by a scheduler that schedules production orders according to an energy efficiency strategy.

The resulting prototype was set up as a demonstrator in the Centro Ricerche Fiat (CRF) labs for validation purposes of SMES data collection features and details of this validation are given below.

As a conclusion, the difficulties which were encountered during the implementation and installation are stated and the challenges for the future mentioned. The results obtained

allow to explore new concepts for online and automatic optimization towards a sustainable manufacturing process.

2 SUSTAINABILITY EVALUATION FRAMEWORK

2.1 Metrics and indicators

Sustainable manufacturing and related energy efficiency are becoming an important topic in industry. Still, in the case of energy efficiency, neither machine tool users nor builders have a clear picture of their energy use in production [1, 2]. This fact is due to individual evaluation approaches which are dependent on the field of industry, motivation, and individual manufacturing processes and needs; the Ford Product Sustainability Index (PSI) [3], for instance, defines a set of indicators based on the ISO 14040 (Life Cycle Assessment - LCA). Those indicators are selected from the point of view of the automotive industry. A common approach on a higher aggregated level is given by the Global Reporting Initiative (GRI) [4]; as this method is globally recognized and is supposed to be generally valid, but it is also controversially discussed [5]. Another large scale approach is given by the Sustainable Value [6]; it evaluates the resource allocation and its effects in money units for economical, ecological and social resources in line with the Triple Bottom Line definition. These examples illustrate various selections of metrics and indicators for the evaluation of sustainability with their dependencies, individual needs and information and levels of application, e.g. LCA or organizational levels, as indicated by [7-9]. Based on this application variety a selection tool was developed by the FoFdation project where more than 120 indicators and metrics were grouped together according to three aspects in order to support users' selections: Life Cycle Assessment status, application level within the factory and the Triple Bottom Line definition. This grouping has led to key performance indicators (KPIs), Environmental Performance Indicators (EnPIs) and Measurement Values (MVs) (Figure 1) and enables various users to set their metrics.
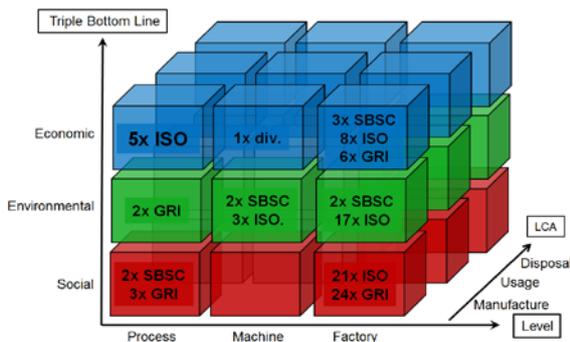

Figure 1: Clustering of metrics and indicators within the FoFdation project

As the strategic level mainly focuses on awareness and control and is dependent on the CRF use case, special focus for metrics and indicators was given on the shopfloor for machine tool energy evaluation according to ISO14955 [10].

2.2 Sustainable performance measurement

As the assessment of the sustainable performance in the field of energy efficiency in production has become a major asset in manufacturing, Bunse et al. [11] concludes that various energy efficiency performance measures already exist in the aggregated sector, e.g. plant, but these performance measures are not necessarily suitable to assess energy efficiency performance of single manufacturing processes or the machine tool. Furthermore, appropriate energy efficiency metrics and measurement frameworks on machine, process and plant level, and energy efficiency benchmarks on machines and equipment for monitoring and optimization are missing. Emerging new sensor technologies and smart embedded devices enable operation based process measurements and therefore can provide accurate information for monitoring the production performance, Karnouskos et al. [12].

In the FoFdation project a framework was chosen that is able to integrate energy efficiency measures in an adequate performance assessment system for manufacturing companies on the shopfloor level. This approach can foster the implementation of energy efficiency improvements and support decision makers in assessing the impact and effects of energy efficiency measures not only on the environmental requirements but also on the overall business performance.
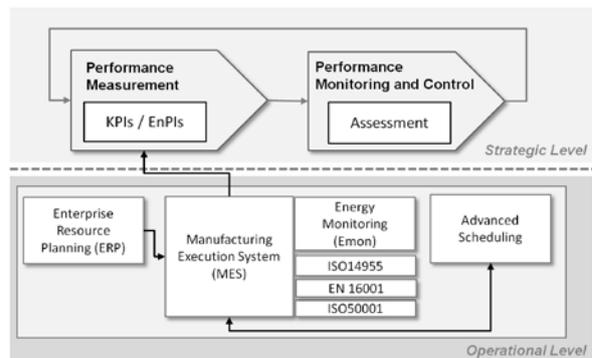

Figure 2: Elements of Sustainable Evaluation Framework in the FoFdation project based on Bunse et al. [11]

3 SMART MANUFACTURING EXECUTION SYSTEM

The SMES aims for leveraging an existing MES to reduce the economical and environmental impact in manufacturing through reducing cycle times, rework, materials, energy, emissions, wastes and scraps.

3.1 State of play in data collection systems

Sustainability evaluation must lie on a proper IT system for data collection. A review on commercial solutions reveals three main kinds of systems devoted to such a purpose: dedicated data collection tools, MES like tools, and specialized systems for energy management.

Most dedicated data collection tools focus only on data monitoring and availability. Their objective is to deliver the information, store it in a base, and visualize it through tables, graphs and reports, e.g. Predator MDC™, RF-SMART, Scytec Hosted DataXchange™, IntegraNet™, Acumen's Automated Shop Data Collection SW, Catalyst PDC™, Q*ADC, etc. They typically use standard database and/or spreadsheet formats for storage and they collaborate with MES and ERP systems for delivering the requested data.

Higher level MES like tools focus mainly on the product/assets information collection such as product tracking information, BOM, assets utilization, equipment

states, resource availability, etc., e.g. EZ-MES. Some of these tools go beyond production data collection and reporting as they provide some extra modules/functions that support semiautomatic scheduling and 'what if' scenarios, e.g. FACTIVITY, Litum, Acumen's Job Tracking SW.

Specialized systems that focus on sustainability issues are also available from several manufacturers. Most of the systems focus mainly on energy management, although they may also support other sustainability metrics (e.g. Schneider Electric, Siemens WinCC, Rockwell Automation EEM, GE Energy Management).

As a consequence of the analysis performed, an existing conventional Manufacturing Execution System (MES) has been selected as a basis for the adopted solution within the FoFdation project context. Although not fully compliant with sustainability requirements, traditional Manufacturing Execution Systems are recognized as the most appropriate solutions towards a comprehensive approach for sustainable monitoring, controlling and assessment [13].

The selected MES has been adapted and improved with a new system (FoF-EMon) that enables the data collection and monitoring of environmental resource consumption on the machine tool. The combination of the MES and FoF-EMon results in a package that relates information on the execution of the manufacturing operations to environmental resource consumption data. Such a combination leads to an improved awareness of the manufacturing operations performance through a configurable set of sustainability KPIs.

3.2 Architecture

In the figure below, the architecture for the conceptual solution of SMES is shown.
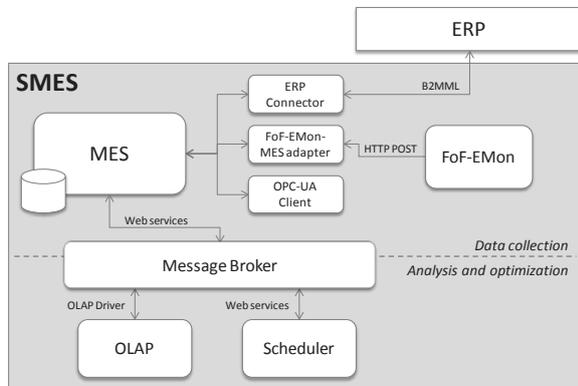

Figure 3: SMES Architecture

The architecture includes a centralized integration point (Message Broker) which coordinates the information flow among all modules within the SMES. It consists of an interoperable platform that operates through Web Services and SOAP protocol and utilizes a message driven mechanism for information exchange. Key elements in the architecture are those related to data collection and analysis and optimization. As part of data collection, the existing conventional MES is devoted to collect manufacturing operations execution data from the shopfloor. It incorporates specific modules to provide higher connectivity with other systems, i.e. the ERP connector to integrate with the ERP, and an OPC UA client to give the SMES the capability to connect to any system that supports this *de facto*

communication technology standard. An adapter relates the MES to FoF-EMon which collects data directly from the machine tool components with internal and external sensors and combines simulations too to save costs on the applied sensors. FoF-EMon monitors the consumption of the different parts of the machine tool and provides categorized information for the shopfloor.

Regarding analysis and optimization, the architecture includes a feature for Online Analytical Processing (OLAP) which allows the consolidation and analysis of sustainability data collected on the shopfloor in a multidimensional space, based on the SMES database, and a scheduler to schedule production orders according to an energy efficiency strategy. Based on operations research and artificial intelligence, it applies a newly developed dispatching rule, Less Energy Consumption (LEC), that allows production schedules to be obtained that lead the enterprise to operate on the lowest energy consumption possible.

3.3 Environmental sustainability data collection

A key element for energy efficiency evaluation and optimization is seen in the accurate quantification of the energetic behavior on the shopfloor, machine tool level [8, 14, 15] and its components. For this reason a data acquisition tool for Energy Monitoring (FoF-EMon) on the machine tool as part of the Smart Manufacturing Execution System (SMES) was developed within the FoFdation project. FoF-EMon is understood as a crosslink between machine control and the Manufacturing Execution System (MES). Based on ISO14955 [10], FoF-EMon collects all relevant energetic information, including electrical components and compressed air and media flow from external sensors and from the machine tool control and simulations for a detailed resource evaluation. With a sampling rate of 5Hz all energetic relevant information, including peak power, are collected, synchronized and displayed (Figure 4). This data is then processed, analyzed and transmitted with a constant rate of 1Hz to the MES.
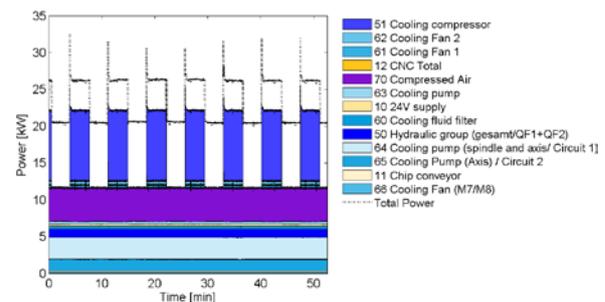

Figure 4: Example of data provided by FoF-EMon

3.4 Production execution data collection

For the collection of production execution data an MES system has been adapted. The MES is able to collect essential data (work order, actual times and quantities, machine failures and times incurred, traceability data, quality data, etc.) both automatically and manually through an HMI on industrial PCs on the shopfloor, and incorporates data coming from the machine through the FoF-EMon. The FoF-EMon-MES adapter provides information on resource consumption (energy, compressed air) from the FoF-EMon. This information is aggregated and stored in the SMES

database for subsequent analysis. The consumption information is stored by time, piece, event/machine status, but also in relation to work order, part number, material (traceability) and process (how it was machined). This aggregation facilitates the analysis that relates energy consumption data with production data which is then presented through an OLAP based dashboard that shows relevant KPIs with their target and actual values.

Nevertheless, the MES itself also has the ability to analyze the performance of the production site in terms of sustainability through sustainability metrics and PIs. The MES includes a dashboard where the operator and line responsible staff can check the status of sustainability performance in a certain machine. It contains information on the production order, its status, metrics and PIs to assess the performance: processing times, setup times, downtimes; produced quantities (good, scrap, and their causes); energy consumption (categorized by compressed air, machine conditioning, machining, process cooling and conditioning, waste handling, tool handling); and several indicators such as OEE, availability, performance and quality or the energy consumption ratio (relationship between energy used for machining compared to the energy for auxiliary systems), which gives an idea of the effectiveness of the machine tool and the efficiency of the energy used.

In order to collect data on the shopfloor, information from the ERP related to the scheduled work orders has to be obtained by the MES. It also needs to feed back the ERP with information of actual production data collected on the shopfloor. Such information is exchanged through a developed ERP connector based on Business To Manufacturing Markup Language (B2MML) schemas, the XML implementation of the ANSI/ISA-95 family of standards, known internationally as IEC/ISO 62264. In addition to this, the MES includes a work order sequencer to enable it to change the production schedule downloaded from the ERP or from the scheduler within the SMES, due to last minute changes (emergencies, lack of resources or material, etc.).

The MES also includes an HMI for production supervision. The corresponding HMI shows the lines and machines under control and gives quick information on the status of the machines, but also detailed information on sustainability performance for each machine on the shopfloor.

3.5 Analysis and optimization

The collection of data for further analysis at a later point in time requires the use of a repository with a structure to support a significant amount of data per machine tool. Implementation of this approach to a larger production scale that will lead to the big data problem is not considered in this paper. In this approach, the collected data are applied to the identified sustainability metrics and act alongside decision support systems. Moreover, the resulting values can be further visualized in dashboard applications or by using commercial spreadsheet applications to perform personalized analysis. The metrics values are accessible by other systems such as the IMPACT scheduler to optimize the plan of the next period based on the energy consumption of the last production period.

This chapter shows the SMES approach for analysis of the collected data through OLAP and for the optimization of sustainability at different levels; at machine level (micro-

optimization) with FoF-EMon and at production line level with a scheduler (macro-optimization).

Online Analytical Processing (OLAP)

The amount of data is quite significant and restricts the selection of the storage system. Online Analytical Processing (OLAP) tools are the foundation of data warehouses [16, 17] supporting analysis of enormous amounts of data in rational response times. In this paper we considered the Relational OLAP (ROLAP) variation as production performances are stored in a traditional Relational Database Management System (RDBMS). Furthermore, the lowest level of production information is considered to be the collected information from the machine tools. OLAP tools structure information in cubes consisting of dimensions, measures and facts. The cube is organized as follows. There are 8 dimensions: (D1) machine tool extends to the hierarchical levels [18], (D2) part, (D3) operation, (D4) work orders, (D5) operators, (D6) time (D7), machine components and (D8) machine status, and 4 facts: (F1) cycles of machine tools including yield quantities and processing times, (F2) energy consumption of each machine function, (F3) production demand and (F4) machine statuses. Table 1 indicates the number of measures implemented in each fact table. Additionally, 22 calculated measures of aggregate raw data i.e. Overall Equipment Efficiency (OEE), Machine Utilization and Machine Efficiency.

Table 1: Facts and Measures

#	Fact	Measures
F1	Machine Cycles	4
F2	Machine Energy	11
F3	Machine Status	5
F4	Machine Power	4
F5	Production Demand	4

This implementation gives us the opportunity to correlate measures such as availability of machines with Mean Time to Repair (MTTR) as shown in Figure 5 more efficiently, or correlate the energy consumption of a factory with the demand volume or the Quality Ratio of facilities. Moreover, the potential to explore the correlation possibilities is left to the end user by selecting the appropriate measures for visualization from dashboard however, the dashboard itself is not included in the current paper.
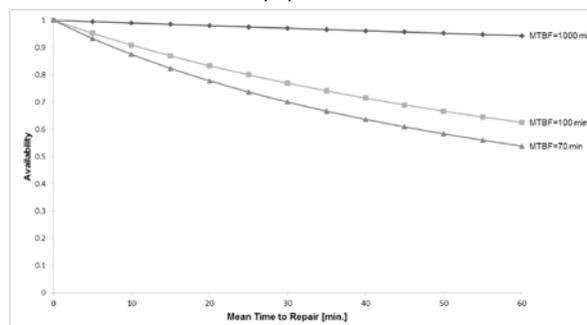

Figure 5: Availability as a Function of Mean Time To Repair [18]

FoF-EMon

For micro optimization, standby monitoring was introduced in the FoFdation project. As the energy used in machine standby can raise up to 43% of the total energy consumed [19], it is essential to address the non value added standby energy consumption which is independent from quality and safety related issues. According to the monitored data and analysis on FoF-EMon certain components can be switched off in conformity with predefined rules. In the given case the cooling compressor indicated in Figure 3 can be switched off after 15 seconds when the machine is in standby without any negative effects on productivity or quality in the given manufacturing process. Further optimization on the micro-optimization level is seen in the predictive service and maintenance by detecting inefficient components according to Gontarz et al. [20].

The presented level of detail in Figure 3 from FoF-EMon can be used not only for micro-optimization, e.g. active machine tool and machine components' switch off [21], but for macro-optimization as well. In combination with higher aggregated information, such as from the MES, optimized production scheduling can be performed.

Scheduler

Production scheduling has been addressed by many researchers over previous decades. Typical scheduling addresses the problem of allocating jobs and tasks to a number of machines. Energy Aware Scheduling aims to optimize either an existing schedule [22] or to follow certain methodology [23] to obtain the minimum possible energy consumption. In this paper, we consider the IMPACT scheduler [18]; a multicriteria scheduler based on MADEMA method [24, 25, 26], as part of the macro-optimization strategy. IMPACT assigns tasks to resources by typical dispatching rules i.e. Shortest Processing Time (SPT), Earliest Due Date (EDD) etc. However, it can produce a schedule based on a multicriteria method with various factors such as cost, quality, flowtime etc. The model of the proposed scheduler has been extended to include the operating and idle power on each machine tool of the production shopfloor. In addition, the energy consumption criterion has been integrated in order to evaluate the energy consumption performance of the schedule. Moreover, we introduce a Less Energy Consumption (LEC) dispatching rule to assign tasks to machine tools based on their estimated energy consumption. Energy aware scheduling minimizes the energy usage and enhances its efficiency.

4   VALIDATION

In a case study, the FoFdation-SMES prototype including FoF-EMon was implemented in the CRF labs on a 5 Axis Milling machine tool. The implementation included the collection of ERP information, machine status and the full details of power consumption of the machine tool components, e.g. pumps, fans, and motors. By knowing the energetic- and control behavior of each machine tool component in combination with production execution and ERP information, quality- and safety-irrelevant components can be controlled by this system. In this context, a cooling compressor switch off message was successfully generated to reduce the power consumption during standby by 12 kW. Together with a reduced air supply, (4,8 kW) an automated

reduction of up to 50% on the total machine tool power consumption during standby is possible with no negative effects on productivity or quality. This implementation is seen as a data acquisition and control tool for all relevant sustainable information related to resource consumption on the machine tool, and proves that the system is able to react to and control certain components to not only monitor but actively increase the environmental performance on the shopfloor with related effects on higher aggregated levels as well.

The validation process did not consider the analysis and optimization implementations which will be tackled in a second phase. The case will be extended to several machines in order to deal with the macro-optimization approach.

5   CONCLUSIONS

The presented work is based on a demo approach that has been built in a pragmatic way to clearly highlight a very practical solution as a proof of concept to address an industry use case where the main requirements are the manufacturing planning process optimization, and the efficiency of the energy consumption in production processes. For this a straightforward approach to achieving sustainability goals has been developed through leveraging an existing MES's functionality to manage raw materials and resources, such as energy. The usage of MES systems for sustainability enhancement opens the door to improve and obtain increased gains in resource optimization.

Therefore the adopted solution is ideal for improving resource utilization – not only in terms of using less material but also by providing better information on how those resources should be used. The MES has been enhanced with resource consumption data collection based on a versatile and easy to install system called FoF-EMon, which includes a dashboard to monitor energy consumption. These results are running as a prototype with both the adapted MES system and the FoF-EMon, and their link. This data collection infrastructure is used by the SMES to optimize the usage of resources through the analysis optimization modules.

The main difficulties encountered in the implementation of the data collection system have been the fact that the machine used is a nonstandard machine tool with multiple retrofits and no up-to-date specifications. A future challenge for the FoF-EMon application is a streamlined and market ready setup procedure for individual implementation. Currently this application is seen as a prototype solution which strongly depends on the goal system architecture. Other important issues are affordable sensors, stability and reliability on both the hardware and software side, improved dashboard and further development in the awareness tool according to the ISO14955 and/or others. For the production execution data collection side, represented by the MES, the main challenges are an easier and faster adaptation to customer functional requirements and the usage of its OPC UA interface in a future factory environment where this technology will be widely spread and, therefore, allows for seamless and interoperable resource consumption data collection from any equipment on the shopfloor.

These results allow us to explore new concepts for online and automatic optimization towards a sustainable manufacturing process, taking into consideration all manufacturing factors.

For further progression, the macro-optimization approach will consider not only energy consumption but also other aspects of sustainability according to the Triple Bottom Line, especially, social ones. Also, the SMES validation will be extended to a scenario with multiple machines.

6 ACKNOWLEDGMENTS

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