Toward Industry 4.0: Efficient and Sustainable Manufacturing Leveraging MAESTRI Total Efficiency Framework

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Abstract. This paper presents an overview of the work under development within MAESTRI EU-funded collaborative project. The MAESTRI Total Efficiency Framework (MTEF) aims to advance the sustainability of manufacturing and process industries by providing a management system in the form of a flexible and scalable platform and methodology. The MTEF is based on four pillars: (a) an effective management system targeted at process continuous improvement; (b) Efficiency assessment tools to support improvements, optimisation strategies and decision support; (c) Industrial Symbiosis paradigm to gain value from waste and energy exchange; (d) an Internet-of-Things infrastructure to support easy integration and data exchange among shop-floor, business systems and tools.

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1 Introduction

Europe was the cradle of the manufacturing industry and it has traditionally led important industrial changes. Process industries are around 20% of the total European manufacturing industry, which include more than 450,000 individual enterprises (EU27), employment of around 6.8 million citizens and generation of more than 1,600 billion € turnover. These industries are largely dependent on resources imports from international markets that are hampering the industry's access to globally traded raw materials, due to the increased political instability in many regions of the globe, which is perfectly visible from a sharp increase in raw material prices during recent years. Moreover, European industry has also accounted for more than a quarter of total energy consumption in 2010 in Europe, with a significant portion of that used within the process industry. This represents both an opportunity and responsibility for this sector's contribution to the sustainability challenges of European societies, as it is imperative to drastically reduce the environmental footprint and increase competitiveness and production systems efficiency by "*doing more with less*". However, to successfully implement sustainability in manufacturing and process industries, a holistic, multidimensional and systematic approach is required. Having this in mind, the MAESTRI Total Efficiency Framework (MTEF), which is currently being developed, aims to advance the sustainability of manufacturing and process industries by providing a management system in the form of a flexible and scalable platform as well as an accompanying methodology. Based on a holistic approach, which combines different assessment methods and tools, the overall purpose of the MTEF is to support improvement on a continuous basis and increase eco-competitiveness by fostering sustainability in routine operations. Its conceptual approach will be based on a life cycle perspective, centered on models for dynamic simulation and optimization of both individual and complex systems, to better understand processes and the opportunities to add value. This life cycle approach is important to avoid problems (waste, environmental impacts, etc.) shifting from one life cycle stage to another.

It should also be noted that in order to enhance process' resource and energy efficiency processes, utilize waste streams and improve recycling in a sustainable manner, modelling and assessing all the interacting value chains is essential. However, despite the environmental, economic and social improvement potentials by sharing resources (e.g. energy, water, residues and recycled materials), it is essential to understand and assess resource and energy efficiency in order to optimize production systems. Moreover, the increased availability of modern technologies for process monitoring and optimization, pursuing the Industry 4.0 concept, should be carefully adapted and integrated for a wider and facilitated adoption of state-of-the-art tools and methodologies for efficiency and eco-efficiency. Such methodologies and tools should support waste and cost reductions in to both large and small companies.

This paper is organized as follows. Section 2 describes the author's vision about the four pillars for obtaining Total Efficiency with an overview about the state-of-the art. Section 3 addresses the tools and methods to be integrated and/or developed as the MAESTRI Total Efficiency Framework. Finally, conclusions and further steps for research are discussed in Sect. 4.

2 The Four Pillars of Total Efficiency: Background and Related Works

The authors believe that total efficiency concept is based on four pillars, aiming to fill the current gaps regarding the effective implementation of energy and resource management (see Table 1).

Table 1. Main gaps regarding the effective implementation of energy and resource management

Technical/Technological gaps	Lack of flexible, scalable and holistic tools to support decision making processes regarding resource and energy efficiency
	Lack of simple and integrated tools to assess and optimize resource and energy efficiency, crossing the different environmental and economic operational aspects
	Deficient knowledge to identify the potential use of wastes as resources (energy, resources, man-power, etc.)
Management gaps	Non-incorporation of sustainability aspects in company strategy and objectives;
	Non-implementation of structured management systems targeting resource consumption and energy efficiency
	Communication of process efficiency relevant data and information across different departments of the company
	Difficulty on the definition of clear and consistent KPIs, and their usage
Organizational gaps	Poor means for sharing resources (e.g. plants, energy, water, residues and recycled materials) through the integration of multiple production units of a single company or multiple companies on a single industrial production site
	Difficulty to collect and share information about all process flows (resource and energy inputs as well as waste and pollutant outputs)

The four pillars enable the total efficiency concept, encompassing the following aspects: *(a)* an effective management system; *(b)* efficiency assessment tools; *(c)* Industrial Symbiosis paradigm; *(d)* an Internet-of-Things infrastructure. The following paragraphs describe them in more details.

Effective Management System – Lean Management recommends the companies to maximize customer value while minimizing waste. The core of the concept was formulated in the form of five lean thinking principles [1] that should help the management: *(i)* precisely specify value for specific product/service; *(ii)* identify the value stream for each product/service; *(iii)* make value flow without interruptions; *(iv)* let the customer pull value; *(v)* pursue perfection. Lean Management has been proven to be a successful way to organize production operation, however in order to sustain changes the Lean Management System has to be implemented [2].

Efficiency Assessment – To have an exhaustive assessment of the production system is important to combine approaches for evaluating both operational efficiency and eco-efficiency perspective, encompassing the basic principles of eco-efficiency [3–5]. As a result of the combination of these two fundamental efficiency concepts, the Efficiency Assessment intends to encourage businesses not only to search for environmental improvements that yield parallel economic benefits, but to put emphasis on value creation and capturing. In this sense, by increasing value of goods, business tend to maximize resource productivity, gain bottom-line benefits, and reward shareholders, rather than simply improve efficiency or eco-efficiency performance, or minimize waste or pollution.

Industrial Symbiosis – Reusing waste from an industrial process as a resource for another industrial process is known as industrial symbiosis (IS). The symbiotic relationship is established between processes (in terms of resource exchanges) and companies (in terms of value exchanges) [6]. IS enables similar cyclic circulation of waste by promoting cooperation between companies, which show that the collective benefits of engaging in IS are greater than the benefits a single entity could achieve by itself [7]. Therefore, it represents a direct positive effect on the efficiency of the whole system and enables the decoupling between the value created through material processing or products' manufacturing, and the environmental impact associated to natural resource intake and waste/pollutants assimilation.

Internet-of-Things – Internet-of-Things technologies provide an ICT infrastructure with middleware functionality, which facilitates the interoperation of heterogeneous hardware and software components, which may be already operating inside the company or not. The aim is to extend pre-existing ICT infrastructure into a broader and more scalable network of generic "things" (i.e. shop-floor machinery, sensors, actuators, controllers, smart objects, mobile devices, servers, ERPs, MESs, third-party systems, cloud services, etc.). In the industrial domain, data sources will be hardware and software components in the shop-floor as well as business systems of the industrial companies. The ubiquitous use of sensors, the expansion of wireless communication and networks, the deployment of decision support systems has the potential to transform the way goods are manufactured. Many observers believe that IoT is the key technology for taking Europe to a new industrial revolution, considered to be the fourth and hence labelled "Industry 4.0". Industry 4.0 concept [8] is a tentative to answer questions, such as: "*How can we exploit the opportunities that digital technologies present for industry, administration, society and political participation, and how we master the relevant challenges?*" Industry 4.0 paradigm is considered a step forward towards industrial future of production, i.e. with highly flexible production environments, early-stage integration of business partners within value-creation processes, also providing support to decisions.

The consensus between researchers suggests that the industrial revisions require a long-time period of development and cover the following aspects, considered as the future manufacturing visions:

- *Factory*. Future factory is going to involve all manufacturing resources (sensors, actuators, machines, robots, conveyors, etc.) are connected and exchange information automatically in purpose of predict and maintain the machines, control the production process, and to manage the factory system – the paradigm known as a Smart Factory [9].
- *Business*. Future business is going to involve a complete communication network between companies, factories, suppliers, logistics, resources, customers, influencing one to other section in purpose of achieving a self-organizing status and provide the real-time response [10, 11].

The main features [12] of Industry 4.0 include the following: *Horizontal Integration* through value networks to facilitate inter-corporation collaboration, describing the cross-company and company-internal intelligent cross-linking and digitalization of value creation modules all over the value chain of the product life cycle and between value chains of adjacent product life cycles, *Vertical Integration* of hierarchical subsystems inside a factory, describes the intelligent cross-linking and digitalization within the different aggregation and hierarchical levels of a value creation module from manufacturing stations via manufacturing cells, lines and factories, also integrating the associated value chain activities such as marketing and sales or technology development to create flexible and reconfigurable manufacturing system.

3 MAESTRI Total Efficiency Framework – MTEF

The MTEF represents a flexible and scalable platform, which provides an effective management system that aims to advance the sustainability of manufacturing and process industries. It combines the four pillars in one holistic platform which enables an overall efficiency performance assessment from environmental (including resource and energy efficiency), value and cost perspectives. MTEF encompasses Environmental Performance Evaluation with Environmental Influence and Cost/Value assessment models through a life cycle perspective. The aim is to support the decision making process, by clearly assessing resource and energy usage (valuable/wasteful) of all process elementary flows, and the eco-efficiency performance. Decision support via value-adding optimization is also foreseen among the integration of the modules.

This basic concept of MTEF is depicted in Fig. 1. The central element is an IoT platform, which facilitates the data transfer from machines, systems, and sensors to end user software tools and applications at the industrial sites.

The IoT Platform is based on the LinkSmart middleware platform, which was originally developed in the previous EU project Hydra [13] and further extended in the course of a variety of research projects. LinkSmart provides interoperable interconnection of appliances, devices, terminals, subsystems, and services. To cover requirements that are not yet supported by LinkSmart, new software modules will be developed and work loosely coupled with existing modules in a service-oriented

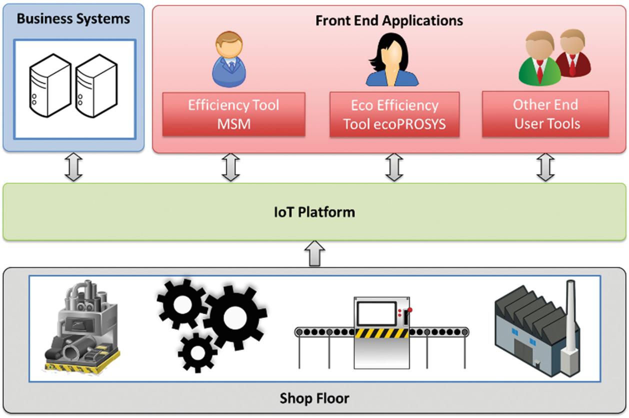

Fig. 1. MAESTRI total efficiency framework architecture

architecture (SoA). Each of the functional submodules of the architecture is explained in the following.

The *Shop Floor* will usually be the place where the major part of the relevant data is being produced. Device Connectors (DC) provide the means for devices to communicate with the rest of the framework regardless of the communication protocol it uses. DCs need to be developed specifically for each new device or protocol. *Business Systems* are the second type of data source for MTEF. ERP and MES systems can be connected to the IoT Platform in order to complement the data about shop floor activities. Besides being data sources for MAESTRI, the business systems could also receive data from the shop floor via the IoT Platform, therefore allowing a bi-directional connection would be possible between the IoT Platform and the Business Systems depending on the specific scenario. *Frontend Applications* represent all the end user software tools and applications, which are the main data consumers from the point of view of the IoT Platform. These include mainly ecoPROSYS and MSM, but could also be other mobile, web applications or simple KPI visualization dashboards, i.e. a GUI module that allows a simple visualization of streaming or historical KPI data.

The Eco-Efficiency Integrated Methodology for Production Systems (eco-PROSYS©) relies on the use of a systematized and organized set of indicators easy to understand/analyze, aiming to promote continuous improvement and a more efficient use of resources and energy. The goal is to assess eco-efficiency performance in order to support decision-making and enable the maximization of product/process value creation and minimization of environmental burdens. Considering the methodological description provided by [14], an algorithm was created, combining the results from three different modules: *(i)* Environmental Performance Evaluation, *(ii)* Environmental Impact Assessment and *(iii)* Cost and Value Assessment. As a consequence of the integration of these three components, the resulting decision support indicators intend to help companies on managing links between environmental and value performance. Their ultimate goal is to provide a clear vision of the production system baseline performance, and to assist on the implementation of improvement strategies by connecting the various levels of the system with clearly defined targets and benchmarks. For this reason, they can also be used to measure progress by evaluating trends or comparing the results along defined periods of time. As a component of the MTEF, ecoPROSYS' overall aim is to provide quantitative evidences to support decision making process pursuing both economic efficiency, which also has positive environmental benefits, and environmental efficiency, which also has positive economic benefits. In addition, it provides flexibility to the MTEF's application and adaptation to different sectors and companies, either from the modular approach applied for the complexity level of calculus, both for the economic value and cost assessment (from more simple cost assessment, to full LCC analysis), and for the environmental impact assessment (from simplified LCA to full LCA analysis).

The Multi-layer Stream Mapping (MSM) represents a method/tool able to achieve an overall efficiency/performance assessment of production systems [15] (see Fig. 2). It takes into account the base design elements from the well spread Lean tool Value Stream Mapping (VSM), in order to identify and quantify all "value adding" and "non-value adding" actions, as well as all types of waste and inefficiencies along the production process. Therefore, the great similarity to the VSM tool consists in the base lean mindset for the identification and quantification, at each stage of the process system, of "what adds value" and "what does not add value" to a product or service, for any given variable of the production system (multiple layers and multiple domains of variables, such as Resource Efficiency, Operational Efficiency, Flow Efficiency, etc.).

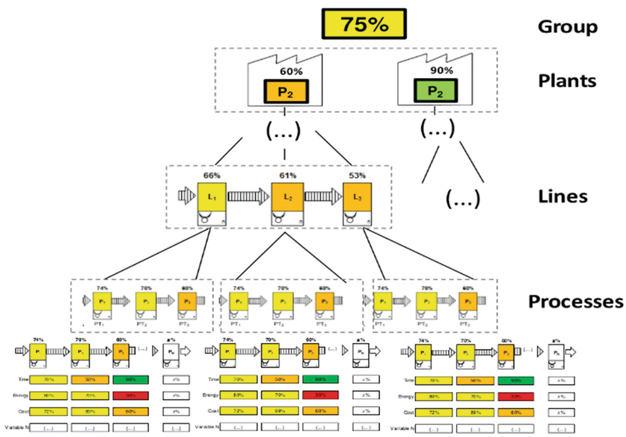

Fig. 2. Schematic representation of MSM© bottom-up analysis and aggregation.

Tools and methods that can support companies in identifying and evaluating the potential opportunities of waste streams that could be part of Industrial Symbiosis (IS) exchanges and to extend procurement approach to include secondary/alternative inputs sources are necessary to advance towards more sustainable operations in manufacturing industry [1]. Complementarily, examples and practical information can support companies on how to make the required mind-set and behavior shift to see waste as a potential resource and identify synergies within and outside their operations. This shift can only occur through the provision of a better understanding of IS. Based on the understanding of theoretical characteristics [16] and practical characteristics of IS, the following categories of possible challenges have been identified [17]: (i) finding embedded norms of exchange, culture and structure of enterprises; (ii) a lack of information on waste exchange; (iii) a lack of technical and financial support; (iv) increased cost incurred during the process of waste exchange (e.g. transaction costs, opportunity cost, labor costs, etc.); (v) a lack of guidance in institutional arrangements; (vi) a lack of inter-firm trust and unstable cooperation between participants in the IS network. The MTEF aims to support a wider application of IS in the process industry through a methodology that builds on a library of case studies, informing companies about possible uses of their waste streams and alternative input sources A stepwise process is to guide companies on their identification of exchanges, on valuing their resources and on building feasible IS-based synergies with other participants. The stepwise process is formed by four guiding questions that can lead companies' path towards creating higher value from IS applications: (a) *How to see waste* in company's processes and manufacturing operations, where the efficiency assessment tools will be applied (as MSM); (b) *How to characterize waste* in a way that allows to understanding the remaining value once a waste stream has been identified (also with the support of ecoPROSYS); (c) *How to value waste*, according to potentially interested stakeholders and waste exchanges opportunities; (d) *How to exploit waste* by selecting the opportunities bringing higher value and devising an action plan.

Eco Orbit View (EOV) methodology has been chosen by the MTEF in order to indicate areas in the production process where the company may focus an improvement activity in order to get simultaneous improvement of business and environmental performance. The Eco Orbit View analysis is performed in 4 steps: (i) identification of production process steps (for a selected product family); (ii) identification of Key Performance Indicators (KPIs) relevant for each process step; (iii) identification of Key Environmental Performance Indicators (KEPIs) or Environmental Aspects relevant for each process step; (iv) identification links and synergies between KPIs and KEPIs. In summary, the Eco Orbit View shows KPIs (reflecting company needs) and KEPIs (reflecting environmental needs) side by side for chosen process steps. The analysis results in the indication of potential improvement areas, reflecting the needs of the company to improve both the economic and environmental performance. Thus, the areas can be identified where the eco-efficiency of the company may be improved.

4 Conclusions and Research Agenda

The overall aim of the proposed MAESTRI Total Efficiency Framework, which is currently under development, is to support the sustainable improvement of industrial companies' environmental and economic performance, in particular the process industry ones.

The MAESTRI approach to support IS applications in the process industry builds on widening the knowledge on IS industrial cases as main source of information and on a stepwise methodology to support the path from waste identification and valuing to exchange definition and exploitation phases. This will support companies willing to engage with the implementation of IS concept in their business. MTEF aims to allow an innovative and practical integration of eco-efficiency analysis, including LCA and LCC, with process efficiency assessment (including both resource efficiency and operational efficiency) analysis from the perspective of Lean Manufacturing, thus implicitly evaluating "value added" and non-value added" (waste) actions and resource usage.

MTEF leverages a middleware platform, which facilitates the automatization of the data transfer from machines, systems, and sensors at the industrial sites to end user software tools and applications. It allows to seamlessly interconnect heterogeneous devices, systems and subsystems in order to achieve higher degree of interactions between the shop floor, the legacy management systems and the end users. The authors consider it an innovative and important instrument that acts as generic enabler of the hyper-connected factory, to support decision-making for the development and simulation of improvement strategies and to support the continuous analysis and monitoring of a companies' efficiency and eco-efficiency.

The further development and validation of the MTEF will be supported by its initial application in four real industrial settings across a variety of different sectors. Those four industrial pilot cases (two of the chemical sector, one of injection moulding, and one from the metalworking sector) represent one of the main sources for identification of the requirements upon the methodological approach and the platform's functionalities as well as for their continuous refinement based on the testing results.

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