Total Resource and Energy Efficiency
Management System for Process Industries

Deliverable 2.3

Simulation and decision support approach for sustainable manufacturing

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Sustainable Process Industry through Resource and Energy Efficiency

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Author

Name: Eduardo
Surname: Silva
Organisation: ISQ

Name: Emanuel
Surname: Lourenço
Organisation: INEGI

Name: António
Surname: Baptista
Organisation: INEGI

Name: Maria
Surname: Holgado
Organisation: UCAM

Name: Miriam
Surname: Benedetti
Organisation: UCAM

Name: Paulo
Surname: Peças
Organisation: IST

Name: Ana Rita
Surname: Alves
Organisation: IST

Name: Stanislaw
Surname: Plebanek
Organisation: LEI

Name: Maja
Surname: Janukiewicz
Organisation: LEI

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List of Acronyms

ANN – Artificial Neural networks

EBITDA – Earning Before Interest, Taxes, Depreciation and Amortization

ecoPROSYS© - Eco-Efficiency Integrated Methodology for Production Systems

EE – Eco-Efficiency

EEPA – Eco-Efficiency Performance Assessment

EVA – Economic Value Added

GA – Genetic Algorithms

GVA – Gross Value Added

IS – Industrial Symbiosis

ISO – International Organization for Standardization

LCA – Life Cycle Assessment

LCC – Life Cycle Cost

LCI – Life Cycle Inventory

LCIA – Life Cycle Impact Assessment

LCT – Life Cycle Thinking

KPI - Key Performance Indicator

KEPI - Key Environmental Performance Indicator

MEFA – Material and energy flow analysis

MOP – multi-objective optimization problem

MSE – Mean Squared Error

MSM© - Multi-Layer Stream Mapping methodology

NIt – Number of Iterations

NPop - Number of elements of the population

NVA - Non value-added

PBCM – Process-Based Cost Model

PBM – Process-Based Model

PDCA – Plan-Do-Check-Act (also known as Deming cycle)

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PSO – Particle Swarm Optimization

OR – Operations Research

S-LCA – Social or Social-economic Life Cycle Assessment

SETAC – Society of Environmental Toxicology and Chemistry

T4IS – Toolkit for Industrial Symbiosis

TEI – Total Efficiency Index

UNEP – United Nations Environmental Programme

VA - Value-added

WBCSD – World Business Council for Sustainable Development

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1 Executive Summary

The MAESTRI project aims to advance the sustainability of European manufacturing and process industries. This will be done by providing a Management System in the form of a flexible and scalable platform, aiming to guide and simplify the implementation of the Total Efficiency Framework in organizations, which encompasses: Efficiency Framework, Management Systems and Industrial Symbiosis, supported by an Internet-of-Things (IoT) platform as base layer.

Aiming to provide an effective support to the decision making regarding the management of production systems efficiency and implementation of sustainability strategies, the Efficiency Framework encompasses several modules not only targeted for assessment, but also to simulation.

This document aims to describe the operation of these assessment and simulation modules from operational point of view, considering their different components and features. In order to provide a better understanding on the outcomes resulting from the implementation of Efficiency Framework tools, a comprehensive analysis is presented regarding the ability of performing simultaneous assessment of production systems efficiency and eco-efficiency.

In addition, main conclusions and insights regarding the application of different optimization models is also presented. In this respect, the main goal is to provide a clear background regarding the best suitable algorithms to perform optimization simulations for materials and energy consumption, via overall efficiency and cost-saving targets. A methodology, in a user guide form, is proposed on this purpose.

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2 Decision Support for Sustainable Manufacturing

To evaluate sustainability of production systems is a complex task. Despite the concept of sustainability might be understood intuitively, to express and assess specific goals poses an important challenge. However, an accurate management of sustainability issues is proven to be essential to achieve continuous improvement, and became a fundamental principle for successful organisations.

Common decision support tools provide the ability to access the immediate state of the process and some add the capability of simulating different configurations. The concept of sustainable manufacturing comprehends a significant number of objectives. The most quoted definition is given by the U.S. Department of Commerce: sustainable manufacturing is "the creation of manufactured products that use processes that minimize negative environmental impacts, conserve energy and natural resources, are safe for employees, communities, and consumers and are economically sound" (U.S Department of Commerce 2007). Thus, maximizing resources and energy efficiency, reducing environmental and social impacts and promoting the use of renewable technologies are all key objectives included in the concept of sustainable manufacturing (Kersten, Mikolajuk and Yeh, 1999). While evaluating these parameters might appear simple, using them for decision making can be more difficult, as these objectives must meet requirements regarding the impacts on employee, community and especially on the economic aspect (Kulatunga et al. 2015). Combining this set of conditions can generate a complex problem. Sustainable decision support tools and frameworks simplify the assessment by using a single value to identify the immediate state of the process and by using carefully chosen indicators to simplify and compare the information.

Simulation tools go a step further and add the possibility to foresee the outcome of possible improvements in the process. However, the quantification of those changes can be a difficult process. Thanks to the indicator based system used in decision support tools there is a common comparison element between the immediate assessment and the simulated scenario.

Furthermore, advances towards industry 4.0 and total control of manufacturing systems, lead to a significant increase of available information. This would be overwhelming without proper tools to assist the treatment of that data. Decision support tools and frameworks assist in simplifying the problem identification process and the comparison of different alternatives.

2.1 Background tools and concepts

Sustainability assessment has become a rapidly developing thematic area with a growing number of concepts and tools being developed during the last decades. This has been particularly relevant for manufacturing industries, main consumers of natural resources. However, the scope of these concepts and tools, sometimes complex and not intuitive, has led industries to deviate from these kind of issues.

For this reason, a careful selection has been made for tools and concepts to base the development of MAESTRI tools. The main goal was to provide an effective support to decision making regarding sustainability issues, rather than to focus only on its characterisation, and to do so by using concepts that are intuitive for industries. Eco-efficiency is one of these concepts, whose origin was based on the companies' perspectives when challenged to define their position and contribution to sustainable development. As main advantage, eco-efficiency

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enables the complementarity and simultaneity of the two eco-dimensions of sustainable development: economy and environment (or ecology). In addition, rather than just pursuing environmental improvements on resource use and pollution reduction, as most of the other sustainability tools, its main goal is much broader. In this respect, emphasis is given to value creation for business and society in general, while providing competitive goods. In this sense, by increasing the value of goods, businesses tend to maximise resources productivity, gain bottom-line benefits, and reward shareholders, rather than simply minimising resource consumption and pollution.

Complementarily, Value Stream Mapping (VSM), as well as other LEAN tools, enable companies to focus on the value added and non-value added activities, and consequently identify waste, leading to the introduction of a culture of continuous improvement and targeting their elimination (Lourenço et al. 2016). Despite targeting mainly value streams and non-value streams within a production system, particularly related to productive time, several extensions have been suggested by different authors (Paju et.al, 2010; Li et.al, 2012; Faulkner et.al, 2014).

From an environmental perspective, Life Cycle Assessment presents a structured and comprehensive approach to identify, quantify and assess the environmental aspects of products and/or production systems. In addition, it presents the advantage of being an international standardised methodology. However, despite being targeted mainly for environmental assessment, it can also be extended by considering its integration with other concepts, such as Materials Flow Analysis. By doing so, it can be turned to a very powerful simulation tool.

In order to better explain the different tools and concepts used to base the Efficiency Framework development, next sections present a detailed description of each of them.

2.1.1 Value Stream Mapping (VSM)

In the past decades, remarkable progresses have been made in terms of productivity gains, either with the introduction of advanced production technology and management systems, or due to improved labour management and efficient consumption of raw materials or semi-finished products.

Lean production principles and tools play an important role regarding productivity and efficiency improvements; they greatly reinforced the competitive progress within organizations over time. One of these tools is Value Stream Mapping (VSM) which originates in the Toyota just-in-time production system.

Value Stream Mapping, or simply VSM as it is commonly known, is a lean tool used to visualize the product or service flow. The tool consists of a representative flow diagram that enables the identification of inefficient processes that have room for improvement in order to increase the final value delivered to the client (Wilson, 2013). Lean tools, like VSM, enable companies to focus on the value added activities, and to consequently identify waste, leading to the introduction of a culture of continuous improvement (Haefner et al., 2014, Shook and Rother, 1999).

VSM is a simple and effective method used for the visualisation of value streams in which the current amount of waste within the production systems is exposed. The analysis focuses on the

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route of a product or service from the moment that the order is placed until its delivery (Shook and Rother, 1999). The analysis promoted by the VSM allows a broader comprehension of all the involved processes and their frontiers in a continuous view, not only focusing on isolated processes. Thus, it breaks barriers imposed by each sector or processing unit that form the value chain. One of the major goals of VSM diagram is to determine, and clearly distinguish, the productive and non-productive time among the production of a given product or during a service provision.

The "productive time" should be interpreted as the time needed for the process to occur (time required to add value). The "non-productive time" is the time spent on transport and waiting (time that adds no value to the product or service, i.e. a waste). Besides the productive and non-productive time of processes / services, the VSM also considers material flows and information flows inherent to the production system (such as work in progress quantification and other stock figures analysis).

The VSM is a particular useful tool to map the production system and identify critical situations for further improvement actions. In addition, it is characterized, such as other lean tools, by its highly visual component contribution for a more intuitive and broader understanding of the need to reduce (time-related) wastes. Several authors point out that these positive characteristics of VSM can be further improved by including in VSM i) a dynamic perspective allowing to understand the system behaviour over time; ii) uncertainty aspects allowing to include the influence of variability in performance and ii) resources-efficiency related indicators towards introducing sustainability aspects in daily decisions in companies (Braglia et. al, 2009; Shook and Rother, 1999; Brown, 2014).

2.1.2 Material and Energy Flow Analysis

Material and energy flow analysis (MEFA) is a systematic assessment of the flows and stocks of materials and energy within a system defined in space and time (Brunner and Rechberger, 2004). Through the identification, quantification and balance of resources, pathways, intermediate and final streams of materials and energy, it is possible to identify waste flows and environmental loads. The basic aim is the reduction of complexity of the system as far as possible, while still guaranteeing a basis for informed decision making. It is this distinct characteristic of MEFA that makes the method attractive as a decision support tool in resource management, waste management or environmental management (Brunner and Rechberger, 2004).

2.1.3 Life cycle thinking

Life cycle thinking (LCT) approaches for decision making involve consideration of all relevant aspects of a system, product or process over its life cycle (McDonough and Braungart 2002, SAIC 2006, and Hellwig and Canals 2014). Their purpose is to provide information to ensure that shifting impacts from one stage to another does not occur, by avoiding unexpected or unanticipated effects during the life cycle (such as a different stage) or different effects, or even implications resulting from changes made at any specific stage (such as new material-acquisition demands with higher impacts). By doing this, LCT approaches help to understand the implications that decisions may have over a larger system/scope of analysis, i.e. the entire life cycle. In this sense, the aim is to provide a systematic and holistic perspective on products, processes or services, as well as to support on the identification of improvements by decreasing impacts covering their entire life cycle.

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In addition, LCT approaches can be used to consider all sustainability pillars (UNEP/SETAC, 2013). From an environmental perspective, Life Cycle Assessment (LCA) presents a structured and comprehensive approach to identify, quantify and assess the environmental issues of product and/or production systems. Hence, it is intended for the analysis of the environmental burdens/impacts at all stages in a product, process or service life cycle (Guinée, 2002). In this respect, International Organization for Standardization (ISO) standards 14040/14044:2006 are the core approach for conducting an LCA studies.

In terms of economics, the Life Cycle Cost (LCC) generally refers to the "assessment of all the costs associated with the life cycle of a product that are directly covered by one or more of the participants in the life cycle, with complimentary inclusion of externalities that are anticipated to be internalized in the decision-relevant future" (Rebitzer et al. 2003). It is used to reinforce life cycle thinking by ensuring that first costs and recurring costs are considered, and support decision regarding the most cost-effective solution among a series of alternatives.

Social and socio-economic LCA (S-LCA) aims to assess the social and socio-economic aspects of products and their potential positive and negative impacts on stakeholders along their life cycle. Although S-LCA follows the ISO 14040:2006 framework, some aspects differ. In this respect, S-LCA documents the product utility but does not have the ability nor the function to inform decision making at that level. It is correct that information on the social conditions of production, use and disposal may provide elements for thoughts on the topic, but will, in itself, seldom be a sufficient basis for decision.

2.1.4 Circularity

The circularity assessment measures the effectiveness of a company in making the transition from 'linear' to 'circular' business models, assessing the extent of restorative flows. At its basis there are the Circular Economy main principles which, by definition, comprise a global economic model that aims to decouple economic growth and development from the consumption of finite resources. In practice, circularity expresses how companies must adapt to circular economy, changing their business models in order to gain most value from various loops. Then, as a support to decision making approach, circularity assessment aims to assure value capturing by minimising linear flows and maximizing restorative flows.

Currently, there are no recognized tools or indicators to measure the transition towards circularity (Ellen MacArthur Foundation et al., 2015). However, both Ellen MacArthur Foundation and Circle Economy have published complete or partial information on circularity measurements. Ellen MacArthur Foundation has developed circularity indicators at product and company level aiming to quantify materials flow restoration. The rationale of these indicators is to specify the quantity and intensity of materials flows circulation, being particularly intended for use in product design, but could also be used in internal reporting or for procurement and investment decisions. Circle Economy aimed to create a Circularity Assessment based on absolute sustainability assessment, meaning that relative measures are substituted by measurements which takes planetary limits (biophysical, economic, and societal) into consideration. The aim of this assessment methodology is to show at a glance a company's level of circularity management, so investors can relate it to fiscal risk (Circle Economy and PGGM, 2014). According to literature, Circle Economy assessment framework seems the most complete and coherent with Circular Economy principles (Beaulieu et al, 2015).

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2.2 Efficiency assessment

The Multi-layer Stream Mapping (MSM©) methodology focuses on the overall efficiency and performance assessment of production systems. There is a great similarity between MSM© and VSM, as both approaches identify and quantify, at each stage of the production system (unit process/processes steps), what adds value and what does not to a product or service. Additionally, MSM© takes into account the base design elements and foundations of VSM.

This methodology is described in detail in Deliverable 2.1 - Efficiency Framework concept description. Nevertheless, in this section a brief description on how the developed tool can be used to support efficiency assessments, including its main features and phases of implementation, will be presented.

MSM© was developed aiming to create a method/tool able to allow an overall efficiency assessment of production systems. MSM© takes into account the base approach from the VSM (value streams), 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 system (as in - Arbulu et al., 2003, Kuhlang et al., 2011). Therefore, the great similarity to the VSM consists in the identification and quantification, at each stage of the process system, of "what adds value" (VA) and "what does not add value" (NVA) to a product or service. Therefore, the basic principle of the MSM© is highly related to Lean Principles (i.e. clear definition of waste and value dichotomy).

In this context, MSM© follows the VSM logics, and gives an overview of value and waste elements (i.e. efficiency). In addition, MSM© overcomes some of the shortcomings of VSM, in particular it was designed to enable an overall efficiency assessment of production systems and the single process steps, which is not possible with VSM. Additionally, the MSM©, provides the means to evaluate the costs related to misapplications and inefficiencies in a disaggregated form (valuable costs and wasteful costs).

There are **4 main phases composing this method**, which need to be executed one after the other.

In the **first phase** a value stream needs to be created. It assesses the value adding actions versus non value adding actions. To this purpose, all the actions or process steps which are needed to produce a given product have to be known and listed (i.e. Identification of the unit processes/process steps). In Figure 1 , these actions would be P1, P2, and P3 on top of the graphic.

After identifying all relevant process variables and parameters (e.g. Energy), actions are either marked as value adding (VA) or non-value adding (NVA). When VA actions are executed, there might still be periods of time which are NVA, for example if there is a waiting state in between. In Figure 1 this is indicated by VA and NVA: the process variable "Time" PT1 is value adding, while everything done in WT1 is waste or non-value adding.

In some situations the distinction between VA and NVA actions is not that clear or/nor easy to identify. In these cases, set points should be carefully defined through a specific analysis of the processes under study, i.e., by defining the VA figure that represents the best amount theoretically attainable in order to eliminate/reduce the NVA activities. Nevertheless, target

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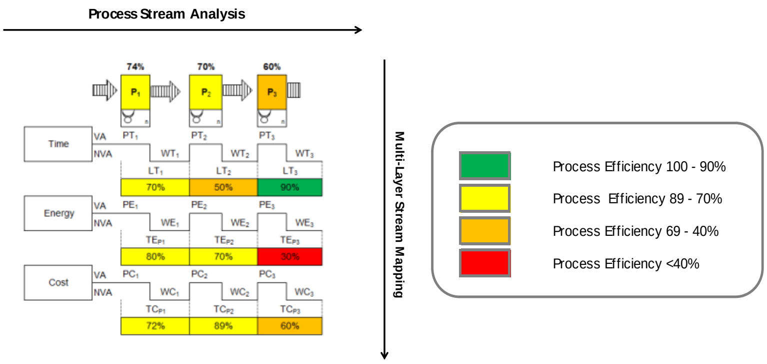
setting strategy should keep in mind that the set-points (targets) should be set in a manner that does not affect the collaborators' motivation.

In this phase, one must also identify the system boundaries, since such definition will limit the scope of the assessment.

In the **second phase** variables and KPIs are to be systematically evaluated through efficiency ratios, which is the value-adding part proportionally to the overall value. The values of the variables should always be between 0 and 100%, and to be maximized, and is calculated as follows:

$$\Phi = \frac{\text{Value added fraction}}{\text{Value added fraction} + \text{Non-value added fraction}} \qquad (1)$$

All variables which effect the value chain need to be identified, including KPIs. The latter should be designed in a way that they are to be maximized. Variables which might be relevant could be for example raw material, electrical energy consumption or CO_2 emission



reduction. In Figure 1

Figure 1 - MSM© expanded diagram with visual management attributes (Lourenço, et. al, 2013)

efficiency ratios of the process variable "Time" are 70% for the first action P1, 50% for P2, and 90% for P3.

In the **third phase** the results will be color-coded in order to distinguish efficiency ratios more quickly. As can be seen in Figure 1, which depicts how the process, process variables and efficiency ratios will be displayed within MSM© expanded diagram with visual management.

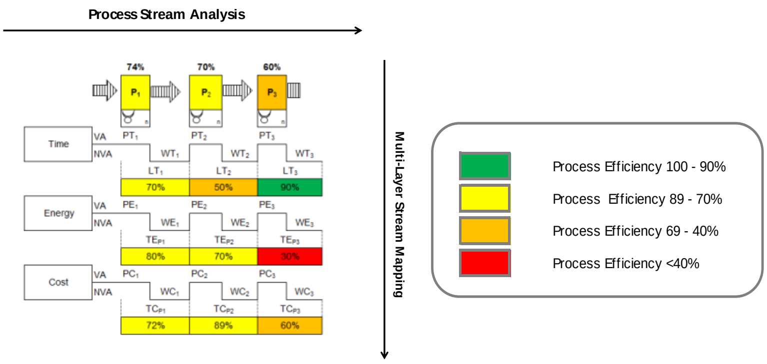


Figure 1 - MSM© expanded diagram with visual management attributes (Lourenço, et. al, 2013)

During the **fourth phase** the efficiencies of the selected variables are aggregated, giving place to the unit process efficiency. Figure 2 shows how such as scorecard will look like and how the work done in the first three phases will be included in it. The global efficiency is the average of the single process efficiency values.

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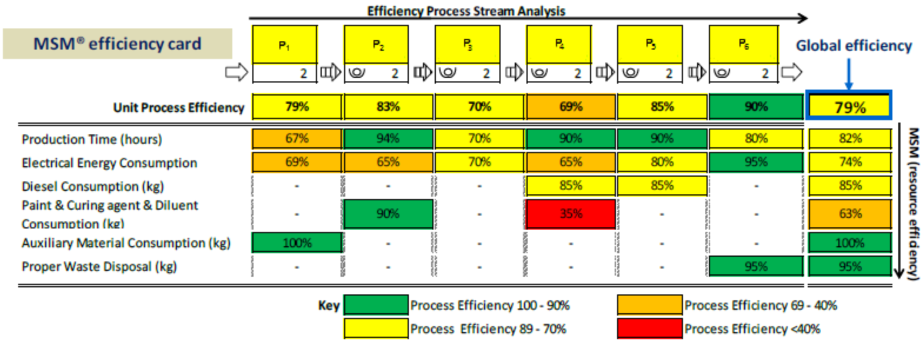

Figure 2 - MSM© efficiency scorecard

This outcome is useful to assess the efficiency and the missuses and waste among the process. Ultimately, MSM© is intended to be used not only for analytical evaluation, but also to support the decision making process, namely through simulations, greenfield design or online systems monitoring, in order to enable the identification and quantification of major inefficiencies and keep track of efficiency progresses.

Moreover, if data is collected at the most elementary level, for instance data form the machine in shop-floor, it is possible to consecutively aggregate the efficiency results along production system, processes, lines, sectors, (…), or even plants, adopting a bottom-up analysis as depicted in Figure 3.

The final steps are related with the results analysis in order to identify the process parameters and unit processes/process steps with lower efficiency results. Consequently, the next step would be to study and prioritize the improvement actions so that these could be implemented, and then asses the efficiency gains evolution and cost reductions, due to implementation of improvement actions.

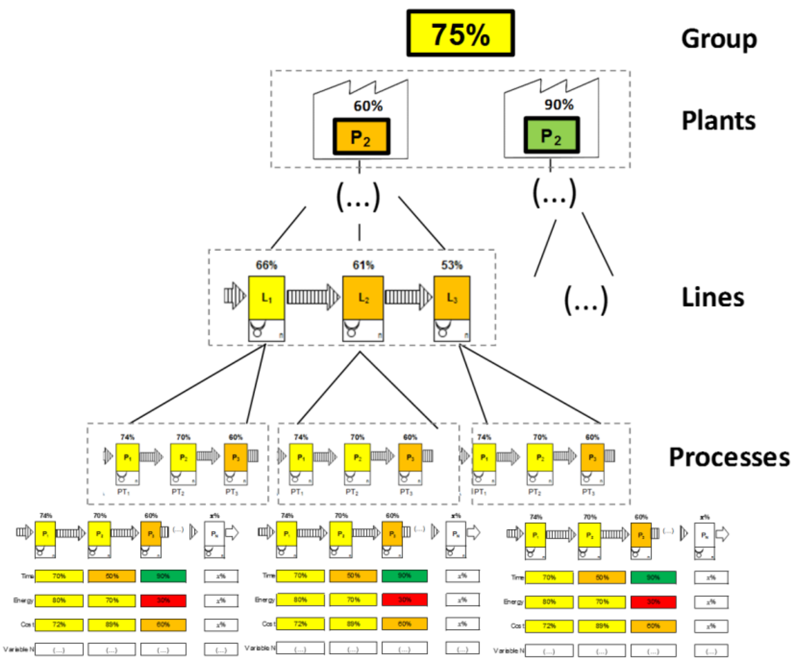

Figure 3 - Schematic representation of MSM© bottom-up analysis and aggregation

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2.3 Eco-efficiency assessment

The developed methodological approach consists of evaluating the eco-efficiency performance and, consequently, supporting the decision-making process regarding the environmental and economic improvement of production systems. Its main goal is then to support and encourage the development of continuous improvement strategies, including the efficient use of resources in particular. In addition, it can be used to two distinct purposes: as a tool to measure performance at a system level (process, product, company etc.), and as a tool to compare different alternatives (benchmarking).

This section is focused on the first identified purpose, aiming to describe how the developed tool can be used to support eco-efficiency assessments, including its main functionalities and phases of implementation. The functionality allowing the comparison of different alternatives by providing the possibility of simulating improvement scenarios is explained in section 4.2 of this report.

In order to assess eco-efficiency performance of production systems, the methodology outlined for the Eco-Efficiency Integrated Methodology for Production Systems (ecoPROSYS©) is suggested as the one to be used. This methodology relies on the use of a systematized and organized set of indicators easy to understand/analyse, aiming to promote continuous improvement and a more efficient use of resources and energy. Its main goal is to lead an eco-efficiency performance assessment in order to support decision-making and enable the maximization of product / processes value creation and minimization of environmental burdens.

From a practical perspective it consists in three main elements, as presented in Figure 4: eco-efficiency performance assessment, life cycle assessment and cost and value assessment.

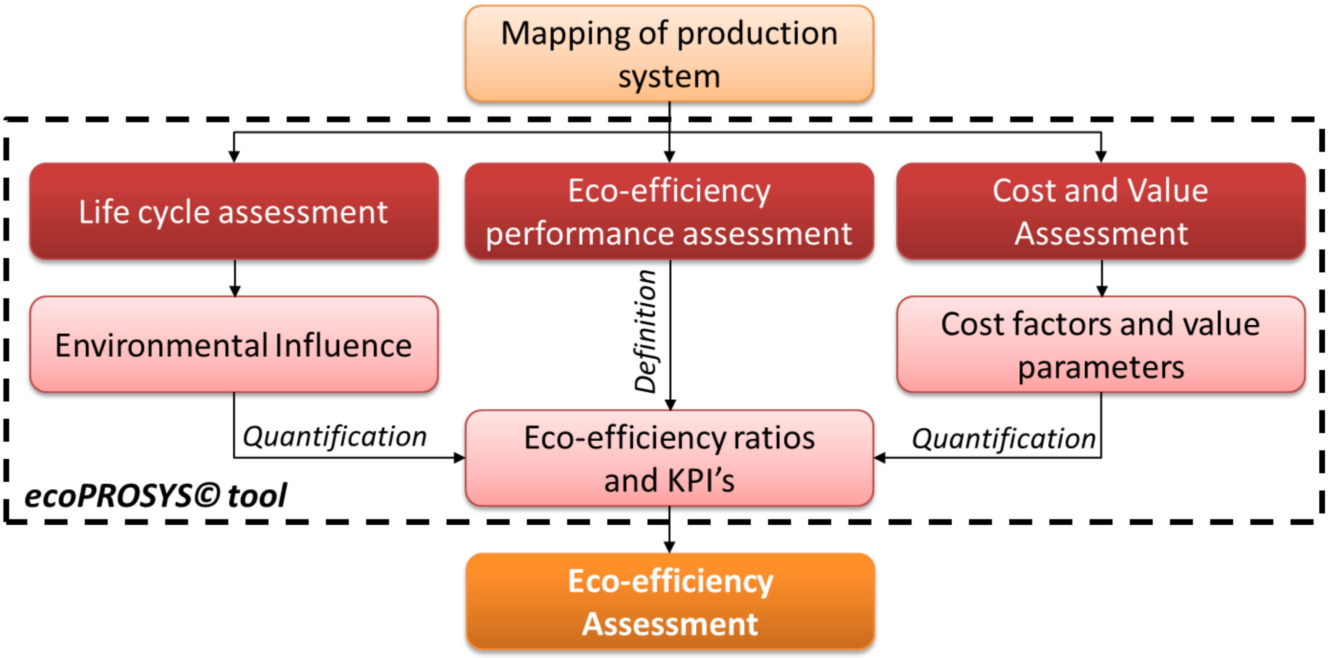

Figure 4 – ecoPROSYS© tool outputs and presentation of results.

Apart from these three elements, the production system mapping process is also of extreme importance, since the quality of the input data influences directly and considerably the

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assessment results. The goal is to compile the necessary data in order to properly characterise each unit process within the production system, from both input and output flows perspectives. The rationale is that the more detailed mapping of each unit process, the greater will be the advantage taken from the methodology and the more comprehensible will be the results. However, despite its extreme importance to the tool implementation, the mapping process is shared between eco-efficiency and efficiency assessment. For this reason, instead of a detailed explanation, next section describes it regarding the implications arising from its proper implementation.

Then, focusing on the identified elements, the eco-efficiency performance assessment (EEPA) is an evaluation process of production system parameters considering the integration of strategies, goals and the targets defined by the company. In methodological terms, it combines a standardised environmental performance assessment with the seven principles defined for eco-efficiency (Lehni et al., 2000). Therefore, it represents a parametrisation of each process parameter considering the view of the participants/company and the way they understand the production system. As a result, the main outcome is the identification of parameters of participants' main concern, i.e. the identification of parameters with high environmental significance and/or high intensity to each eco-efficiency principle.

For this reason, the EEPA is crucial to integrate company's environmental protection and economic growth objectives into the assessment, being its results a set of parameters considered important to the eco-efficiency improvement. This means that, rather than the actual environmental impacts, costs or value related to the production system, the results represent the company's eco-efficiency objectives. As a consequence, to support decision regarding eco-efficiency improvement process, the results from EEPA also points towards eco-efficiency ratios and the main KPIs that better characterise the production system. These eco-efficiency ratios and KPIs are quantified by life cycle assessment and cost and value assessment modules.

For the purpose of the present methodology, the determination of production system environmental influence is recommended to be done by using LCA methods. The LCA is an internationally standardised methodology widely described in previous project deliverables[1]. Its main goal is to quantify and provide an overall understanding of the production system environmental impacts and damage, as well as to provide a quantified environmental influence for the defined eco-efficiency ratios and KPIs.

Regarding the determination of cost factors and value parameters, a specific cost and value assessment module has been included in the tool. The followed approach aims to provide a technical understanding of how costs evolve along the production system and the characteristics of the production process. In particular, the results intend to show that the scope and timing of costs vary throughout the production system depending on their technical and financial characteristics.

To facilitate the understanding of its implementation the next sections explain the main operational phases.

[1] MAESTRI project Deliverable 2.1 - Efficiency Framework concept description and MAESTRI project Deliverable 2.2 - Methods for Efficiency Framework for resource and energy efficiency description

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Phase 1 – Definition of Goal and Scope

Following the same approach of other environmental assessment methodologies, the eco-efficiency assessment should start with an explicit definition of the goal and scope. Defining goals is crucial for success because it determines why the assessment is being conducted as well as its general purpose and target audience. The scope definition is intended to outline the temporal, technological and geographic boundaries of the assessment, i.e. what is being assessed and when the assessment takes place. This definition should include a clear characterisation of the production system targeted for the assessment and, in particular, its boundaries. Considering that production systems are composed by unit processes [2] connected by flows of intermediate products, which perform one or more defined functions, the unit processes to be included and excluded from the assessment should be also designated.

The definition of the functional unit is also of utmost importance during this stage. As described in deliverable 2.2[3], the functional unit is vital to assure the correlation between environmental and economic parameters and the different unit processes composing the production system. By definition, the functional unit is a quantitative measure and corresponds to a reference function to which all flows in the assessment are related. The rationale is that all processes and parameters of the production system must be evaluated on a functionally equivalent basis. Therefore, it normalizes data based on an equivalent use to provide a reference for relating each unit process input and output flows with a production system specific function or performance.

Phase 2 – Production system mapping

Considering the characterisation of the production system performed in the previous phase, during production system mapping the input and output flows for each unit process should be identified and characterised. As a common practice, a flow model of the production system should be constructed giving a clear picture of the technical system boundary, and including the activities that are going to be assessed and also data on flows. Next table resumes the typical input and output flows used to characterise unit processes.

Table 1 – Input and output flows characterization

Data Category	Characterisation Data	Description
Material flows	Type, quantity/volume and cost of materials	Actual materials that make up the final product for a particular process (primary materials) and materials that are used in the processing of a product for a particular process. Materials may be non-renewable (i.e., materials extracted from nature that are non-renewable or stock resources such as coal), renewable, or flow resources such as water.
Energy flows and costs	Type of energy forms, consumed quantities and costs	Process energy and pre-combustion energy (i.e., energy expended to extract, process, refine, and deliver a usable fuel for combustion) consumed and/or generated by any process in the business case.

[2] Unit process is the smallest considered element of the production system for which input and output flows should be considered.

[3] MAESTRI project Deliverable 2.2 - Methods for Efficiency Framework for resource and energy efficiency description

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Data Category	Characterisation Data	Description
Water flows and costs	Type, quantity/volume and cost of consumed water	Water consumed and/or generated by any process within the business case, including effluents.
Emissions to Air	Type of substances and quantities emitted	Air outputs represent the releases to the environment of gaseous or particulates from a point or diffuse source of any stage of business case, after passing through emission control devices, if applicable.
Emissions to water	Type of substances and quantities emitted	Water outputs represent liquid surface and groundwater discharges to from point or diffuse sources of any stage of business case, after passing through any water treatment devices.
Emissions to soil	Type of substances and quantities emitted	Soil emissions represent discharges chemical substances that are considered pollutants to soil from point or diffuse sources of any stage of business case.
Residues	Type, quantity/volume and disposal of generated residues	Represents the mass of a product or material, either solids or liquids, that are deposited as hazardous or non-hazardous waste, either before or after treatment (e.g., incineration, composting), recovery, or recycling processes.
Primary Products	Quantity/volume of primary products	Material or substance outputs from a process that are received as input by a subsequent unit process within the business case.
By-Products	Type and quantity/volume of by-products	Material outputs from any process that can be used, either with or without further processing, and are not part of the final functional product of the business case.
Equipment data and cost	Direct and indirect equipment costs.	Includes data on equipment used in the different processes within the business case, working related costs, including amortization, opportunity cost, etc.
Labour cost	Direct and indirect labour costs.	Direct and indirect (benefits and payroll taxes) labour costs.
Maintenance Activities and Costs	Maintenance schedule and related costs.	Maintenance activities schedule and costs related to any process and/or equipment or infrastructure used in a process within the business case.
Process general data	It depends on the production system.	Incudes the general data required to characterise the different processes within the business case, including production volumes, installed capacity, total working days per unit of time, shifts occurrence, total area, etc.
Process time data	It depends on the production system.	Includes the time data required to characterise the different processes within the business case, including working times, set-up times, idle times, assembly time, stopped times, etc.
Process value data	Economic, financial or monetary units.	Includes the value and economic data required to characterise the different processes within the business case, including sales, gross value added, EBITDA, indirect costs, etc.
Environmental related costs	Costs related to environmental activities.	All costs and benefits or advantages related to environmental activities related to any process, or its outputs, within the business case. This may include taxes, fees, investment or sales resulting from the business case activity.

Considering the complexity and the enormous amount of data associated to several industrial processes, it is recommended the definition of decision rules. This decision rules are applied to make manageable the collection process and to facilitate the identification of input and output flows related to each unit process. They represent a set of criteria established by

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participants to the assessment, and are used to determine if a given unit process or flow should be included in the assessment.

In addition, this decision process should be also complemented with the identification of sources for required data as well as a data quality assessment. Data quality requirements specify in general terms the characteristics of the data needed for the assessment, and are important to properly interpret and understand the outcome, results and reliability of the assessment. The most usual requirements to assess data quality are typically related to:

- the data source;
- the method in which the data were obtained (e.g., measurement, calculation, estimation or assumption);
- the time-related period for which the data are representative; and
- the geographical or technological coverage for which the data is representative (e.g., specific machine, production line, whole company);

In addition, uncertainties regarding the information or related to the data collection process can be also determined.

To complete the flow model, the input and output flows should be related to the selected functional unit. For this purpose, considering that most industrial processes yield more than a single product and recycle intermediate or discarded products as raw materials, allocation procedures are usually required. This means that input and output flows of a given unit process should be distributed among its different product lines to prevent an overestimation of costs and environmental loads. Depending on the unit process functions, the allocation procedures are usually based on weight, volume or energy, as more appropriate.

Depending on the data quality and collection process, allocation can be also facilitated by sub-dividing the unit process into two or more sub-unit processes. Hence, the sub-unit processes using a sub-product that are not of interest may be eliminated from the analysis, reducing allocation procedures.

Regarding the residues or emissions disposal scenarios, allocation procedures may be extensive and detailed and, for that reason, requires further analysis. Despite giving prevalence to the implementation recovery and valorisation processes, not all system parts (materials or energy wastes) have viable valorisation processes. Furthermore, for instance during recycling, changes in the inherent properties of the material are common, directly affecting its subsequent use as material, and indirectly affecting its recyclability rate. This must be taken into account during the definition of the most accurate allocation procedures, in order to guarantee a proper assessment and the completeness of results.

Phase 3 – Eco-efficiency performance assessment

The main goal of this phase is to characterize and classify the parameters of each unit process in terms of intensity to the eco-efficiency principles and environmental significance. From the practical point of view, to facilitate its implementation, the EEPA is divided into two main steps: (1) eco-efficiency intensity assessment and (2) environmental performance evaluation. The outcome of this two steps is then the identification of production systems parameters with higher intensity in terms of eco-efficiency, and for each one of the seven mentioned principles, as well as the production system parameters with higher environmental significance. This results

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from a matrix iteration considering the participant' classification using specific criteria, as explained in the next paragraphs.

During the first step, participants should classify each process parameter in terms of intensity according to each eco-efficiency principle. Despite the different available definitions for eco-efficiency, the WBCSD[4] definition is used for the purpose of MAESTRI project. In order to improve overall performance, the WBCSD identified seven principles that can be addressed (Lehni et al., 2000):

1. Reduce material intensity
2. Reduce energy intensity
3. Reduce dispersion of toxic substances
4. Enhance recyclability
5. Maximize use of renewable resources
6. Extend product durability
7. Increase service intensity

A scale from 1 to 5 was selected for this classification of intensity, representing the identification of what parameters are important, from participants' point of view, to achieve the goals defined for each one of the seven eco-efficiency principles. The next table presents the definitions for the defined scale.

Table 2 – Classification used to define eco-efficiency intensity.

Classification	Definition
1	The process parameter has **low intensity** to achieve the goals defined by the company for the eco-efficiency principle.
3	The process parameter has **medium intensity** to achieve the goals defined by the company for the eco-efficiency principle.
5	The process parameter has **high intensity** to achieve the goals defined by the company for the eco-efficiency principle.

The final intensity is determined by a weighting procedure between the intensity classification and environmental significance of each process parameter, which results from the environmental performance evaluation.

The environmental performance evaluation is the next step in which the participants should classify each process parameter against a set of significance criteria. For the purpose of the current eco-efficiency assessment, these criteria include:

- Frequency;
- Reversibility;
- Duration;
- Magnitude; and,
- Extension.

From the classification of these criteria, also environmental severity and risk are derived, which is done also by an iteration processes. Thus, the environmental severity would be the product

[4] World Business Council for Sustainable Development

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between the classification of reversibility, duration and magnitude (equation 3). The environmental risk is the product between frequency and environmental severity (equation 2). Finally, the environmental significance is determined by the product between extension and environmental risk (equation 1).

$$Environmental\ Significance = Environmental\ Risk * Extension \quad (1)$$

$$Environmental\ Riks = Frequency * Severity \quad (2)$$

$$Environmental\ Severity = Reversibility * Duration * Magnitude \quad (3)$$

The classification scale to be used for each criteria is presented in the following table.

Table 3 – Classification used for environmental performance evaluation.

Criteria	Classification	Definition
Frequency	1	**Sporadic** – the process parameter occurs sporadically, or it is not possible to predict its occurrence.
	3	**Cyclic** – the process parameter occurs in regular intervals.
	5	**Continuous** – the process parameter occurs continuously, without interruptions.
Reversibility	1	**Reversible** – after the process parameter ceases, the environmental factor affected by the impacts resulting from its occurrence, is able to return to its original state.
	5	**Irreversible** – the environmental factor, affected by the impacts resulting from the occurrence of the process parameter, is not able to return to its original state, at least in an acceptable time frame.
Duration	1	**Temporary** – the impacts resulting from the process parameter occurrence have fixed duration effects, being usually associated to short / medium term.
	5	**Permanent** - the impacts resulting from the process parameter occurrence, once occurred, do not change in a known time horizon.
Magnitude[5]	1	**Low magnitude** – the impacts resulting from the process parameter occurrence are of negligible magnitude, and the effects on the environmental factor are low or even irrelevant.
	3	**Medium magnitude** - the impacts resulting from the process parameter occurrence have considerable magnitude and the effects on the environmental factor are relevant. However, human intervention is not needed to make the environmental factor resume to its original state.
	5	**High magnitude** - the impacts resulting from the process parameter occurrence have considerable magnitude and the effects on the environmental factor are relevant. Human intervention is needed to make the environmental factor resume to its original state.

[5] Magnitude represents the size of the impact in absolute terms, being defined by the scope of the change caused to the environmental factor, in quantitative or qualitative terms.

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Criteria	Classification	Definition
Extension	1	**Internal** – the impacts resulting from the process parameter occurrence are circumscribed to the company's area, without affecting any of the external environmental factors.
	3	**Local** - the impacts resulting from the process parameter occurrence happen in the surrounding area of the company, affecting one or more environmental factors.
	5	**Regional or higher** - the impacts resulting from the process parameter occurrence happen beyond the surrounding area of the company, affecting one or more regional environmental factors (e.g. water lines).

As previously mentioned, from EEPA it is possible to derive the identification of significant environmental aspects and parameters with high intensity to each one of the eco-efficiency principles, representing the goals of participants and/or company in terms of production system eco-efficiency improvement. For this reason, the eco-efficiency ratios and KPIs representing the production system performance are also derived from EEPA. This is done by selecting the most appropriate metrics to characterise the process parameters defined as being with high intensity to the eco-efficiency principles. As a consequence, considering the EEPA results, the tool suggests a set of KPIs as a standard procedure. However, participants are obviously able to change the suggested set of KPIs.

Phase 4 – Quantification of environmental influence

The ecoPROSYS© tool includes a specific environmental influence module that can be used in two different ways, depending on the purpose and the maturity level of the company regarding the implementation of LCA methods.

For companies with higher levels of maturity concerning LCA methods implementation (i.e. with previous experience on LCA), the environmental influence module includes a platform where participants may directly import results from an LCA performed in an external software. Considering its widespread application, as well as the amount of market available software and databases for LCA purposes, this represents the most accurate way to assess production system environmental influence. However, despite being completely aligned in methodological terms, this usually means that a specific LCA should be conducted considering the goal and scope previously defined for the eco-efficiency assessment. In addition, as a good practice, the LCA should also include exactly the same production system characterisation, i.e. the same unit processes and the same input and output flows as considered for the eco-efficiency assessment.

Moreover, in order to use properly the LCA results import platform, a set of parameterisations are also needed. As a required practice during LCA, participants should define how the impact assessment should be performed. For this purpose, a Life Cycle Impact Assessment (LCIA) method and/or the LCIA impact and damage categories should be selected, depending on the goal and scope defined for the eco-efficiency assessment. The purpose of the assessment should be also considered during this selection, being particularly important when the results are targeted for communication purposes.

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Methodologically, the LCA results are used in three distinct purposes within the ecoPROSYS© tool:

- Present LCA results;
- Generate eco-efficiency ratios;
- Generate KPIs.

Then, apart from the system overall environmental influence, the presentation of LCA results aims to provide accurate information on the environmental performance individually exerted by different process parameters. Also, resulting from an aggregation metric, these results can be also assessed in a broader perspective, i.e. considering the different levels of the company and for which data has been characterised during the definition of the eco-efficiency assessment goal and scope (e.g. unit process, production line, production system, product, plant, company, etc. – following the logic depicted in Figure 3).

At the same time, process parameters with higher environmental influence are usually associated to higher costs, contributing to a decrease in the economic value of the production system. As a consequence, the LCA results may also support participants on the identification of process parameters that should be targeted during the development of improvement measures, presenting complementary information to the EEPA, in quantitative format.

In addition, LCA results can also support company's communication procedures by providing concrete information that can be directly used for legal, management or voluntary communication purposes.

Then, in order to consider these different possibilities, the platform to import LCA results presents a flexible approach allowing the selection of different LCIA methods and different LCIA impact categories accordingly to the eco-efficiency assessment defined purpose. From the practical point of view, a LCIA methods should be always selected in order to allow the quantification of the production system total environmental influence. Once this quantification is done by weighting the LCIA results, as described in ISO 14040:2006, only LCIA methods with this specific feature should be selected. Otherwise, the tool proper operation is compromised due to the impossibility of determining the overall environmental influence. Then, considering the current available LCIA methods, participants should bound their selection to the following ones, presenting weighting procedures:

- Ecological Scarcity
- EDIP 2003
- EPS 2000
- ILCD 2011 Midpoint+
- IMPACT 2002+
- ReCiPe

In addition to the definition of the LCIA weighting method, participants are also allowed to select the impact and damage categories as used by the defined or any other LCIA method. This intends to support the previously mentioned communication procedures, allowing the customisation of the tool outcomes according to the defined assessment purpose. In this

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respect, the tool allows the selection of any impact category of any of the following LCIA methods:

- CML-IA
- Ecological Scarcity
- EDIP 2003
- EPD 2013
- EPS 2000
- ILCD 2011 Midpoint+
- IMPACT 2002+
- ReCiPe
- Cumulative Energy Demand
- Cumulative Exergy Demand
- Greenhouse Gas Protocol
- IPCC 2013
- USEtox

Considering that different communication purposes (e.g. ecolabel, product/company environmental footprint report, global report initiative, environmental product declarations, etc.) have different communication procedures, for different industrial sectors and product categories, this flexibility intends to increase the adaptability of the efficiency framework to different industrial realities and sectors.

Nevertheless, although being the oldest and the most accepted method for quantitative environmental assessment (Radovanović et al., 2012), some difficulties arise during LCA method implementation. Most common problems include:

- High costs of implementation (specific software and databases are needed, which usually represent a considerable investment);
- Time needed to properly master the methodology;
- It requires a considerable amount of information to characterise the production system, which is not always available and often leads to inaccurate data collections and, consequently inaccurate results;

As a consequence, the truth is that most companies, and SMEs in particular, are not able to properly implement LCA procedures on frequent basis.

For this purpose, and to enlarge the application spectrum of the tools, MAESTRI intends to fill this gap by providing a specific module to generate environmental influence and, in particular, to quantify this environmental influence. This can be done by using the LCA module that has been developed and included in the ecoPROSYS© tool. This module runs over a database developed specifically for this purpose, representing conversion factors for the different input and output flows.

Taking into account the specificities of each input and output flow defined for the product system, the methodology presents a multiple approach. With regard to emissions, it is easily possible to identify substances of major importance for both gaseous emissions and liquid effluents, as they are duly covered by the legislation. This also helps with the implementation of the tools, because their monitoring is usually mandatory, meaning that companies have

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access to their quantification. In this sense, an analysis of the influence of the substances was carried out taking into account the different impact and damage categories of the previously identified methods.

For the remaining flows, their calculation is made using available Life Cycle Inventory (LCI) databases, namely those identified as being freely available on deliverable D.2.1[6]. Through this databases, conversion factors have been defined for each impact and damage categories.

Once participants have already identified the different unit processes during the process mapping, as well as their input and output flows, this module runs automatically considering the characterisation and the quantities defined for each flow.

Phase 5 – Determination of cost factors and value parameters

In order to model the costs related to the production system, the process-based cost modelling (PBCM) has been used. In short, PBCM comprises three main steps: (i) to correlate the effects and properties of a part/unit process with the characteristics of the production system, (ii) to relate the characteristics of each process to the requirements of manufacturing resources, and (iii) to translate requirements for a specific cost.

Processing requirements are accounted in the operational part of the model, which takes into account the cost data provided for input and output flows, involved equipment and labour related to each defined unit process of the production system. As for environmental influence results, in terms of results presentation, these inputs to the model are subsequently compiled and aggregated to the different level of the production system, being the highest level referring to the production system costs, and the lowest level to unit process costs, or even process parameter costs.

From the value perspective, participants should start the assessment by defining the production system value parameters. Depending on the goal and scope of the assessment, as well as the availability of data, these can include EBIDTA[7], GVA[8], EVA[9], sales, earnings, etc. Subsequently, the defined costs are allocated to the different value parameters defined by the participants, considering their standard calculation procedures.

Phase 6 – Interpretation of assessment results

The main aim of the eco-efficiency assessment results interpretation is to analyse results, reach conclusions and provide recommendations based on the findings of the previous phases. This process is usually iterative and intends to validate the results in accordance with the defined goal and scope. Then, from a methodological perspective, the results of previous stages should be evaluated and assessed regarding completeness, reliability and consistency.

Despite being a process to be conducted directly by the eco-efficiency assessment participants, the ecoPROSYS© tool has been developed also to facilitate this phase. Next

[6] MAESTRI project Deliverable 2.1 - Efficiency Framework concept description
[7] EBITDA – Earnings Before Interest, Taxes, Depreciation and Amortization
[8] GVA – Gross Value Added
[9] EVA – Economic Value Added

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figure presents the main tool outputs for which specific dashboards are available, as well as their interactions in terms of dependencies.

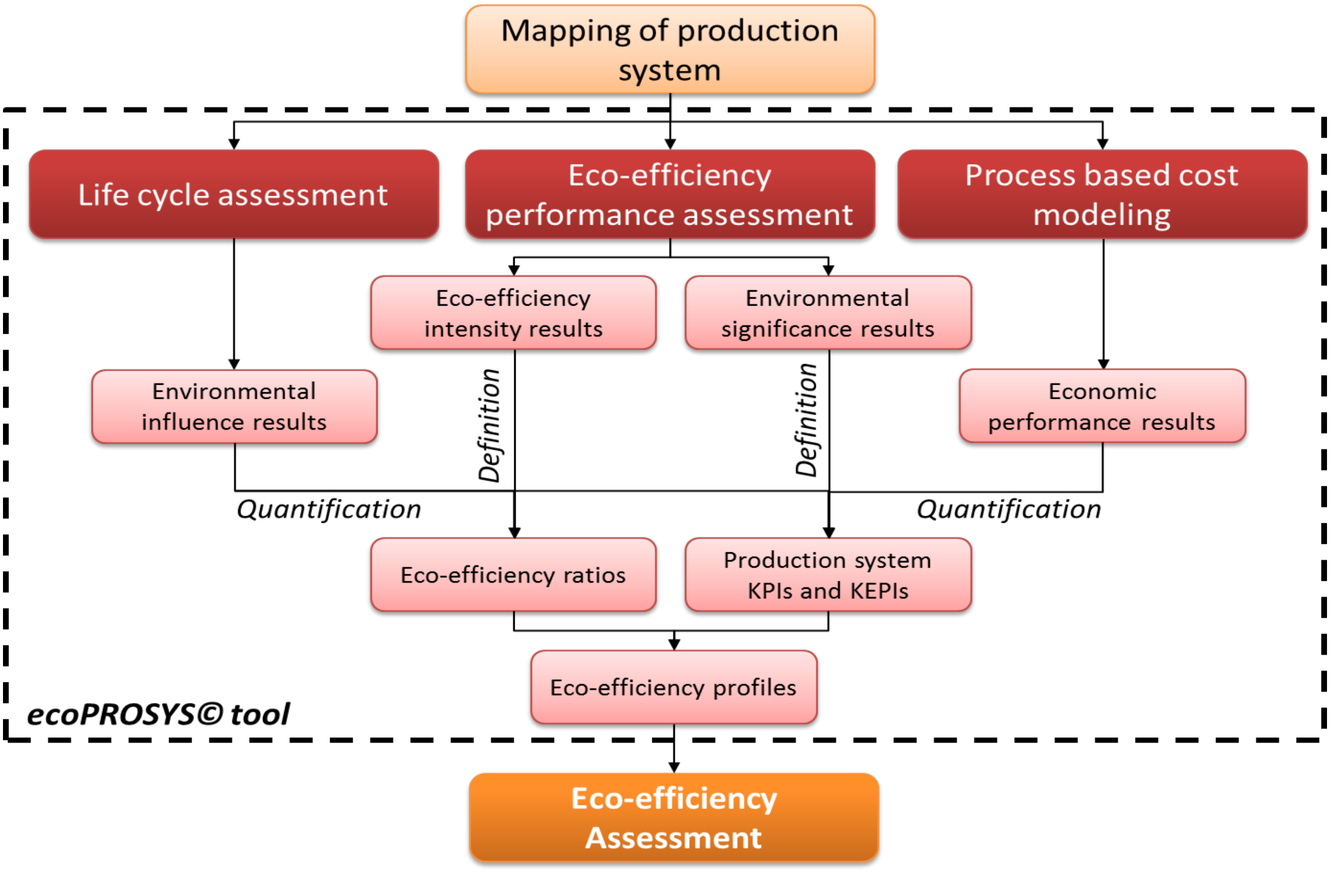

Figure 5 – ecoPROSYS(c) tool outputs and presentation of results.

In order to effectively support decision making, the available results intend to provide a better understanding of the production system and allow a quick and effective interpretation of results. This is done by presenting the results from both individual and aggregated perspectives, similarly to the efficiency assessment described in previous section.

In fact, rather than understanding only the environmental performance or economic value losses of a production system, one of the main purposes of an eco-efficiency assessment is to understand both dimensions from a combined perspective. However, the eco-efficiency assessment overall outcome results from specific ratios, and is presented in a non-dimensional way. This means that the tools, in order to provide a concrete support to results interpretation, should also allow participants to assess this results regarding the most contributing factors. Then, the main purpose of this aggregation is to provide a scalable perspective of the different levels of the production system, allowing the perception of main influencing factors.

This is particular important regarding eco-efficiency ratios. As they intend to support participants in managing and understanding the links between environmental and value performance. Their ultimate goal is to provide a clear vision of the production system performance, and to assist on the implementation of improvement strategies, by connecting the different levels of the production system with clearly defined targets and benchmarks.

In the same way, KPIs are quantifiable metrics that reflect the performance of the production system. They provide participants with metrics focusing on 'key' measures – i.e. those most

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important to an understanding of a business. In addition, while eco-efficiency ratios present the generated value in accordance to the environmental influence produced, KPI's and KEPI's are usually presented as general quantities, including costs, environmental impacts or environmental damage or a specific function of specific parameters (e.g. kg of residues sent to recycling, tonnes of CO_2 eq. emitted, MJ of primary energy).

Targeting mainly communication purposes, for both internal or external initiatives, the tool is also able to produce of reports, based on a specific profile template. These report aims to compile the most relevant results regarding the eco-efficiency assessment, by presenting clear information concerning the production system performance. Apart from communication, these profiles can be also used to measure the production system progress in terms of overall eco-efficiency. For this reason, both eco-efficiency ratios and KPIs are obviously a clear content to help participants on this purpose.

2.4 Integrated assessment and results

Rather than a complete integration of eco-efficiency and efficiency tools, the consortium involved in WP2 activities, has opted for a modular approach allowing both a separate and simultaneous use of the tools. Considering that each company has its specific goals, and presents different levels of maturity regarding efficiency and eco-efficiency implementation, this option intends to provide flexibility to the proposed approach. However, the possibility of assessing production systems in such detail regarding environmental, economic and value based parameters, including value adding and non-value adding activities and flows, has also been considered. For this purpose, the integration of efficiency and eco-efficiency has been made at results level.

In fact, efficiency and eco-efficiency assessments are perfectly compatible and present complementary results. This can be easily understood not only by observing the complexity related to the vast majority of industrial production systems but also by observing the dependence that both concepts have regarding the actual performance of these production systems. For instance, the improvement of a production system performance regarding any of the eco-efficiency principles is usually associated to the reduction of a specific process parameter (e.g. materials or energy consumption). However, it must always be taken into account that production systems are usually balanced, i.e. all process parameters are associated to a specific function that guarantees the production process performance in terms of productivity. This basically means that a simple reduction of a process parameter should be always associated with an increase of its efficiency. Otherwise, it has a strong probability to affect directly the productivity of the production system. As a consequence, production system productivity tends to decrease, i.e. the amount of final products being produced is reduced, influencing also negatively the eco-efficiency performance.

Similarly, considering only the efficiency perspective, the analysis excludes the sustainability perception, but the efficiency assessment is based on the principle that the efficient and effective materials and energy use can reduce natural resource inputs and waste or pollutant outputs. Yet, the efficient use of materials, energy or resources does not take into account the related environmental impact, and consequently never incites companies to look for alternatives and improvements that can enhance economic and environmental performance. Additionally, efficient production systems are one of the main objectives for

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companies. However, one of the fundamental principles for successful organisations, in particular to achieve continuous improvement, is to have also an accurate management of environmental issues. Implementing an effective environmental assessment on elements that have an impact on the environment, can lead not only to a better understanding of performing activities, drivers, and barriers, but also to the long-term prosperity of the organisation.

Then, to ensure a comprehensive assessment of a production system, both concepts should be considered simultaneously. The rationale behind this approach is to provide a better understanding of the different flows dependencies, both in efficiency and eco-efficiency terms, and to avoid misleading conclusions. This means that by assessing the production system from both perspectives, participants are able to evaluate how each process flow is affecting production system performance and how they can improve it without affecting or compromising the production system operation. The main goal of this approach is clearly to influence the inclusion of the concept of effectiveness alongside the concept of efficiency, allowing the implementation of strategies conducting to effective, efficient and eco-efficient production systems. Moreover, in order to simultaneously assesses the environmental, economic and efficiency performance of complex production systems, to provide support in the identification of major inefficiencies and circumstances of low eco-efficiency performance, thus, supporting the decision making process and enabling managers to take actions that will improve both, efficiency and eco-efficiency performance.

In addition, apart from providing the results from both efficiency and eco-efficiency perspectives, and effective integration of these results was also developed in order to meet the challenges listed in the previous paragraphs. This has been done by monitoring deviations between the actual efficiency and eco-efficiency of the production system and targeted eco-efficiency. For the purpose of the current assessment, targeted efficiency and eco-efficiency represent the maximum theoretical performance that company is able to achieve with the current production system, i.e. with the current technological settings. From this approach a new performance metric was developed – the Total Efficiency Index (TEI). As explained in previous project deliverables[10], TEI is obtained by multiplying the normalized eco-efficiency and the efficiency performance of each unit process composing the production system. However, it can also be successively aggregated for the complete production process of a given product.

Consequently, TEI main outcome is related to the ability of evaluating if eco-efficiency performance variation is due to higher or lower environmental influence, or due to higher or lower economic value. In practice, this results from the distribution variance of TEI results that occur on two major axes: the efficiency and eco-efficiency. Next figure presents in a graphical way this distribution.

[10] MAESTRI project Deliverable 2.2 - Methods for Efficiency Framework for resource and energy efficiency description

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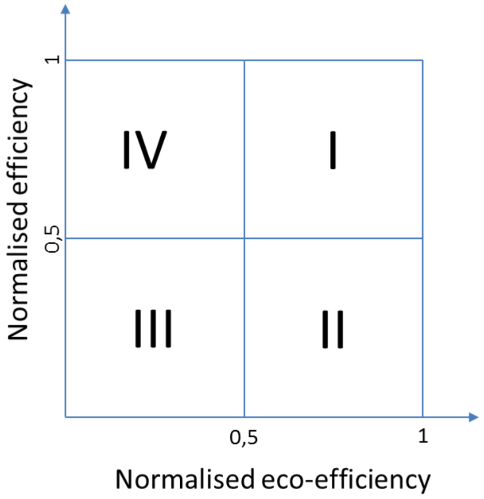

Figure 6 – Theoretical distribution of TEI values.

As it can be depicted by the figure, the distribution of TEI results can be characterised into four quadrants, representing distinct characteristics of the unit processes or overall production system. These characteristics are presented in the next table.

Table 4 – Main characteristics and insights related to the distribution of Total Efficiency Index results distribution.

Quadrant	Gap to theoretical maximum		Improvement potential		Main insights
	Efficiency	Eco-efficiency	Efficiency	Eco-efficiency	
I	Small	Small	Low	Low	The production system generates an acceptable economic value considering the environmental impacts caused by its activities. Then, considering the current technological settings, it has a low improvement potential.
II	Large	Small	High	Low	The acceptable eco-efficiency performance is likely to be led by low environmental impacts related to the production system activities. Improvement actions to increase the economic value generation are advisable, namely by improving process parameters efficiency.
III	Large	Large	High	High	The production system presents low performance at all levels. The implementation of improvement actions is extremely recommended.
IV	Small	Large	Low	High	Despite presenting acceptable efficiency, the production system is not generating the expected value. Technological changes are also recommended to decrease environmental impacts.

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3 Simulation of Manufacturing Systems

Companies are increasingly forced to adjust their production systems due to the constantly changing requirements from customers, market or legislation. Considering that manufacturing processes are usually complex systems, this typically represents a very difficult task. It involves a substantial amount of different parameters which are correlated, in the form of direct or indirect dependencies, to guarantee the manufacturing system proper functionality. As a consequence, this tends to cause turbulence on the production system, affecting negatively its performance, robustness and stability. Then, to support companies on improving production systems, simulation studies are often conducted.

With this in mind, and also to enlarge the scope of Efficiency Framework application, it was intended to provide the opportunity for production systems simulation, in terms of efficiency and eco-efficiency, by using its ability to assess complex systems. The main goal of this simulation module is twofold: to provide a better understanding of the production system performance and, to assess the expected impacts of changes and/or improvements occurring in the production system. Then, as prior point, it is important to frame the simulation of alternatives into the Efficiency Framework implementation. In practice, considering the defined goals, the simulation of the production system can occur in two different stages of the implementation process:

- During the efficiency and/or eco-efficiency assessment the simulation module allows participants to better understand the influence of any process parameter on the production system performance. This can be done by introducing changes regarding the process parameters quantitative amount, and assessing the influence of these changes on the production system efficiency and/or eco-efficiency performance. As a consequence, participants are able to identify and select process parameters that should be targeted for the identification of improvement actions.
- After the identification of improvement actions, the simulation module allows participants to assess their impacts in the production system efficiency and eco-efficiency performance, from efficiency, environmental, cost and value point of view. This feature can be used to support participants' decision regarding the actual implementation of the improvement actions, to define implementation strategies and priorities, or even the definition of goals and targets regarding the production system performance.

Therefore, it becomes clear that the Efficiency Framework follows a PDCA[11] cycle, meaning that its implementation should be an iterative and cyclic continuous process, as all other continuous improvement methodologies. This results not only from the features of the different modules composing the Efficiency Framework, but also from the need of measuring the performance progress according to company goals or requirements.

Regarding the technical approach followed by the simulation module, it is mainly based on changes operated at production system mapping process. Therefore, it runs simultaneously from both efficiency (through MSM©) and eco-efficiency (through ecoPROSYS©). However, in

[11] Plan-Do-Check-Act (also known as Deming cycle)

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order to better understand the different functionalities, next sections present a description of each perspective, individually.

3.1 Efficiency simulation – MSM©

MSM© is intended to be used not only for analytical evaluation, but also to support the decision making process, namely greenfield design or online systems monitoring, in order to enable the identification and quantification of major inefficiencies and keep track of efficiency progress. Therefore, it is sensible to combine simulation feature of different scenarios.

Indeed, it is necessary for MSM© to be able to perform simulations, namely simulations based on scenarios. The importance of having simulations within MSM© framework is related with the fact that the user will be able to foresee the overall behaviour of the production processes in terms of efficiency in a virtual manner, i.e. without changing the process.

Additionally, the user is able to simulate what could be the gains, economic and efficiency wise, if a certain improvement action (e.g. improve raw material usage) or a change in technology is implemented. In other words, before implementing the improvement action or technology, the user is able to foresee how much the NVA-related costs will reduce considering that the user is able to estimate NVA reduction. On the other hand, it is also possible to simply simulate what would be the figures if, for instance the NVA is reduced until a certain value. All in all, the efficiency simulation consists in performing "what if scenarios".

In order to create different scenarios using MSM©, first a baseline should be calculated. The baseline assessment can refer to the real working conditions of the process or as mentioned could refer to a greenfield assessment. For both situations the baseline must be calculated, according to the flow of events described in section 3.2 of this document and depicted in Figure 7. After baseline assessment is carried out, it is possible to create the different scenarios.

The scenarios creation begins with making a "copy" of the baseline value stream[12]. The following step consist in changing the values (VA and NVA) that were, initially, in the baseline value stream, this gives place to the simulation value stream. The user should create the simulation value stream considering the foreseen/attainable values related, for instance to technology changes or to the implementation of an improvement action. However, as stated the user can change some values that make sense, just to have a view of the efficiency performance i.e. "what if scenarios". Ultimately, the user may create scenarios which depict the reduction of NVA of a certain process parameter (e.g. steel) This scenario may be suitable to support preliminary "evaluation of IS potential".

It is important to say that one or more scenarios can be created. For this, instead of just making one copy of the baseline value stream the user could make as many as the number of scenarios required. Consequently, the user will have to create a simulation value for each required. Additionally, the user could create a copy, or several, of an existing scenario, in order to reduce the effort of parameterisation of the scenario value stream.

[12] Value stream contains basically of all actions (actions that add value – VA; and actions that do not add value – NVA) that are required to bring a product or a group of products through the main flow, starting with the customer and ending with the raw-material (upstream)

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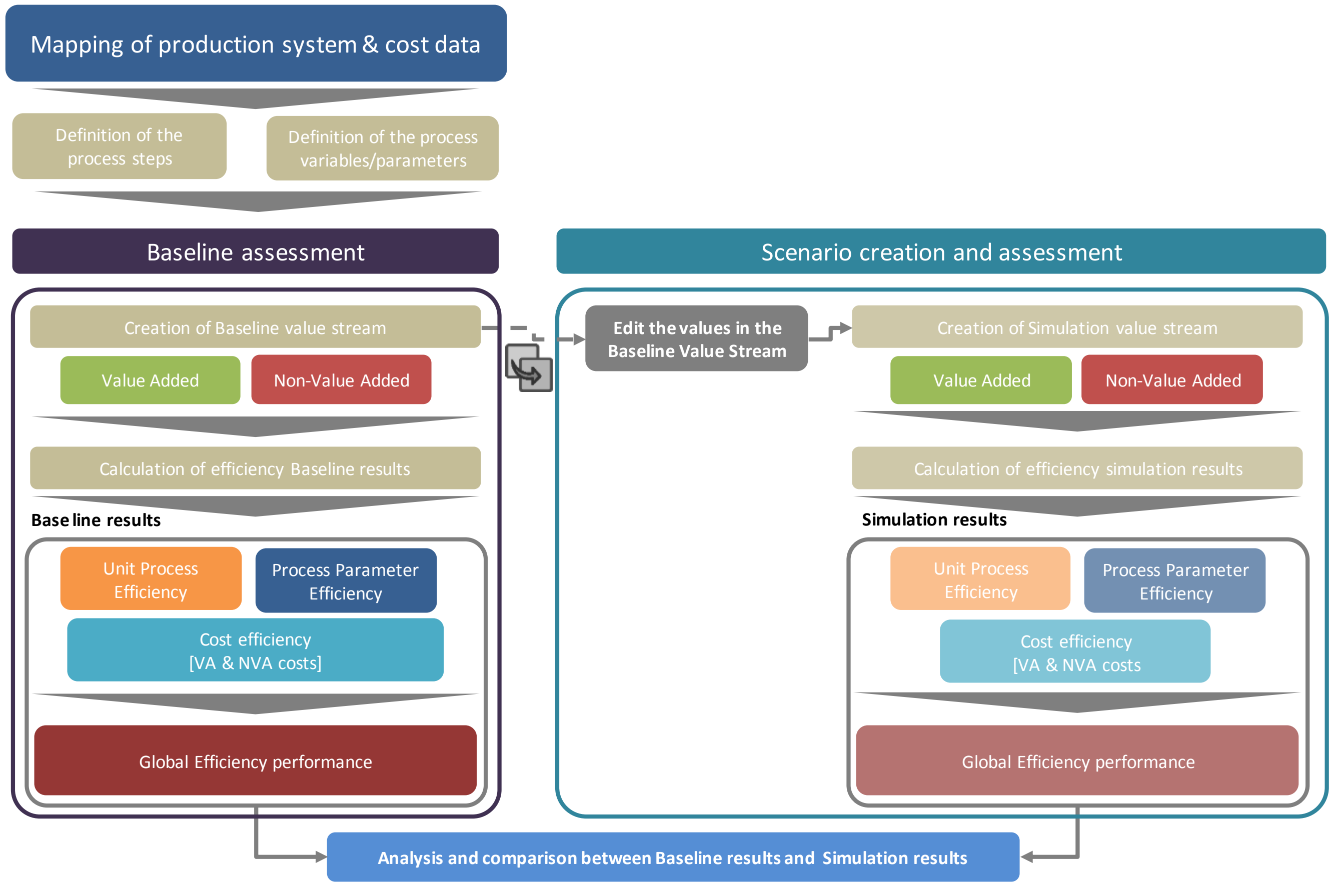

Figure 7 - MSM© baseline assessment and scenario creation

The different scenarios and the baseline results are evaluated in the same manner for efficiency assessment, i.e. through the calculation of the efficiency results. These results are comprised mainly by the unit process efficiency, process parameter efficiency and the cost efficiency, and give clear picture of the Global Efficiency Performance Figure 7.

To assess the different scenarios, the baseline and simulation results must already be calculated. The next step is to analyse and compare the simulations results with the baseline, as depicted in Figure 7. Or even compare the results obtained from the different scenarios.

All in all, the user will compare the different results, and have a clear figure of cost efficiency and overall efficiency performance variation between baseline and the scenarios, and between the several scenarios. Additionally, if the scenarios under consideration refers to the implementation of improvement actions, the user can prioritize the implementation order/strategy by analysing which improvement action has highest cost reduction. It is important to keep in mind that a process parameter, within a unit process, could have low efficiency but, for instance, if its unitary cost is low, the users may prefer to start the implementation action to increase efficiency of a process parameter with higher efficiency but also with higher unitary cost.

3.2 Eco-efficiency simulation – ecoPROSYS ©

Considering a similar approach, the eco-efficiency simulation results mainly from changes made by participants in the process mapping. From operational point of view, the eco-efficiency simulation module uses the ecoPROSYS© tool to generate alternative results and scores, considering the changes made by the participants in process mapping. In practice, its

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operation occurs in a similar way as the described eco-efficiency assessment process (see section 3.3). In this regard, one or several parameters can be changed both in terms of quantity or quality. Considering the correlation between the different flows, and in order to provide comparable scenarios, each one of these options presents different approaches.

To change process parameters from quantitative point of view is definitely the simplest one. Regarding this option, participants can reduce or increase the quantitative amount related to one or several process parameters, for instance, resulting from an increase of efficiency related to their consumption or generation. Considering this new quantitative characterisation, and once the characterisation made on the original process mapping includes also the costs related to these parameters, the simulation module determines alternative results and scores regarding environmental influence, through the LCA module, and cost factors and value parameters, by using the cost and value assessment module. In respect to the value determination, the approach follows a direct relation between the process parameters costs and value parameters. This is done by determining the expected variation of each value parameter (*delta* (Δ)), considering the costs resulting from the changes made in the process mapping, and the standard formulas used to calculate the value parameters. As a results, alternative results and scores are generated creating an alternative scenario, including eco-efficiency ratios and KPIs for the different levels of the production system.

Regarding qualitative changes being made in process parameters, a special remark should be made. In practice, this aims to allow participants to assess specific changes regarding technological settings. This can be particular important concerning materials or energy (e.g. to assess the introduction of a new, or change a specific type of material or energy source within the process) or residues (e.g. to assess the influence of other valorisation processes), but also from a more technological perspective, for instance, related to a technological shift or process equipment change. Once this process variations are usually related to investment, the implementation of this kind of tools can represent a great advantage. However, it is important to highlight that this kind of changes influence directly the production system parameterization, as available from the eco-efficiency assessment. For this reason, special attention should be given to the implications occurring on process characterisation. One of the most important steps regarding this, is to characterise the new process parameters in both environmental and economic (in particular, cost) perspectives. In terms of environmental characterisation, participants can use both an external or the available LCA module of ecoPROSYS© (limited to free available LCI databases). Only this way the tool is able to present proper and comparable score regarding the different level of results.

The presentation of results is made exactly in the same way as previously explained for eco-efficiency assessment (see section 3.2). The main goal is to provide a quick understanding regarding the influence of any change operated in the production system on the eco-efficiency scores, considering the different levels of analysis. For this purpose, scores are presented side by side, highlighting the main deviations. Visual management methodologies are used to allow quick interpretation of results.

Therefore, by changing process parameters quantities, participants can evaluate their influence to both environmental and value perspectives, as well as to the overall eco-efficiency performance. This is particular important when participants intend to identify the most influencing parameters to a specific production system or unit process, in order to define

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strategies regarding improvement actions. In this respect the production system performance presents a direct proportion. In practice, this means that improvement actions implemented on process parameters with great contribution to the production system performance, represent higher benefits both in terms of environmental influence reduction and value generation increase.

In addition, changing process parameters quantities also allows a better perception regarding what is generally influencing the eco-efficiency ratios and scores. In fact, the eco-efficiency scores are dependent both from environmental and value perspectives. This means that a good score can be due a high generation of value, but also to a small environmental influence resulting from production system activities. However, the occurrence of both events, even simultaneously, does not mean that production system improvements are not need. This is actually strong related to the eco-efficiency main paradigm: doing more with less. Then, the rationale of an eco-efficiency implementation strategy should be always to search for opportunities that represent an increase of generated value, without jeopardising the environmental issues.

One important final remark regarding the simulation of different scenarios is related to the EEPA initial parametrisation. As previously described, EEPA presents a crucial role within the ecoPROSYS© tool, mainly because it supports participants on the identification of most intense and significant parameters, considering the company strategy and goals. For this reason, within ecoPROSYS© tool, it is also used to support on the definition of the most appropriate eco-efficiency ratios and KPIs regarding the defined assessment scope. This means that by introducing changes in process parameters, in particular on qualitative terms, a proper performance assessment should be also made considering the introduced variations. However, along with the simulation of different scenarios, changing inputs (in quantity or quality) will enhance the participants' ability to define what really matters for the core measurements and what is really significant for eco-efficiency.

3.3 Integrated simulation

The biggest advantage of the Efficiency Framework is to provide the ability of simultaneous analysis of production systems efficiency and eco-efficiency. Similarly to the assessment results presentation, the Efficiency Framework aims to provide also the results considering the efficiency and eco-efficiency simulations, as explained in previous sections, from an integrated perspective. In fact, it is from the utilisation of this features that actually results the support to the decision making. This is done by providing the participants with the ability of understanding the dependencies occurring between the input and output flows, from the different unit process composing the production system, as well as from these flows with the three main dimension of analysis (efficiency, value creation and environmental influence), i.e. how each flow is influencing these dimensions.

Then, apart being able to use the each of the tools individually, this feature provides participants with a broad perspective regarding the expected impacts and alternatives influence, considering an integrated point of view. Theoretically, this may not seem intuitive once it combines different metrics, with different units and, sometimes, even different meanings. In fact, much of this view is related to the background concepts that were used for the Efficiency Framework genesis (i.e. efficiency and eco-efficiency). Although both aim to

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increase production systems value, and be presented in a form of ratios, their meanings are relatively different.

In terms of efficiency, it is typically represented by the ratio of the useful output to the necessary inputs. Thus, it is strongly related to the basic physical laws representing the effort needed to achieve the output. Mathematically, the results range from 0 (totally inefficient process) to 1 (a perfect process). Regarding eco-efficiency, a completely different subject is considered. Despite being equally represented as a ratio, also using the useful output, it uses the caused effects instead of necessary inputs. Then, it expands the production system concept to an external level, considering its impacts on external entities (usually measured in terms of environment influence).

In addition, their relationship is not theoretically reciprocal. Typically, when a production system is improved in terms of efficiency, it means that less inputs are needed to produce the useful output. Ultimately, this represents the basic paradigm of eco-efficiency: doing more with less. But in fact, reducing inputs represent lowering production costs and environmental impacts, and if the useful output remains constant, i.e. the production generated value is the same, the eco-efficiency performance tends to increase. This means that the relation between efficiency and eco-efficiency is usually direct.

However, the same does not happen when the relation between eco-efficiency and efficiency is considered. This is mainly due to the external dimension of eco-efficiency that, apart from the effort needed to produce the useful output, it considers also the effects caused to external entities. In addition, some of the eco-efficiency principles are strictly related to its "eco" dimension (e.g. extend product durability or increase service intensity). Despite not being impossible, changes operated in the production process targeting these principles will hardly have influence on process efficiency. This means that the relation between eco-efficiency and efficiency is not always direct.

As a consequence, by integrating the simulation results, participants are able to assess the influence of each process input and output flow, or improvements made in each flow, over all these dimensions. With this, Efficiency Framework aims is to support companies decision regarding the definition of strategies to increase the sustainability metrics related to production system operations.

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4 Optimization in Manufacturing Systems

Eco-efficiency assessment is not an easy task – from the inherent existence of environmental and economic trade-offs, up to the consideration of many different EE indicators having their own preferred solutions, the designer has many dilemmas in the decision making process. To help make better decisions, there is a discipline, Operations Research (OR), within which metaheuristics are highlighted for being amongst the most promising and successful optimization techniques.

4.1 Introduction to optimization

Resorting to OR is applying advanced analytical methods in the pursuit of improved decision-making and efficiency. Metaheuristics stand out for their ability to provide "acceptable" solutions in a reasonable time for solving hard and complex problems in science and engineering (Glover, 2009).

Furthermore, the presence of many indicators to define Eco-efficiency and the fact of optimizing them all at the same time, characterizes this problem as a multi-objective optimization problem (MOP). Consequently, there will be a multiplicity of solutions which in turn promotes the usage of population-based search metaheuristics (many candidate solutions are manipulated in every iteration). Even for a single-objective problem, this is particularly useful because metaheuristics may return many near optimal solutions that provide important information for the designer.

Towards Eco-efficiency assessment, the MOP has to be defined according to equation 1 (Coello Coello, Dhaenens, & Jourdan, 2010):

$$(MOP)\begin{cases} Optimize\ f(x) = \big(f_1(x), f_2(x), \ldots, f_k(x)\big) \\ with\ x\ \in D \end{cases} \qquad (1)$$

Where x is the vector of decision/design variables, D represents the set of feasible solutions, and $f(x)$ is a vector of objective/cost functions, in this case, representing the Eco-efficiency of the system that is to be optimized.

Metaheuristics are high level strategies for exploring search spaces by using different methods (Coello Coello et al., 2010). Different metaheuristics apply different methods and there were explored two different algorithms: Genetic Algorithms (GA) for being one of the most studied and applied population-based algorithms (Talbi, 2009), and Particle Swarm Optimization (PSO) which has been used for solving MOPs for its simplicity and robustness (Saka, Doğan, & Aydogdu, 2013).

Within the manufacturing industry there was a study undertaken regarding the injection moulding process, namely to analyse the influence of its design phase in Eco-efficiency. The system was modelled through a Process-Based Model (PBM) which allows to evaluate the influence of different design alternatives concerning the resources needed for mould's production and usage.

Analysing all design alternatives requires an extensive analysis where the designer has to analyse all design combinations, one by one, for each indicator. This isn't an efficient approach and has a certain error susceptibility, so metaheuristics are also appropriate to

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overcome that fact by returning the convergent solutions towards the goals established by the designer in equation 1.

Assessing Eco-efficiency requires modelling the system to be optimized. There are linear relationships that can represent the behaviour of some variables, though energy is a variable that is not included in that group. There is a nonlinear mapping between inputs and outputs concerning the energy modelling which comes to difficult its estimation. Artificial Neural networks (ANN) stand out for their high ability to capture nonlinear complex relationships between inputs and outputs (Rojas, 2013) – This aptitude will be profitable for creating a model to forecast the energy consumption.

4.2 Optimization models

The previous chapter refers to the Problem Characterization frame of Figure 8. Eco-efficiency assessment through the application of metaheuristics and the energy consumption estimation through ANN.

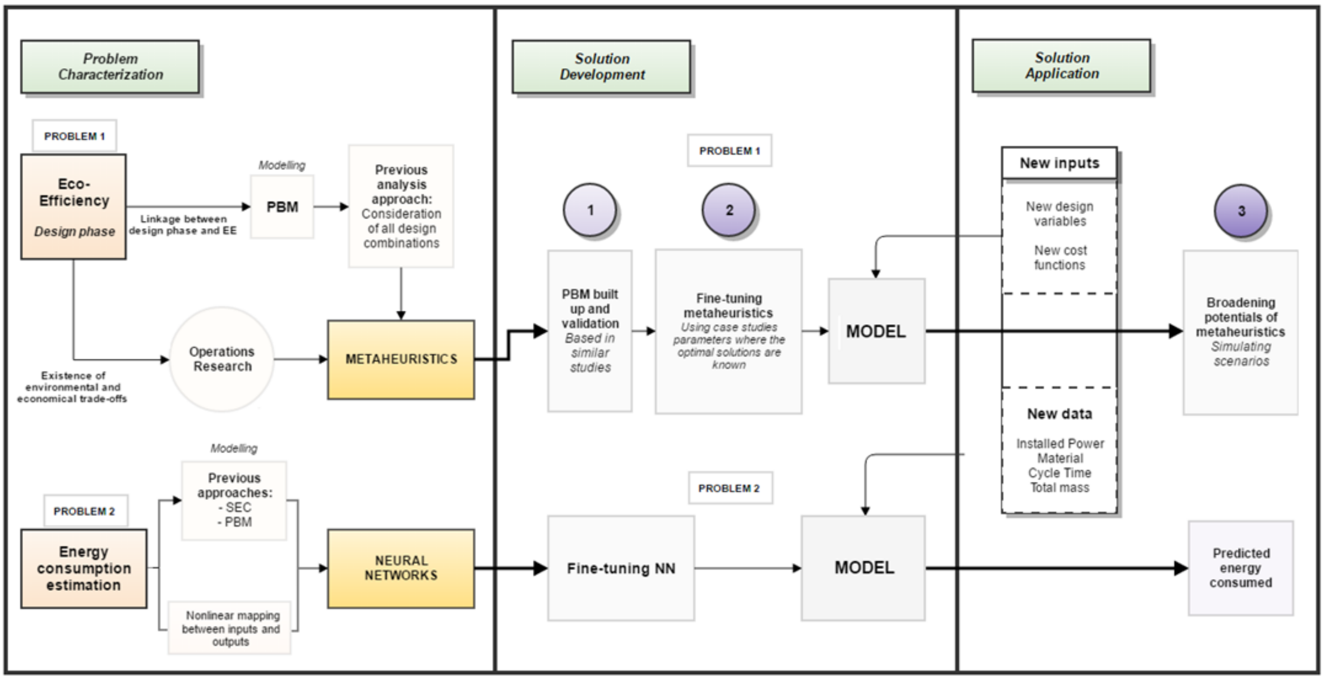

Figure 8 - Macro scheme of the problems and respective solutions

So far, solutions have been proposed. Their implementation will follow, which comprehends the Solution Development and the Solution Application phases of Figure 8.

Regarding Eco-efficiency assessment there were three stages. The first two are included in the Solution Development phase whereas the third corresponds to the Solution Application phase:

1) The PBM built-up and its validation – in order to guarantee that the system to be optimized is properly modelled.
2) The integration of metaheuristics and the definition of the mathematical model in equation 1, according to designer's goals.
   At this stage, metaheuristics have to be fine-tuned towards providing quality solutions.

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3) Broadening potentials of metaheuristics by trying different scenarios with different design variables and different Eco-efficiency indicators.

Regarding the energy consumption estimation, aiming to use ANN for modelling, this one has to be firstly fine-tuned in order to have an accurate model.

An ANN is an information processing paradigm that is inspired by the way biological nervous systems, such as the brain, process information. It is an information processing system that is composed of a large number of highly interconnected processing elements called neurones, working in unison to solve specific problems. ANNs, like people, learn by example. They are configured for a specific application, such as pattern recognition or data classification, through a learning process (Haykin, 1999).

4.3 Eco-Efficiency Optimization

After having the PBM, the second stage comprehends the integration and the fine-tuning of the metaheuristics. At each iteration, the algorithms apply some operators that will lead to the optimized solution(s). However, they have to be firstly fine-tuned in order to guarantee that the algorithms are having a good performance and are reliable.

A methodology was developed towards fine-tuning PSO and GA parameters.

Firstly, it is important to retain that both algorithms are population-based, so the number of elements of the population (NPop) and the number of iterations (NIt) are parameters in common. But these parameters only affect the degree of exploration and exploitation in the search space.

There are specific parameters that characterize and define the dynamics of the algorithms (operators that transform solutions at each iteration) and those will be the ones that are to be fine-tuned.

Thence, the methodology comprises different fine-tuning phases represented by a code of colours, while varying NIt and NPop that will test different sets of specific parameters. As performance indicator that could differentiate the results when changing and testing the different sets of parameters, emerged the hypothesis testing. A study was found where it was used to assess and compare the effectiveness of GA and PSO (Hassan & Cohanim, 2005). Effectiveness is defined as the ability of the algorithm to repeatedly find the known global solution or arrive at sufficiently close solutions when the algorithm is started from many random different points in the design space (Hassan & Cohanim, 2005).

So the hypothesis testing has to be defined according to designer's standards. For instance, in the case study:

- The results are presented with the Eco-efficiency indicator normalized, by using the relation in equation 2.

$$Q_{sol} = \frac{solution}{known\ global\ solution} \tag{2}$$

- The null hypothesis was defined as analysing the effectiveness of the set of parameters which provide results whose mean of Q_sol of equation 2, is equal or above 99 % of the global optimum.

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- In other words, there is the objective to test whether:

$$H_o: \mu_{Q_{sol}} \geq 0.99 \text{ vs. } H_a: \mu_{Q_{sol}} < 0.99 \qquad (3)$$

At a significance level a of 5 %.

This methodology is an exhaustive strategy where the sets of parameters which don't provide convergent solutions according to the hypothesis test of equation 3, are dropped off and don't pass to the next phase.

After a brief description about the methodology, here it comes in a user guide form. In this way, this methodology can be used for fine-tuning metaheuristics parameters for different applications. It is presented in a user-friendly way that the user doesn't need to have insight about these optimization fields.

USER GUIDE:

Table 5 – Methodology for fine-tuning the algorithms

<table>
<tr><th colspan="2">START</th><th colspan="2">EXPLORE</th><th colspan="2">EXPLOIT</th></tr>
<tr><td colspan="2" rowspan="2">NIt and NPop should be high enough to achieve convergence but low enough to not spend too much computational time. By trial and error.</td><td colspan="2">Decrease NIt and increase NPop – more exploration, less exploitation.</td><td colspan="2">Increase NIt and decrease NPop – more exploitation, less exploration.</td></tr>
<tr><td colspan="4">Consider the set of parameters which weren't rejected in the previous phase.</td></tr>
<tr><td colspan="6">Passage to the next phase: Regardless the set of parameters…Convergence of</td></tr>
<tr><td colspan="2">≤ 80 % of the solutions?</td><td colspan="4">≤ 30 % of the solutions?</td></tr>
<tr><td>YES</td><td>NO</td><td>YES</td><td>NO</td><td>YES</td><td>NO</td></tr>
<tr><td>Go to EXPLORE phase.
Reject the set of parameters whose solutions doesn't converge.</td><td>Increase NIt and NPop. Repeat.</td><td>Reject the set of parameters whose solutions doesn't converge.
Decrease NIt while maintaining or increasing NPop and repeat; OR go to EXPLOIT phase.</td><td>Results are not meaningful as NIt is too small.
None set of parameters is rejected and go to EXPLOIT phase.</td><td>Reject the set of parameters whose solutions doesn't converge.
Increase NIt while maintaining or decreasing NPop.</td><td>Reject the set of parameters whose solutions doesn't converge.

<u>Optional action:</u>
Decrease NIt and NPop.</td></tr>
</table>

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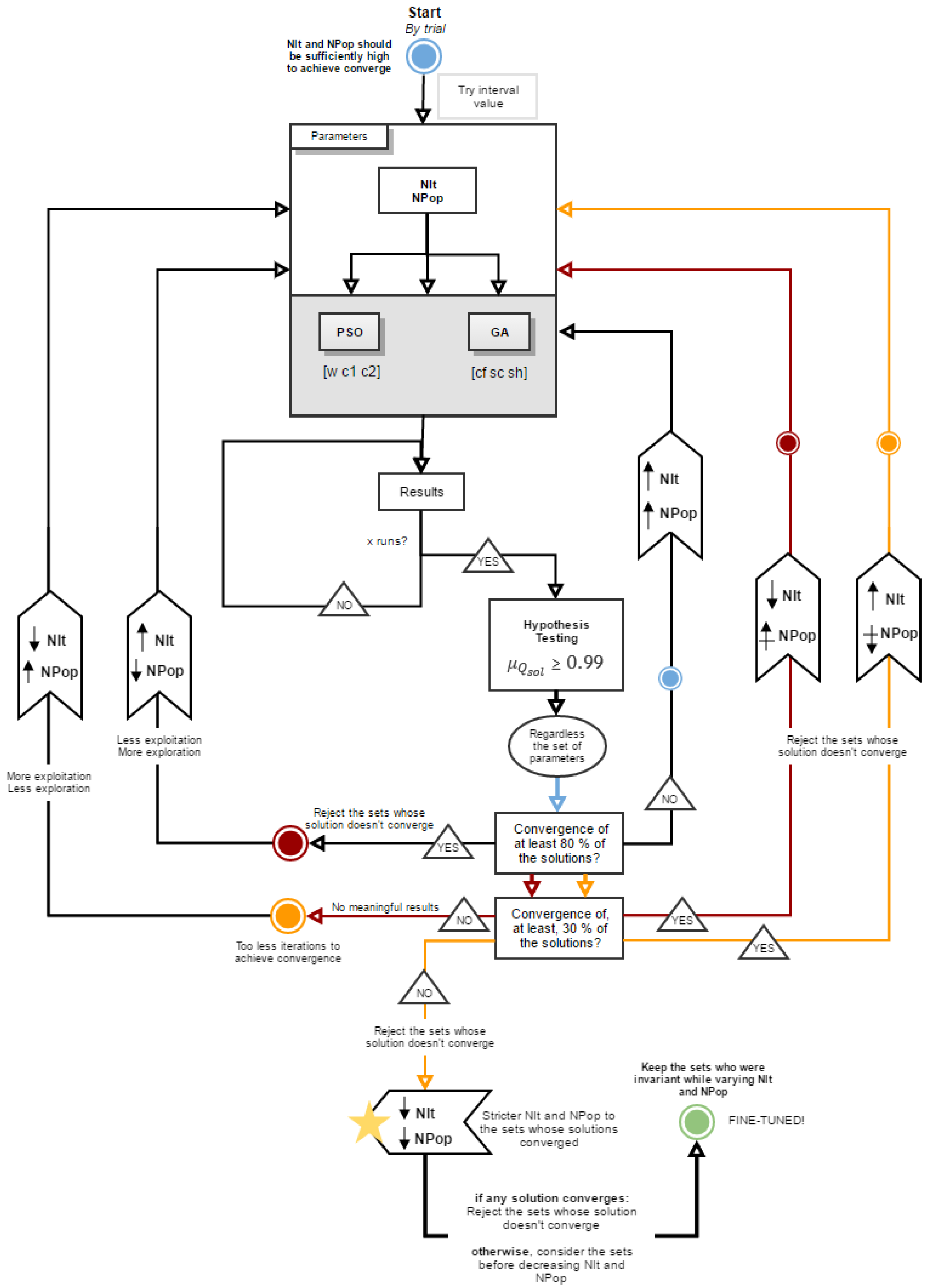

Figure 9 - User guide: Methodology for fine-tuning the algorithms.

After fine-tuning metaheuristics by following methodology of Figure 9, comes the third stage of EE assessment. During this stage new design variables were variable, and new/modified

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cost functions resulting in new scenarios. Here is given one example. Either the Eco-efficiency indicators and the design variables are in Table 6.

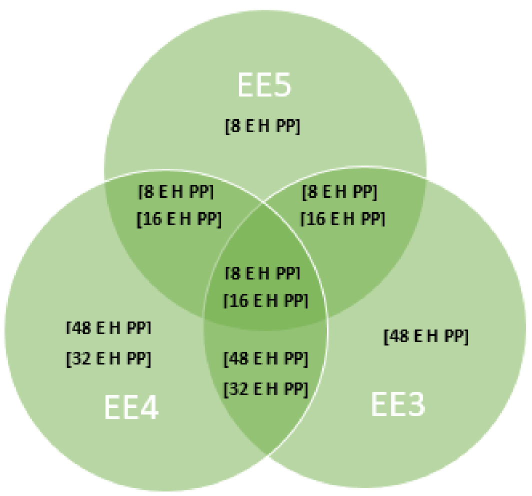
Table 6 – Scenario of a MOP with 3 Eco-efficiency (EE) indicators and 4 design variables.

Design Variables	**Cavities** {4, 8, 16, 32, 48, 64}	**Type of Machine** {H (Hydraulic), E (electric)}	**Runners** {H (Hot), C (Cold)}	**Material** {PP, PBT}
Cost Functions	$\mathbf{EE5} = \frac{Mould's\ profit}{Mould\ LCA}$	$\mathbf{EE3} = \frac{Part's\ profit}{Energy\ consumption\ in\ injection\ process}$	$\mathbf{EE4} = \frac{Part's\ profit}{Material\ consumption\ in\ injection\ process}$	

Solutions	**EE5**	**EE3**	**EE4**	***MACRO EE / MACRO EE NORMALIZED***		**EE5**	**EE3**	**EE4**	***MACRO EE / MACRO EE NORMALIZED***
[4 E H PP]	1	0.429	0.679	*0.703 / 0.93*	**[16 E C PP]**	0.271	0.852	0.984	*0.702 / 0.93*
GA	6/30	PSO	3/30		GA	0	PSO	6/30	
[4 E C PP]	0.598	0.627	0.867	*0.697 / 0.92*	**[32 E H PP]**	0.327	0.919	0.974	*0.740 / 0.98*
GA	1/10	PSO	0		GA	2/30	PSO	0	
[4 H H PP]	0.969	0.321	0.666	*0.652 / 0.86*	**[32 E C PP]**	0.212	0.773	1	*0.662 / 0.88*
GA	3/30	PSO	0		GA	6/30	PSO	0	
[8 E H PP]	0.633	0.700	0.833	*0.722 / 0.96*	**[48 E H PP]**	0.295	1	0.971	*0.755 / 1*
GA	3/30	PSO	6/30		GA	3/30	PSO	0	
[16 E H PP]	0.429	0.847	0.930	*0.734 / 0.97*	**[48 E C PP]**	0.192	0.719	0.987	*0.633 / 0.84*
GA	0	PSO	12/30		GA	6/30	PSO	3/30	

There is an extensive list of solutions because there are three EE indicators as objective functions. However, there was defined the MACRO EE normalized criteria that selects solutions that have a MACRO EE normalized ⩾ 0.95 (the MACRO EE is computed through equation 4). Those solutions are outlined in green and are the preferred solutions of this list. Additionally, for a more practical interpretation, those solutions are allocated in the most applicable areas of the figure 3 regarding the highest EE indicator weighting, and follows its interpretation in the side table.

$$MACRO\ EE = \frac{EE3 + EE4 + EE5}{3} \tag{4}$$



Prize			**Solution Arrangement**
1 EE	**2 EE**	**3 EE**	Best solutions: Upwards *Example:* Valuing EE4 and EE5, [8 E H PP] is preferable to [16 E H PP].

Figure 10 - Optimal solutions according to MACRO EE normalized criteria.

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For the energy consumption modelling, the ANN has to be fine-tuned. Giving empirical data for the learning process, some parameters were changed and combined towards minimizing the Mean Squared Error (MSE) performance function. The MSE is the average squared difference between outputs and targets.

After fine-tuning the parameters, another experiments were undertaken in order to find out which input variables were the most meaningful for creating the model. The input variables were ranked with K nearest neighbour algorithm which stores all available cases and predict the numerical target based on a similarity measure (e.g. distance functions). The variables are presented in Table **6** – Scenario of a MOP with 3 Eco-efficiency (EE) indicators and 4 design variables.Table 7 along with their ranking.

Table 7 – Entries of ANN for learning process and inputs rankings.

Inputs	Installed Power (1)	Total Mass (2)	Cycle Time (3)	Material (4)
Output	Experimental Power			

The results were evaluated with regression R values measuring the correlation between outputs and targets – An R value of 1, means a close relationship; and 0, means a random relationship. The results of considering the 4 inputs (w/ material) and 3 inputs (w/o material) are shown in Figure 11. When meaning "All", the group comprises the data of training, validation and test sets.

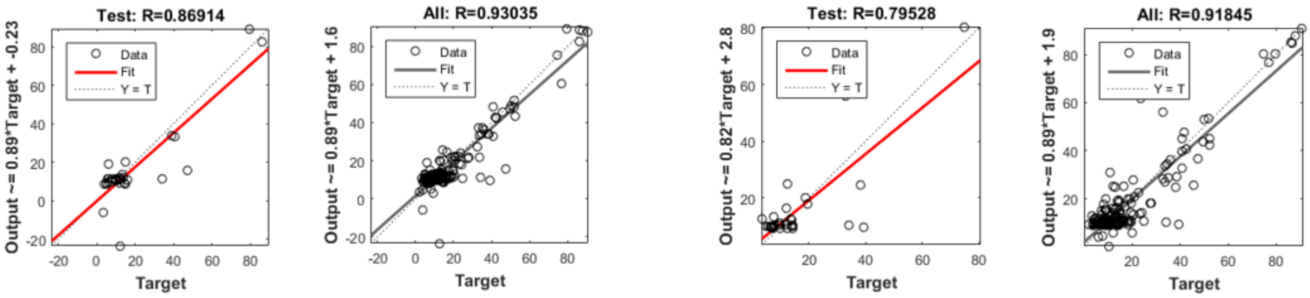

Figure 11 - Correlation between outputs and targets (w/ material, left); (w/o material, right).

The R values are high, which means that ANN are a reliable approach for energy consumption modelling. Although the model with material is more accurate, the model created for forecasting energy consumption with only 3 inputs shall not be misprized, especially when there isn't information about the material that is to be injected.

4.4 Conclusions

Concerning problem 1 of Figure 8, the application of metaheuristics resulted in good solutions with high Eco-efficiency ratios. Therefore, the methodology proposed for fine-tuning the algorithms worked, as the algorithms could be reliable and could provide quality solutions. With no need to analyse all design combinations, the algorithms could provide many useful and propitious solutions for decision making.

The fact of applying both algorithms was advantageous as they provided coherent and complementary solutions with high Eco-efficiency ratios, offering the user a good span of

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possibilities. The solutions were also accompanied by their cost values which help the designer to know the weights that are being attributed to each cost function.

Aiming to explore metaheuristics for other applications requires the passage of a fine-tuning process - the methodology was proposed in a user guide form (Table 5 and Figure 9). However, this methodology restricts the usage of population-based metaheuristics as it is based on NPop variations, a parameter that is only present in this type of metaheuristics. Besides GA and PSO, other algorithms can be used but it requires the study of their specific parameters towards fine-tuning them.

The ANN application resulted in an accurate model for energy consumption. Additionally, to rank the inputs importance is particularly useful when there is some missing data, which is supposedly needed to create the model. In the end, either the model with 3 or 4 inputs was good to estimate the energy consumption.

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5 Implications to Total Efficiency Framework

The main concept of the MAESTRI project consists in the development of a flexible and holistic integrated Framework to foster manufacturing sustainability in process industry, the "Total Efficiency Framework". The overall aim of this framework is to promote improvement culture within process industries by assisting decision-making process, supporting the development of improvement strategies and helping on the definition of priorities to improve the company's environmental and economic performance. For this purpose, the Total Efficiency Framework is based on four main pillars to overcome the current barriers and promote sustainable improvements, namely:

- **Management system** – to support the incorporation of sustainable strategies and goals targeted for continuous improvement;
- **Efficiency Framework** – composed by above explained efficiency and eco-efficiency assessment and simulation tools, targeted to support decision making process;
- **Industrial Symbiosis** – focusing on material and energy exchange;
- **Iot Platform** – to simplify the concept implementation and ensure an integrated control of improvement process.

The interactions and implications of the above explained tools to the other three pillars of the Total Efficiency Framework are discussed on next sections.

5.1 Management system

Within the Total Efficiency Framework, the management system is focused on the incorporation of sustainability aspects in company strategy and objectives. For that purpose, it embraces management tools encompassing LEAN strategies related to sustainable continuous improvements (i.e. targeting environmental, social and economic issues). In fact, as already described in deliverable 2.2[13], there are several similarities between both pillars of Total Efficiency Framework (namely between the Management System and the Efficiency Framework). This deliverable describes in detail the interactions occurring between the different background concepts used during the development of MAESTRI tools.

The core of the management system concept was formulated in the form of five lean thinking principles (Womack and Jones, 2003):

1. Precisely specify value for specific product/service;
2. Identify the value stream for each product/service;
3. Make value flow without interruptions;
4. Let the customer pull value;
5. Pursue perfection.

Lean Management is an effective way to organize operations paying attention to: leader standard work, (ii) visual controls, (iii) daily accountability process and (iv) leadership discipline.

Within the management system pillar 3 main connections with tools from Efficiency Framework have been identified:

[13] MAESTRI project Deliverable 2.2 - Methods for Efficiency Framework for resource and energy efficiency description

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1. Eco Orbit View – connected with MSM© (plant level analysis);
2. Application of low cost improvement methods – connected with MSM© and ecoPROSYS© results;
3. Identification of high intensity process parameters – connected with Eco-efficiency Performance Assessment (also including significant environmental aspects).

Multi-layer Stream Mapping, as mentioned above is based on Value Stream Mapping, is used to identify clear definition of waste and value dichotomy. Resources are treated as variables and enable to determine processes to improvement thereby achieving data for Eco Orbit View. Therefore, as a result, Eco Orbit View presents KPIs (reflecting company needs) and supports the definition of strategies related to the implementation of identified improvements. Actually, more than a factual relation, the information arising from their implementation is clearly complementary, aiming to characterise a production system from different perspectives. In this respect, Eco Orbit View is a very powerful self-assessment tool which allows companies to understand their main problems, and to define strategies to assure that they are properly managed. Data provided by MSM© or ecoPROSYS© may also be used in order to support decision making process related to application of low cost improvement methods.

Environmental Performance Assessment (ecoPROSYS©) enables to delimit scope, collect significant data and deliver KEPI for Environmental Profile for the Identification of significant environmental aspects. Environmental aspects which ecoPROSYS© is focused on are materials and raw materials, water, energy, residues, emissions, products, co-products. Moreover, ecoPROSYS© provides standard accounting system, production factors, functional features and cost factors.

In complement, the Efficiency Framework is able to provide a more comprehensive analysis regarding the most complex details of production systems. This is particular important considering the relation and dependencies between the different process flows, which are not always easy to understand.

In addition, they both use the same metrics to presents results. They are based on the selection of most suitable performance indicators regarding the scope of the intended assessment. From this results also one other complementarity related to the measure of production system progress. From previous section, it becomes clear that the Efficiency Framework can support the management system implementation, by providing a concrete structure to support the production system evolution over time.

5.2 Industrial Symbiosis

To effectively support the implementation of Industrial Symbiosis (IS) in manufacturing and process industry, MAESTRI project includes the development of a library of case studies, containing examples of IS implementation, and a toolkit (T4IS), which is based on four guiding questions:

- How to see waste?
- How to characterise waste?
- How to value waste?
- How to exploit waste?

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Considering results arising from the implementation of the Efficiency Framework, a clear set of information may be used to address these guiding questions in a more detailed perspective. This is particularly relevant due to the possibility of quantification of waste materials and energy in the production system during process mapping, as well as the expected impact of industrial symbiosis practices/actions implementation. Then, the interaction between Efficiency Framework tools and Industrial Symbiosis toolkit is clearly a complementary and iterative process. This means that decision support results from a simultaneous and, sometimes, cyclic use of the different tools which provide complementary outcomes, up to obtain necessary information for the target decision-making process.

As a clear starting point, the production system mapping provides the identification of all residues and wastes occurring in each unit process of the production system. This provides a clear understanding of what type of residues and wastes are generated in the processes and a comprehensive list of potential target resources to take into consideration during the definition of improvement opportunities. In addition, apart from this identification, the process mapping also provides the characterisation (by using European Waste Catalogue), current quantities of these residues and wastes (per unit process), as well as their costs considering the current disposal or treatment scenarios.

Complementarily, during the EEPA feature of ecoPROSYS©, each process parameter is assessed in terms of eco-efficiency intensity and environmental significance. It basically represents an evaluation of each parameter considering the view of the company and the way they understand the production system. This results on the identification of residues and wastes with high environmental significance and high intensity to each eco-efficiency principle, representing participant's main concerns.

Both of these outcomes are clearly useful as an input to T4IS, in particular to scope the identification of current practices, capabilities and challenges regarding production system residues and wastes. This would be beneficial to guide discussions on "how to see waste".

In a more comprehensive perspective, several other information can be also retrieved from the Efficiency Framework features. This is the case of residues and wastes environmental characterisation resulting from Life Cycle Assessment. From this specific module of ecoPROSYS©, a detailed characterisation of each unit process parameter is made in terms of impact and damage to the environment. Participants can also use this information to assess and evaluate the influence of each residue and waste to the production system environmental performance. Likewise, similar results are provided considering an economic perspective using the Process Based Cost Modelling module also from ecoPROSYS©. As a result, this module provides information on how each unit process parameter is contributing to overall costs of the production system. In addition, using the results aggregation feature, participants can understand how each unit process parameter is contributing to the economic value of the production system. This may be particularly important for residues and wastes considered as not significant during the EEPA, which may have severe environmental impacts or economic costs that were not considered during this assessment.

In addition, the Efficiency Framework can be used to understand what is the contribution of each residue and waste to the production system's efficiency and eco-efficiency performance. In this respect, considering that residues and wastes are clearly related to a loss of material or energy, i.e. an increment of non-value added activities, unit processes with lower

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efficiency or eco-efficiency tend to present higher rates of wastes and residues generation. Therefore, despite not meaning that these processes are easier to improve, it definitely means that they have higher improvement potentials. They can be considered a key target for identifying improvement opportunities. Moreover, considering the efficiency assessment, it is possible to allocate to each unit process the amount of waste and quantify it, such information could be used to preliminary "evaluate" IS potential.

The approach to be considered for this type of circumstances will be clearly to focus on a reduction of related non-value added activities, i.e. to reduce the generation of residues and wastes. However, the fully elimination of residues and waste may not be possible in all cases or it may imply the definition of improvement actions leading to substantial economic investments or technological shifts that may not be in line with company's targets and goals. Industrial Symbiosis represents a distinct complementary approach which allows the creation/capture of value related to the inevitable generation of these residues and wastes. In this respect, T4IS aims to support the identification and implementation of this Industrial Symbiosis opportunities.

The complementarity between information resulting from the Efficiency Framework and the T4IS is then evident, and may be implemented considering different ways and perspectives. Apart from the above mentioned information being closely related to "how to characterise waste" guiding question of T4IS, it may represent a trigger/catalyst for Industrial Symbiosis implementation which, in its absolute concept, aims to increase resource and energy efficiency in overall terms. As stated by Ehrenfeld and Gertler (1997): "Industrial Symbiosis is closely related to closed-loop material and energy use and involves the creation of linkages between firms to raise the efficiency, measured at the scale of the system as a whole, of material and energy flows through the entire cluster of processes".

Within this perspective, it is clear that both, the Efficiency Framework and Industrial Symbiosis, share the same goals and, in order to achieve higher efficient and valuable production systems, interactions between the developed tools should be explored as far as possible at several implementation levels. This means that, apart from using the information resulting directly from the Efficiency Framework implementation, Industrial Symbiosis tools should be also complementarily used by Efficiency Framework features. This is particular important considering the potential of Industrial Symbiosis tools of providing solutions to specific problems occurring in the production system, namely, on the identification of improvement opportunities. The Library of Case Studies, aiming to compile information on examples of Industrial Symbiosis implementation, is a good example of this potential. In practice, by using this tool, the participants are able to access and understand the approaches followed by other companies to the same, or similar, types of residues and wastes they are assessing. This represents a considerable reduction of the necessary effort to find potential solutions and deploy value creation/capture in a lost cost and time efficient way. Therefore, companies can extract improvement ideas from the library of case studies, which can be later assessed through the use of the Efficiency Framework tools. Concretely, companies could develop solutions around these improvement ideas, which would be later evaluated using their own feasibility / viability tools or other MAESTRI tools either from WP2 or WP4.

Then, exploiting the complementarity between the tools, participants can also use the Efficiency Framework, in particular its simulation module, to assess the identified/selected

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solutions. This module aims to present the expected impacts of these solutions, in terms of production system efficiency, environmental, cost and economic value performance, by generating alternative scenarios. Moreover, the solutions can be assessed in both joint or standalone perspective, which could help participants on the definition of priorities by selecting those, for instance, with higher economic value generation, higher increase of efficiency or representing a higher reduction of costs or environmental influence.

This simulation functionality gives the opportunity to choose the most profitable solution among several potential improvement options, which were identified using, both or either, the T4IS and the Efficiency Framework. This is complementary to the last two guiding questions of the T4IS, as it could support the selection/definition of actions to generate more value ("how to value waste?") and to understand what critical mass would be needed to make it successfully ("how to exploit waste?"). Both the simulation module and the T4IS will bring additional information to companies regarding the improvement / symbiotic opportunities, in order to allow them to make better decisions related to their residues and wastes. As a consequence, and targeting the overall aims of the different tools, participants are able to take more informed decisions, by understanding not only their specific requirements but also by knowing in advance their potential consequences.

As a simplification of the above mentioned interactions and information flows occurring between the different tools, next figure presents how this complementarity can be achieved.

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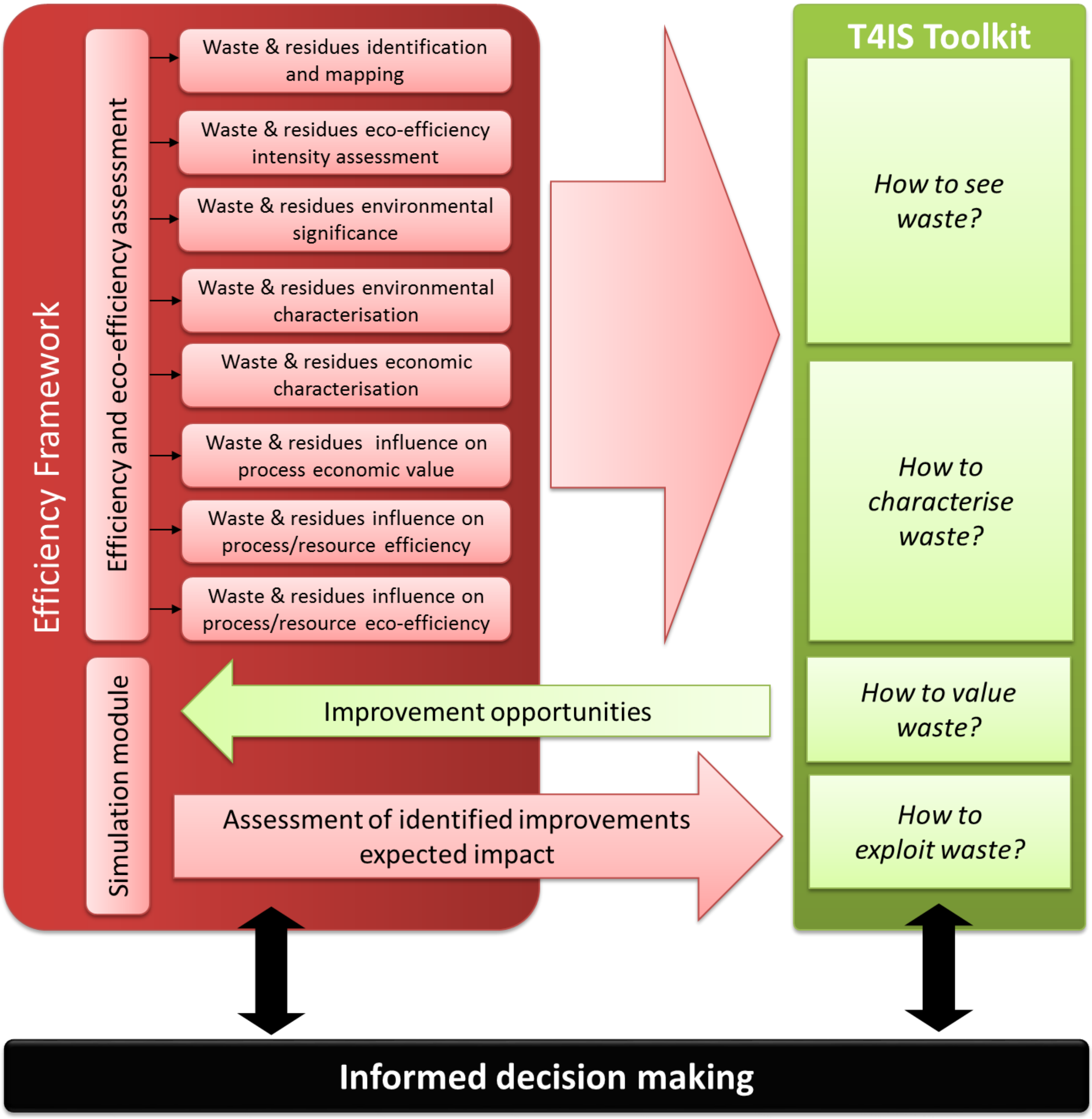

Figure 12 - Interactions and information flows between Efficiency Framework and Industrial Symbiosis tools.

5.3 IoT platform

The relationship between the Efficiency Framework and IoT platform is mainly related to enable an effective control of production systems efficiency and eco-efficiency by providing data and information in a systematic way. In fact, data collection is of utmost importance since the quality of the input data influences considerably the final results and conclusions. In addition, industrial production systems are usually complex. This means that to assess both efficiency and eco-efficiency properly, a large volume of data regarding input and output flows quantification is expected to be needed. As mentioned, the more detailed process mapping,

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greater will be the advantage taken from the Efficiency Framework and more comprehensible will be the results.

Therefore, in terms of interaction the Efficiency Framework will be mainly a data consumer from the point of view of the IoT Platform. However, special attention should be given to the implementation and parametrization of IoT Platform in terms of data requirements. In this respect, companies should start by identifying concretely the type of data requirements taking into account the objectives and goals of the assessment.

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6 Final remarks

Within the MAESTRI Project, WP2 copes with the development of the Efficiency Framework, which encompasses several modules. Included in the Efficiency Framework development, Task 2.3 aims to the development of a specific module to allow the simulation of production systems different set-ups and alternative scenarios, regarding its eco-efficiency (environmental influence in relation to economic performance), its resource and energy efficiency, and its overall efficiency.

The biggest advantage of the Efficiency Framework is to provide the ability of analysis and simulation of production systems from efficiency and eco-efficiency perspectives. It is from this ability that actually results the support to the decision making. In this respect it has been proved that both efficiency and eco-efficiency concepts should be considered simultaneously to ensure a comprehensive assessment of a production system. This is done by allowing the assessment participants to understand the dependencies occurring between the different input and out flows, from the different unit process composing the production system, as well as from these flows with the three main analytical dimensions (efficiency, value creation and environmental influence), i.e. how each flow is influencing these dimensions.

However, the vast majority of industrial production systems have a considerable complexity. This means that to improve them from an optimal perspective is most of times a difficult task. For that reason, different optimization models were tested to provide a clear background regarding the best suitable algorithms to perform optimization simulations for materials and energy consumption, via overall efficiency and cost-saving targets. Considering the successful results achieved regarding the application of metaheuristics, a methodology for its implementation is proposed, in a user guide form.

All in all, within a holistic perspective, the Efficiency Framework main goal is to influence the inclusion of the concept of effectiveness alongside the concept of efficiency, allowing the implementation of strategies conducting to effective, efficient and eco-efficient production systems. However, it just provides assessment and simulation perspectives on efficiency and eco-efficiency. This means that its integration with the other Total Efficiency Framework pillars should be exploited during its application. For this, tools being able to provide solutions are particularly relevant, as both the Management System or Industrial Symbiosis tools. It was proved that the Efficiency Framework can also support their implementation, by providing a concrete structure to support follow-ups of the production system evolution over time. In addition, the IoT platform also substantially increases its applicability, providing better and more accurate outcomes, as well as it reduces the complexity of its use.

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