Resources Value Mapping: a method to assess the resource efficiency of manufacturing systems

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Abstract

The assessment and monitoring of energy and resource efficiency is an essential activity toward the implementation of sustainable manufacturing practices. Existing energy/resource assessment methods and tools are not based on a comprehensive approach, lack on the use of specific key performance indicators, are dedicated to expert stakeholders and do not provide useful suggestions for improving production systems. This paper proposes an innovative method, called *Resources Value Mapping* that aims to map and classify activities and related energy/resource consumptions according to lean philosophy principles (value-added, non value-added, waste). A user-friendly map and two efficiency indicators (*Cost Index* and *Muda Index*) are proposed to quantitatively support the identification of criticalities related to activities, processes, lines, plants, etc., and to successively guide the decision-making process during the improvement strategies implementation. The method has been used to analyze a manufacturing plant that produces cooking appliances. The case study demonstrated the applicability of the method in real industrial contexts and its effectiveness in identifying the energy/resource flows (electricity and compressed air), departments (sheet department) and lines (mechanical and hydraulic presses) for which the waste and non value-added consumptions are prominent. The analysis highlighted that less of 20% of the resources consumed during the process creates value, offering wide margins for improvement. Finally, it aided the definition of an action plan leading to relevant reduction of resource consumptions, economic savings and environmental benefits.

Keywords

Sustainable manufacturing

Lean manufacturing

Resources Value Mapping

Energy efficiency

Key performance indicators

Highlights

- A method for mapping energy/resource flows of manufacturing systems is proposed
- Key performance indicators highlighting the inefficiencies are developed
- The method allows defining corrective actions to improve production efficiency
- Case study results show a significant saving of energy and resources

Nomenclature

AD	assembly department
BAT	Best Available Techniques
C_{comp_air}	compressed air consumption $\left[\frac{m^3}{pc}\right]$
$c_{hydraulic}$	hydraulic capacity of the analyzed machine $[l]$
c_i	unitary cost of the resource i
CI	Cost Index
$c_{machine}$	average compressed air consumption of the analyzed machine $\left[\frac{m^3}{pc}\right]$
C_{oil}	oil consumption $\left[\frac{l}{pc}\right]$
$C_{w,comp\_air}$	waste compressed air consumption $\left[\frac{m^3}{pc}\right]$
C_{water}	water consumption $\left[\frac{m^3}{pc}\right]$
$c_{water,heat}$	nominal water consumption of the heat exchanger at the operating temperature $\left[\frac{l}{h}\right]$
EFA	Energy Flow Accounting
EVSM	Energy Value Stream Mapping
GD	glazing department
IDEF	Integration DEFinition
KPI	Key Performance Indicator
L1	Line 1
L2	Line 2
L3	Line 3
L4	Line 4
LCA	Life Cycle Assessment
MEFA	Material and Energy Flow Analysis
MFA	Material Flow Analysis
MFN	Material Flow Network
MI	Muda Index
$n_{operations}$	average number of operations for a piece
n_{pieces}	pieces produced in one hour $\left[\frac{pc}{h}\right]$
NVA	non value-added
p	operating pressure [Pa]
p_{drops}	total pressure drops [Pa]
R_{NVAi}	amount of resource i consumed by NVA activities
r_{NVAij}	hourly consumption per piece of resource i by the NVA activity j
R_{VAi}	amount of resource i consumed by VA activities
r_{VAij}	hourly consumption per piece of resource i by the VA activity j
R_{Wi}	amount of resource i consumed by W activities
r_{Wij}	hourly consumption per piece of resource i by the W activity j
SD	sheet department
SER	Specific Energy Ratio
Sus-VSM	Sustainable VSM
TBS	technical building systems
t_{NVAij}	duration of the NVA activity j consuming the resource i
t_{VAij}	duration of the VA activity j consuming the resource i

$t_{\text{viscous properties}}$	time necessary to maintain the oil viscous properties' unaltered $[h]$
t_{Wij}	duration of the W activity j consuming the resource i
UML	Unified Modeling Language
VA	value-added
VSM	Value Stream Mapping
W	waste
η_{NVAi}	yield related to the resource i consumed by NVA activities
η_{VAi}	yield related to the resource i consumed by VA activities
η_{Wi}	yield related to the resource i consumed by W activities

1 Introduction

The continuous growing of the global world population and the improvement of the overall economic conditions are causing a sensible increase of energy and resource consumption, both at domestic and industrial levels. Specifically, the industrial manufacturing is largely considered a critical sector, with its relevant consumption of primary energy (more than 30% of the total) [1] and emission of greenhouse gases (about 36% of the total) [2]. This situation, together with the rapid depletion of non-renewable resources and the increasing consciousness on environmental problems (e.g., pollution, waste), is forcing industries to pursue sustainability and energy efficiency [3].

In this context, the 2030 Agenda for Sustainable Development defined Sustainable Production as one of the seventeen goals to build a better world for all people [4]. In industry, a sustainable production means creating goods "*by using processes and systems that are non-polluting, that conserve energy and natural resources in economically viable, safe and healthy ways for employees, communities, and consumers and which are socially and creatively rewarding for all stakeholders for the short- and long-term future*" [5]. In addition, National and International governments are issuing more stringent regulations and action plans (e.g., 2020 Climate and Energy Package, European Roadmap to a Resource Efficiency, Circular Economy Package) to promote energy and resource efficient technologies, favor the generation and consumption of renewable energy and limit pollutant emissions [6]. As a consequence, industrial companies must implement sustainable manufacturing approaches to improve the design, management and operation of manufacturing plants, considering energy efficiency, resource consumption, and sustainability issues [7].

Given the importance of the topic, during last years the scientific community is focusing the attention on the development of methods and tools related to technology selection, process monitoring, energy benchmarking, energy consumption simulation, energy and resource saving measures, etc. [8]. Indeed, pursuing energy and resource efficiency in a manufacturing industry does not involve a single department (e.g., production office) or a single manufacturing process (e.g., sheet metal stamping), but requires the assessment of the whole production plant through a multidisciplinary approach (i.e., involving several departments and expertise) [9]. According to literature, tools and methods to support energy/resource-related analyses can be classified into four main groups [10]: (i) modelling and analysis [11], (ii) emission calculation and sustainability assessment (e.g., Life Cycle Assessment [12], Carbon footprint [13]), (iii) energy/resource assessment, and (iv) benchmarking (e.g., Energy benchmarking [14], Energy performance indicator [15]). Such methods are able to effectively describe complex energy and resource flows within a production system [16], including life-cycle environmental performance [17]. However, they have been developed for specific applications and for occasional use, cannot be used for short-term decisions and do not generally allow real-time analysis of manufacturing processes [18].

The present study focuses on the third group (i.e., energy/resource assessment methods and tools) by proposing an innovative method, called *Resources Value Mapping*, for the analysis and optimization of manufacturing processes aimed at the optimal use of energy and resources. It tries to bridge the gap between research and implementation by supporting both the evaluation of resource efficiency and the definition of corrective strategies in a structured and effective manner. Firstly, the method foresees the energy and resource consumption assessment at different levels of detail, through a hierarchical approach. Secondly, it supports the categorization of activities in value-added, non value-added and waste, according to the lean philosophy principles. Thirdly, it provides a user-friendly map and several key performance indicators to easily and rapidly visualize how and where energy and resources are efficiently used or wasted. Finally, it suggests a set of corrective actions to solve or at least mitigate the identified issues, with the aim to reduce the environmental and economic impact of resource usage. The final goal is to propose a comprehensive method able to provide an overview of the whole plant and guide the decision-making process toward the implementation of sustainable manufacturing principles.

The rest of the paper is organized as follows. Section 2 provides a critical analysis of the most relevant scientific literature on energy/resource assessment methods and tools. Section 3 describes in detail the five steps of the proposed method. Section 4 shows how the method can be implemented in a real industrial context (i.e. household appliances manufacturing plant). Finally, Section 5 discusses the obtained results and presents conclusions, strengths, limitations and proposals for future work.

2 Energy/resource efficiency of manufacturing systems

In recent years, several methods and tools have been developed to evaluate the energy and resource efficiency of a manufacturing system. They aim to improve the stakeholders' awareness and extend the analysis boundaries to multiple aspects of production (e.g., technologies, raw materials, energy flows, time) [19].

In the 1980s, the Material and Energy Flow Analysis (MEFA) method was introduced to investigate the deployment of raw materials, resources and energy in a production process. It deals with environmental and economic problems from a new perspective based on energy and mass balances, with the aim to assess the influence of human activities over the environment [9]. An example is the study of Sendra et al. [20], who proposed a method based on the material and energy flows modelling. Studying the input/output relationships of manufacturing processes, they provided a structured approach to identify "energetic hotspots" in a factory. A similar method, proposed by Smith and Ball [21], focuses on the development of a qualitative factory model based on material, energy, and waste flows. It allows identifying the areas with the highest energy/resource consumption and analyzing the local or even system-wide improvement opportunities. Other variants of MEFA, such as the material flow network (MFN) [22], the material flow analysis (MFA) [23] and the energy flow accounting (EFA) [24] focus only on material or energy flows. Such methods allow visualizing and optimizing material flows and waste streams of production processes [25], with low effort in terms of time and costs. The main drawbacks of these methods are the lack of time information and the incompleteness of the evaluation models that do not generally consider auxiliary equipment. Moreover, they do not provide further guidance on how to derive and implement improvement measures.

Kluczek [26] combined MEFA with the best available techniques (BAT). This approach, based on the Integrated Pollution Prevention and Control Directive (2008/1/EC) by the European Commission, identifies the energy and material flows, supports the selection of the best technology to improve environmental sustainability and energy efficiency, and enables a significant reduction of the required energy. Although the combination of flow analysis and technology research fills the gap between analysis and improvements, this method excludes the dynamic nature and temporal dimension of manufacturing processes.

Other authors developed methods and tools based on the lean methodology and inner logic of Value Stream Mapping (VSM). According to the US Environmental Protection Agency, Muller et al. [27] presented the Energy Value Stream Mapping (EVSM), a tool that, in addition to the cycle time, correlates energy consumption with value-added and non value-added activities. The experimentation on a chip removal process only considered value adding and non-value adding energy, neglecting energy waste. In addition, auxiliary systems are not considered and no suggestions to improve energy efficiency are provided. To solve some of these issues, Posselt et al. [28] presented an expanded EVSM approach able to investigate indirect energy demands upon specific entities of the value stream, focusing on technical building systems (TBS).

Extended methods that include the analysis of resources consumed by a production process (e.g., energy and material stream mapping [29]) or more generally focused on the measurement of process sustainability were also proposed. The latter include the Environmental Value Stream Mapping (E-VSM) [30] and the Green Value Stream Mapping (G-VSM) [31] that broaden the concept of value stream, looking at it from the environmental perspective. Another example is the Sustainable VSM (Sus-VSM) [32] that introduces new metrics for the environmental impact assessment and to simultaneously represent the cycle time and consumption of water, raw materials and energy throughout the manufacturing process. Further developments were carried out with the Economic and Environmental value stream map (E^2VSM) [33] that combines the life cycle environmental input analysis with the total cost and energy consumption analysis.

Thiede et al. [34] presented an approach that combines VSM with MEFA to provide an assessment of the most critical issues in a production process through the use of specific indicators (e.g., energy per part, raw material per part, longest lead time) and a Sankey diagram for visualization.

Although such methods potentially represent an effective way to achieve significant results and highlight inefficiencies, they provide a static image of a limited range of products [35] and are not able to handle the general dynamics and uncertainties occurring in industrial practice, which hinder real-time or frequent assessments and, consequently, the continuous improvement of energy performance.

Methods and tools for advanced management of industrial processes were also developed, but they only focus on energy carriers and do not consider the material and resource flows. For example, the works proposed by

Kara et al. [36] and Vikhorev et al. [37] consider only the electrical energy consumption of machine tools, neglecting the TBS. Perroni et al. [38] developed a method to continuously measure energy performance through a framework, a map of indicators, and a longitudinal input-output process model. Hopf and Müller [39] developed the "Energy Cards" tool that allows a complete assessment of factory systems (i.e., the entire production, the TBS and the supply system), but does not support the identification of those production lines and/or machines with low energy efficiency. Wang et al. [40] presented a real-time energy efficiency assessment tool based on the computation of specific energy-related key performance indicators (KPIs). Although such tools allow offline and real-time assessments of the energy consumption of a manufacturing system, they require advanced knowledge and can be only used by expert operators (e.g. energy and facility managers).

Summarizing, existing methods and tools for energy/resource assessment were classified according to specific criteria in order to highlight current limits and research challenges. The selected criteria consider both technical issues in the context of energy management in manufacturing (e.g., implementation strategy [8], analysis objectives [35], best-practices [41]) and barriers to the adoption of energy-efficiency measures in different contexts (e.g., SMEs [42], high energy-consuming industries [43]). Table 1 summarizes the main requirements used for the evaluation, while Table 2 presents the comparison among the existing methods.

Table 1. Criteria for the evaluation of energy/resource assessment methods and tools

	Input data	**Completeness of flows**	**Completeness of systems**	**Type of assessments**	**KPI**	**Improvements**	**Usability**
-	Huge amount of data difficulty to collect	Energy assessment	Production processes evaluation	Offline analysis	No KPI	None	Significant investment in training and learning time
○	Huge amount of available data	Energy and resources assessment	Assessment of the factory systems (without TBS)	Real-time analysis	KPIs related to consumption	Highlighting of critical issues	Minimal training for experts
●	Few and available data	Energy and resources evaluation and their correlation with production data	Complete assessment of the factory systems	Offline and real-time analysis	KPIs related to multiple topics	Corrective measures suggestion	Minimal training for all stakeholders

Source: Authors.

Table 2. Evaluation of energy/resource assessment methods and tools based on the identified criteria

	Input data	**Completeness of flows**	**Completeness of systems**	**Type of assessments**	**KPI**	**Improvements**	**Usability**
Alvandi et al. [33]	●	○	-	-	-	○	●
Darmawan et al. [31]	●	○	-	-	-	○	●
Faulkner and Badurdeen [32]	●	○	-	-	-	○	●
Herrmann et al. [22]	○	-	○	-	-	-	●
Hopf and Müller [39]	●	-	●	●	○	-	○
Kara et al. [36]	○	-	○	○	○	○	-
Kluczek [26]	●	○	-	-	-	○	●

Müller et al. [27]	●	-	-	-	-	○	●
Perroni et al. [38]	○	○	○	-	●	○	-
Plehn et al. [30]	●	○	-	-	-	○	●
Posselt et al. [28]	●	-	●	-	-	○	○
Schmidt et al. [29]	●	○	-	-	-	○	●
Sendra et al. [20]	○	○	○	-	-	-	●
Smith and Ball [21]	○	○	○	-	-	○	○
Thiede et al. [34]	○	○	○	-	●	-	○
Torres et al. [24]	○	-	○	-	-	-	●
Vikhorev et al. [37]	○	-	○	○	○	○	-
Wang et al. [40]	●	-	●	●	●	○	-
Wohlgemuth et al. [23]	○	-	○	-	-	-	●

Source: Authors' compilation based on referenced studies as listed above.

The results of the review (Table 2) highlight that none of the analyzed methods and tools completely fulfil the identified criteria and meet the needs of industrial companies in the area of energy management in production. In detail, most of them focus on quantitative analyses of consumptions (often only energy) with the aim to increase (energy) awareness rather than on the efficiency analysis. The attention is mainly placed upon the evaluation and visualization of energy consumption information, while research on how to examine and use real-time energy data to provide chances for enhancing efficiency is insufficient. A framework that examines the production process in a holistic and multi-resource way is still lacking. The methods are usually specific for a given manufacturing sector and often consider only production systems.

Moreover, it emerged that existing methods and tools do not provide appropriate indices and/or KPIs to analyze the energy use profiles of machines and processes. The limited use of specific KPIs does not enable the identification of the less efficient operations and/or departments and the practical solutions to improve the manufacturing process performance. Additionally, only few KPIs are suitable at the process and plant levels and standardized indicators are missing.

Further shortcomings concern the complete representation of the factory system (i.e., the flows completeness and the TBS evaluation) and the real-time analysis of the production process.

To address the above-mentioned limitations, this paper proposes a comprehensive method to visualize and assess manufacturing process flows and extract meaningful insights from data to improve resource efficiency. In particular, the main novelties of the Resources Value Mapping method are the following:

- Allocation, representation and analysis of resources consumption according to their contribution to value generation. The final aim is to provide a useful means to minimize waste and improve efficiency by exploiting the established and widely used knowledge and procedures of the lean philosophy;

- Hierarchical approach to the problem with different zoom levels that allows performing a complete assessment of the factory systems both offline and real-time;
- Correlation of data related to energy, resources, production and manufacturing activities to calculate specific, understandable, and effective KPIs, which easily allow identifying inefficiencies from an environmental and economic perspective. Moreover, the analysis results are displayed through an innovative, simple and clear dashboard to communicate insights to different stakeholders;
- Support in the definition of a concrete and feasible action plan to effectively address inefficiencies.

3 Method

The proposed method aims to evaluate resources hotspots at different levels of detail, providing qualitative and quantitative feedbacks to improve the factory resource efficiency. Through the method, a process manager is able to answer the following questions: When, where and why does waste of resources occur? Who is responsible for it? Which are the most suitable improvement strategies?

As shown in Figure 1, the method is based on the continuous improvement approach and consists of 5 main steps.

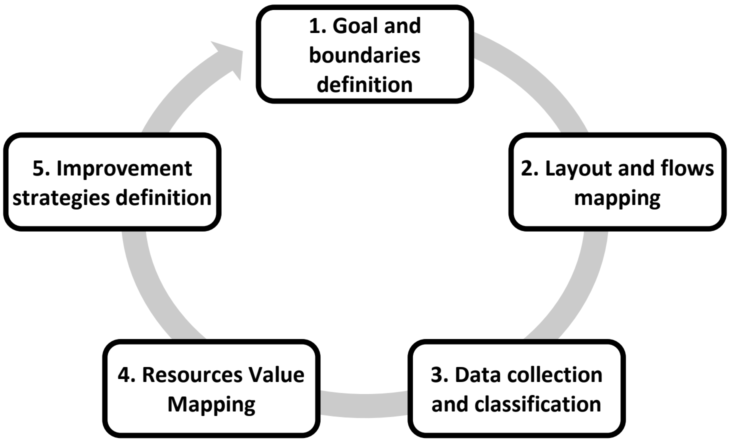

Figure 1. Steps of the Resources Value Mapping method (Source: Authors)

3.1 STEP 1. Goal and boundaries definition

A consistent analysis requires the definition and sharing of the following aspects: main goal, accuracy, frequency and system boundaries.

Company drivers and stakeholders’ expectations should guide the definition of a clear and achievable analysis goal. For example, the goal could be the simulation of machine operation from an energetic point of view or the awareness of company global consumptions. Possible scenarios, choices or hypotheses should be also described in this phase.

The accuracy of analysis results strictly depends on the information granularity. A high level of detail requires the combination of direct measurements, asset characteristics and production data, while a lower level of detail could be limited to a preliminary allocation of consumptions on the basis of utility bills. However, the method is applicable and useful in both the situations.

Considering the frequency parameter, a static, dynamic or hybrid analysis could be performed. A static analysis is carried out once to have a clear picture of the state of the art (e.g., in occasion of an audit to pursue an energetic certification) and implies offline interventions. A dynamic analysis is based on the continuous monitoring of assets, requires real-time data, and enables both online and offline actions. A hybrid analysis can be viewed as a combination of static and dynamic analyses. It is based on the periodic manual update of the initial analysis to verify the achievement of established objectives.

The system boundaries demarcate the limits of the analysis. It could focus on a single machine, on production areas, on the whole shop floor, etc. It could involve all resources or only a subset of them. It could refer to different time slots, from a single cycle time to the entire annual production. It could consider one or more products or product families (i.e., groups of goods that undergo similar production processes). According to the hierarchical model, different levels of detail can be adopted. The system boundaries definition is strictly related to the main goal of the analysis and additional available data coming from previous studies (e.g., Pareto analysis, cost deployment).

The choices made at this stage enable different analysis scenarios, as shown in Figure 2.

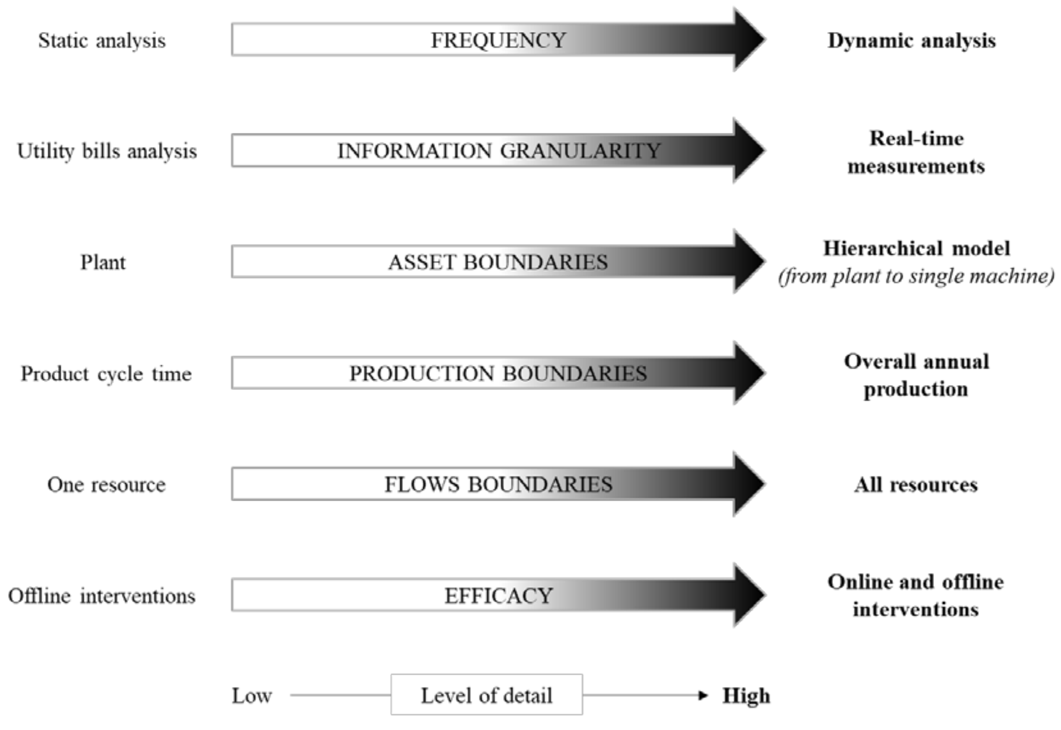

Figure 2. Scenarios for resource efficiency analysis (Source: Authors)

3.2 STEP 2. Layout and flows mapping

An overall vision of the plant is needed to fully understand how the resources are used, to properly allocate consumptions and to effectively interpret results. It means to analyze the physical configuration of the manufacturing plant, which affects the efficiency of subsequent operations, and all production flows (materials, resources, information, etc.). Consolidated techniques such as IDEF0 (i.e. Integration DEFinition), UML (i.e. Unified Modeling Language), etc. can support the identification of all production steps and the related input, output, constraints and resources. A deeper level of detail is achievable whether the process is analyzed on site and data are acquired through plant walks (i.e. Gemba walk).

The output of Step 2 is a first map (Figure 3) representing the following items:

- *Layout*, which is the physical arrangement of machines, shops, cells, etc. within the plant;
- *Processes*, which refer to a single operation or a sequence of operations performed on a product by machines, operators or both;
- *Resources*, which are required to perform the operations, such as electricity, water, gas, compressed air, etc.;
- *Product path*, which is the sequence of processes followed by a single product or product family.

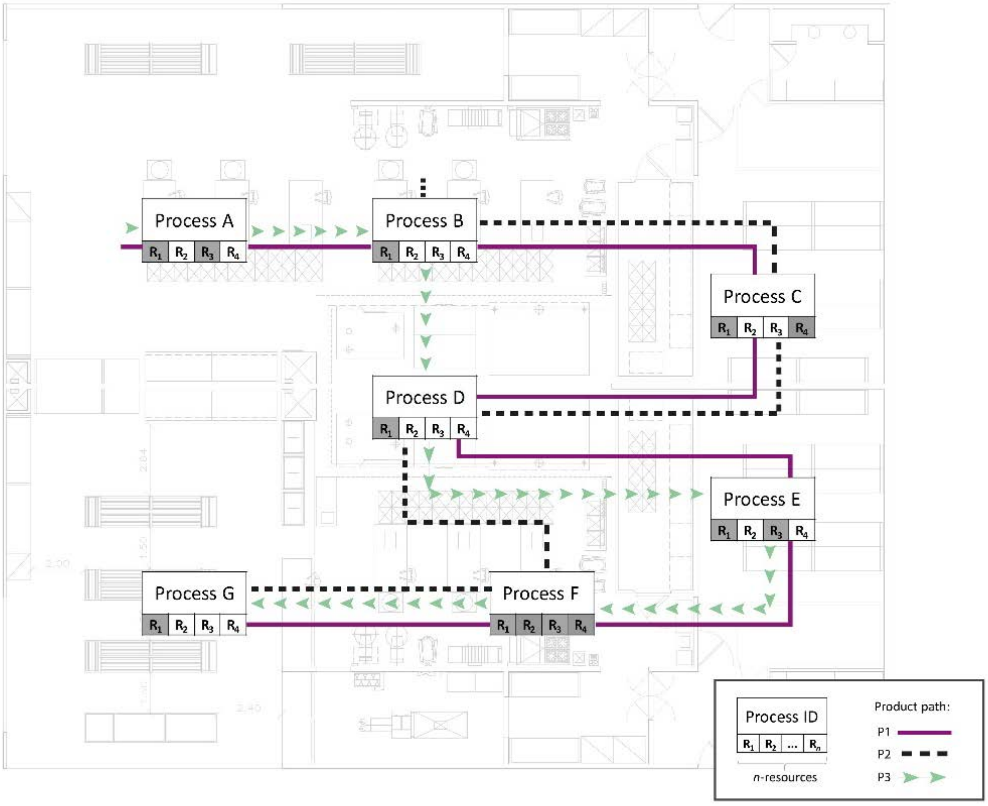

Figure 3. Example of plant layout and production flows mapping (Source: Authors)

3.3 STEP 3. Data collection and classification

Step 3 essentially consists in the collection and classification of all data related to (i) resources, (ii) assets, and (iii) processes.

The first item refers to consumptions of resources. If specific sensors are available, these data can be automatically collected. If not, bills and meters are the main information sources. In both cases, the processes that contribute to each consumption need to be specified.

The second item includes all asset characteristics such as name, power, operating time, etc. These data can be gathered by consulting the plant manager, machine plates and manuals, plant design documents, etc. Some of them can vary according to the product family, therefore, different values must be collected for each station/process.

The third item refers to the production flow and consists in the classification of activities, according to the lean philosophy principles [44]:

- *Value-added (VA) activities* are operations for which the customer is willing to pay. They include all operations that change the state of a component/semi-finished part and are necessary to realize the product. These activities refer to only compliant products;
- *Non value-added (NVA) activities* include operations that are necessary but do not transform the product toward completion. The customer does not care for them;
- *Waste (W) activities* include operations that do not transform the item toward completion and are unnecessary. They usually generate extra costs: the customer is not willing to pay for them.

For example, considering a plate painting operation, only the application of the paint on the plate surface is VA. The movement of the plate to favor the painting process is NVA, while the excess of paint or compressed air to apply the paint on the plate can be classified as W.

This classification plays a key role in the evaluation of process performance with respect to the optimal consumption of resources. Specifically, it allows to understand the resources value flow and focus the improvement strategies toward the minimization of resources consumed by W and NVA activities.

Based on lean literature [45] and authors' expertise, a general classification of activities is proposed in Table 3. Some activities could be classified both as NVA and W, depending on the specific case. For example, considering the activity "Movement of materials or products", it should be classified as NVA if it refers to the space to be covered from one station to the next, or as W if it includes extra movements from those ones strictly needed (e.g. bad layout, inefficient production scheduling).

If the analysis refers to more than one cycle time, other data related to production need to be collected, such as pieces produced, non-compliant pieces, maintenance interventions, etc. In case of aggregate data (i.e.

referred to more than one product or product family), also proper allocation criteria must be selected (e.g. quantity, turnover, etc.).

Table 3. Classification of manufacturing activities according to lean principles

ACTIVITY *(resources consumption for…)*	**VA**	**NVA**	**W**
Processing of compliant products	x		
More (or faster) production than required (overproduction)			x
Inventory of products, materials, energy, etc.		x	x
Production of non-compliant products (defects)			x
Performing processes that are not required or with inappropriate techniques, oversize equipment, inefficient machinery etc. (overprocessing)			x
Machinery setup		x	
Movement of materials or products		x	x
Movements of man or machine		x	x
Transport of resources		x	x
Corrective maintenance			x
Preventive or predictive maintenance		x	
Waiting, that is no operation is occurring		x	x

Source: Authors' compilation based on [45].

3.4 STEP 4. Resources Value Mapping

Step 4 aims to represent how each process contributes to the consumption of each resource, highlighting the VA, NVA and W percentage. The proposed map is visual, clear and linear for a simplified interpretation. It is based on a proper data management and a user-friendly structure that allows easily detecting possible inefficiencies. It can be defined as the "layout" of plant resources consumptions.

The core of the map is the *Process Box* (Figure 4), which describes each considered production process according to its impact on resources consumption. The upper part of the box contains the ID of the process. In the central part, the allocation of resources consumption, by means of yields and colored bars, is represented. In the lower part the values of the *Cost Index*, which allows quantifying the resources consumptions from an economic point of view, and of the *Muda Index*, which highlights the consumptions not related to VA activities, are reported. This structure avoids "infobesity", since the box only embeds the essential information needed by decision-makers to understand: (i) where the criticalities in terms of resources consumption are located, and (ii) how much margin of improvement exists for each process.

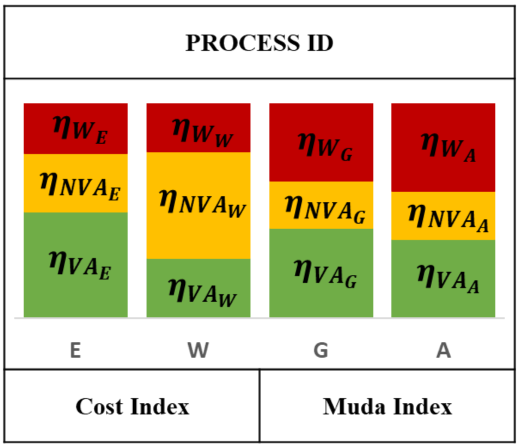

Figure 4. Example of Process Box (Source: Authors)

Hereafter, the equations to calculate the indicators contained in the process box are described. According to system boundaries, they are calculated for single machinery, single process, and the overall plant.

η_{VA_i} is the yield related to the resource *i* consumed by VA activities with respect to the total amount of consumed resource. Ideally, it should be 100%.

$$\eta_{VA_i} = \frac{R_{VA_i}}{\left(R_{VA_i} + R_{NVA_i} + R_{W_i}\right)}$$

η_{NVA_i} is the yield related to the resource *i* consumed by NVA activities with respect to the total amount of consumed resource. This value should be minimized.

$$\eta_{NVA_i} = \frac{R_{NVA_i}}{\left(R_{VA_i} + R_{NVA_i} + R_{W_i}\right)}$$

η_{W_i} is the yield related to the resource *i* consumed by W activities with respect to the total amount of consumed resource. Ideally, it should be 0%.

$$\eta_{W_i} = \frac{R_{W_i}}{\left(R_{VA_i} + R_{NVA_i} + R_{W_i}\right)}$$

where:

R_{VAi} is the amount of resource *i* consumed by VA activities (*j*). It means the minimum amount of resource *i* theoretically necessary to transform a material or a semi-finished product into a product (e.g. heat necessary to quench a steel component). However, theoretical consumption is influenced by multiple factors (e.g. set-up, obsolescence, product heterogeneity) and its calculation requires an excessive effort. Therefore, in real industrial contexts, R_{VAi} is often calculated as sum of hourly consumptions per piece of VA activities ($r_{VA_{ij}}$) multiplied by their duration. Therefore, a Δ between theoretical and measured/estimated values, which refers to machinery inefficiency (resource waste), should be considered. The consumption should be as close as possible to the theoretical consumption, which represents the minimum amount of resource required for the considered processing.

$$R_{VA_i} = \sum_j r_{VA_{ij}} * t_{VA_{ij}} - \Delta$$

R_{NVAi} is the amount of resource i consumed by NVA activities (j). It means the amount of auxiliary resource required by the process, which does not add value to the material or semi-finished product, but is necessary to run the process in a correct way (e.g. energy required to position the component). It is obtained as sum of hourly consumptions per piece of NVA activities ($r_{NVA_{ij}}$) multiplied by their duration:

$$R_{NVA_i} = \sum_j r_{NVA_{ij}} * t_{NVA_{ij}}$$

R_{Wi} is the amount of resource i consumed by W activities (j). It means the amount of resource lost because of wrong use of machineries, failures, or inappropriate use of equipment (e.g. use of oversized electric motors). It is obtained as sum of hourly consumptions per piece of W activities ($r_{W_{ij}}$) multiplied by their duration:

$$R_{W_i} = \sum_j r_{W_{ij}} * t_{W_{ij}}$$

The hourly consumptions per piece have to be estimated or measured according to the product families and machines setting.

A preliminary check of the flows mapping goodness can be executed by comparing the sum of R_{VAi}, R_{NVAi} and R_{Wi} with the total resources consumption measured. If they differ, some sources of waste are missing. If the extent of such difference is not negligible an in-depth analysis is required.

The *Cost Index (CI)* allows identifying which process is responsible of the highest cost related to resources consumptions. It is obtained as sum of unitary cost of the resource (c_i) multiplied by the relative total amount of resource consumed:

$$Cost\ Index = \sum_i c_i * \left(R_{VA_i} + R_{NVA_i} + R_{W_i}\right)$$

The *Muda Index (MI)*, instead, allows quantifying the cost of resource not related to VA activities. The basic idea of this index is to provide a clear representation of flows criticalities, other than a clear representation of resource flows. The more the MI value is higher, the more corrective actions are needed for the considered operation/process. An essential contribution to the definition of the Muda Index has been provided by the lean managers of the industrial company involved in this study (i.e. the multinational company operating in the appliances sector that actively participated in the method definition and particularly in the method experimentation), who offer their industrial point of view for the definition of an index as useful and easy to interpret as possible. This metric is calculated according to the following equation:

$$Muda\ Index = \sum_i c_i * \left(R_{NVA_i} + 2R_{W_i}\right)$$

Regarding the resource consumed by W activities, they are multiplied by a coefficient major than one in order to particularly focus the indicator on wasted resources. Indeed, according to lean philosophy principles, which constitute the basis of the proposed method, the analyses and definition of corrective actions should be mainly focused on the identification and minimization of W activities, while NVA activities should have less priority. This weighting choice has been defined empirically by mapping and deeply analysing different common processes of manufacturing industries: milling of metal parts, casting, injection moulding, etc. In particular, the value of the multiplication factor for wasted resources (2) has been defined after testing three different values (1, 1,5 and 2) in several experimental case studies of different companies. The experimentation led to a success rate of 90% with the multiplication factor = 2 that finally has been chosen. As an example, the following Table 4 reports full details about three representative case studies used for the definition and validation of the Muda Index formula. Results shows that, by using a multiplication factor of 1 or 1,5, it is difficult to identify the most impactful resource (in each line there are two different resources with similar MI_i values). By using a multiplication factor of 2, instead, the differences among the MI_i calculated for the different resources are amplified and the most critical resource is better highlighted. However, the optimization of the Muda Index will be one of the most important future work, as discussed in the Discussion and Concluding remarks section.

Table 4. Example of three experimental case studies used to define the R_{Wi} multiplication factor

Line	**Resource**	η_{VAi}	η_{NVAi}	η_{Wi}	**Consumption**	**MI$_i$**		
						R_{Wi} **multiplication factor = 1**	R_{Wi} **multiplication factor = 1,5**	R_{Wi} **multiplication factor = 2**
Line A	Electricity	26%	4%	70%	1,129 kWh/pc	0,84	1,23	1,63
	Water	0%	0%	100%	0,003 m^3/pc	0,00	0,00	0,01
	Oil	0%	100%	0%	0,11 l/pc	0,01	0,01	0,01
	Compressed Air	0%	15%	85%	0,84 m^3/pc	0,84	1,20	1,55
Line B	Electricity	5%	70%	25%	0,16 kWh/pc	0,15	0,17	0,19
	Water	0%	80%	20%	0,02 m^3/pc	0,02	0,02	0,02
	Compressed Air	0%	55%	45%	0,15 m^3/pc	0,15	0,17	0,22
Line C	Electricity	25%	5%	70%	0,34 kWh/pc	0,26	0,37	0,49
	Water	0%	85%	15%	0,01 m^3/pc	0,01	0,02	0,02
	Oil	0%	100%	0%	0,001 l/pc	0,00	0,00	0,00
	Compressed Air	10%	25%	65%	0,29 m^3/pc	0,26	0,37	0,45

Source: Authors’ calculation.

The production line is the result of sequential processes, therefore, in the map, the process boxes are connected by the paths of the different product families. In order to make the comprehension intuitive, the position of process boxes should respect the real plant layout (Figure 5). The map can refer to all products and flows or single product and resource. In the first case, each box includes the total consumption generated by the specific process and the related cost. In the second case, only the consumptions of the selected resource generated by the production of the selected product are shown in the box and the cost index is recalculated accordingly.

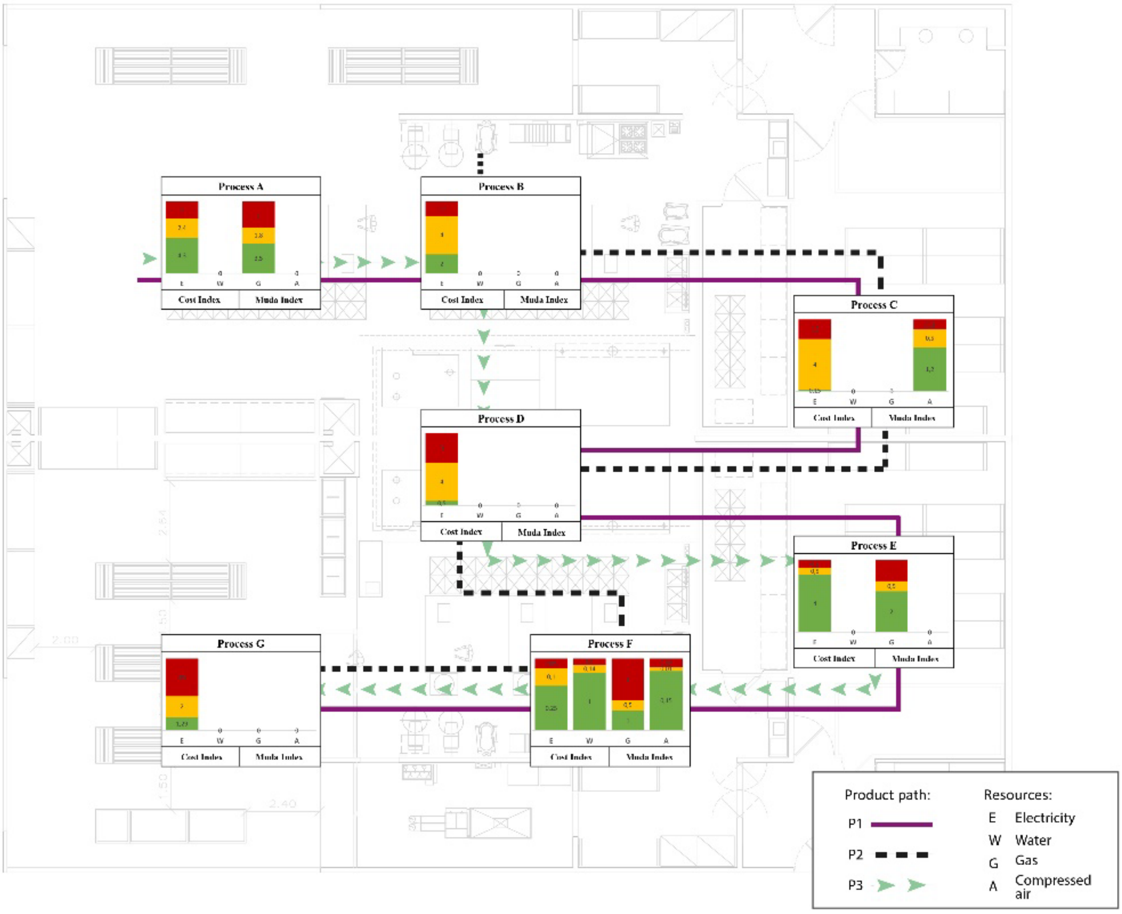

Figure 5. Example of resource value map (Source: Authors)

As shown in Figure 6, the method exploits the hierarchical data management technique, which allows exploding in size a process box going down in the hierarchy. In order to ensure a proper hierarchy modelling, it is worth to specify that the sum of consumptions of all lower-level processes has to be equal to the resources' consumption of the related higher-level process.

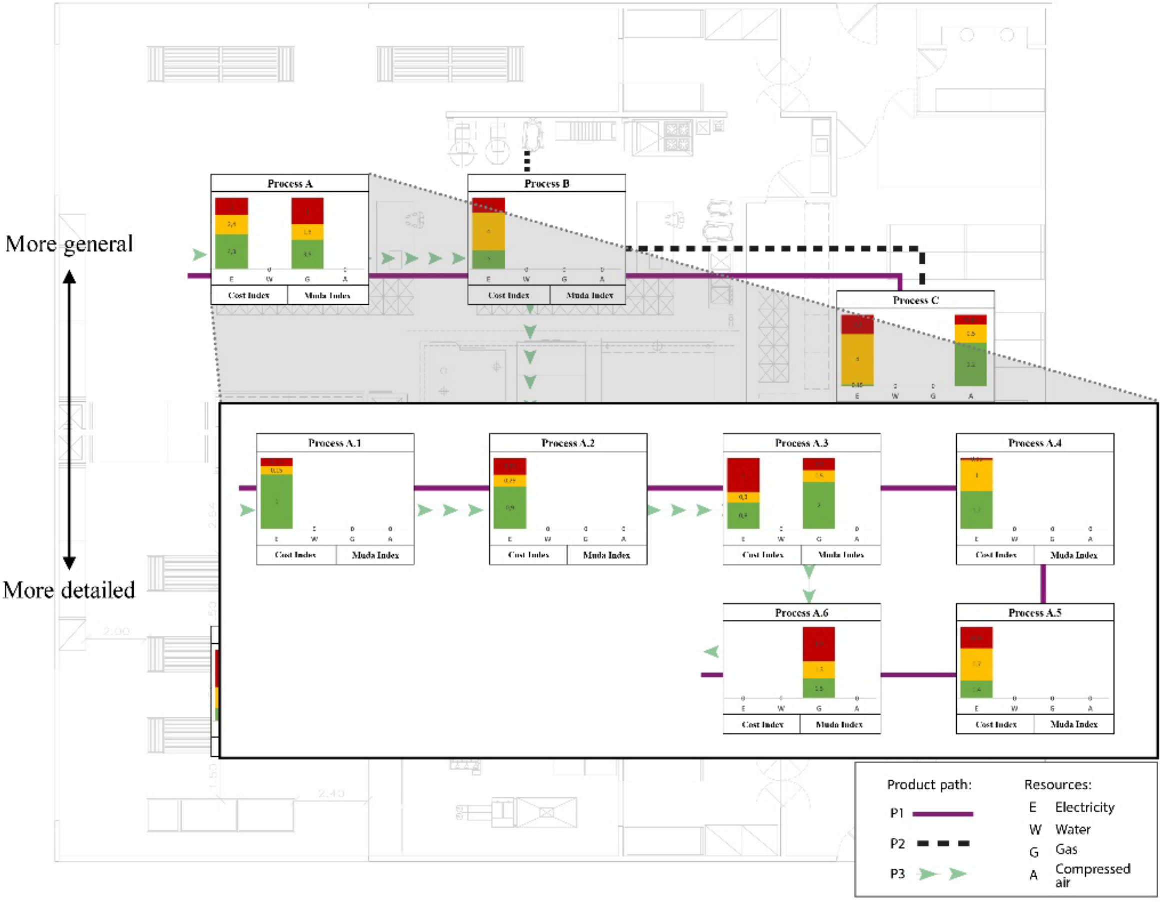

Figure 6. Hierarchy of the resource value map (Source: Authors)

3.5 STEP 5. Improvement strategies definition

An ideal process requires and consumes only the resources needed to VA activities. However, in real contexts this limit cannot be reached. Therefore, the objective of Step 5 is to define an action plan to eliminate the W resources, to reduce the consumption of NVA resources, and to maximize the resource efficiency of the VA activities, diminishing the cost of production and the environmental impacts (Figure 7).

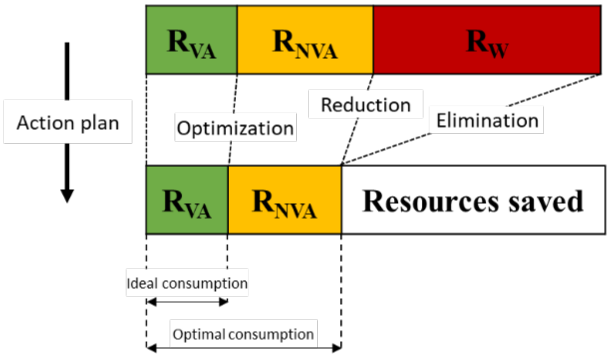

Figure 7. Optimization strategies aim (Source: Authors)

Figure 8 shows the workflow to define the action plan. Once identified the main hotspots through the map analysis, each inefficiency should be investigated to identify possible causes and set improvement strategies. A Pareto analysis [46], based on MI, could support the identification of 20% of processes that need to be addressed to reduce the 80% of resources consumption not related to VA activities. It consists of the construction of a Pareto diagram according to the following steps:

1. List each process with its associated MI;
2. Calculate the MI% for each process *k* as follows

$$MI\%_k = \frac{MI_k}{\sum_k MI_k}$$

3. Sort the processes in descending order placing the one with the highest MI% first;
4. Calculate the MI% cumulative values by adding each MI% to the sum of its predecessors;
5. Plot a bar for each process and the MI% cumulative values (horizontal axis: process; left-hand vertical axis: MI; right-hand vertical axis: MI%);
6. Draw a line at 80% of the MI% cumulative value onto the x-axis. This point on the x-axis separates the important causes on the left and less important causes on the right.

The Pareto analysis also allows to identify the important causes by process and resource simultaneously. In this case, each couple process (k)-resource (*i*) must be listed and the relative MI and MI% must be calculated as follows:

$$MI_{ki} = c_i * \left(R_{NVA_i} + 2R_{W_i}\right)$$

$$MI\%_{ki} = \frac{MI_{ki}}{\sum_k MI_{ki}}$$

At this point, for each identified cause one or more solutions should be defined. For this aim, a set of general corrective actions is proposed in Table 5. They have been defined on the basis of BAT Reference documents (BREFs) [47], lean/green strategy [48] and practical approach to create a Green Value Stream [49], including lean tools and techniques that support waste elimination/minimization [35]. Corrective actions have to be preliminary contextualized and selected on the basis of their impact on the reduction of resource consumptions and the relative investment scale. Actions with high impact level and low investment level are preferred. However, before the effective implementation, their feasibility and cost-benefit ratio have to be preliminarily evaluated. In case of positive feedback, they can be implemented, otherwise, a further analysis is required.

According to the developed plan, actions are implemented and have to be monitored in order to verify their real effectiveness. Some milestones have to be defined to quantify the achieved benefits in terms of resource efficiency and cost. According to the continuous improvement approach, the method should be iterated to identify hotspots of the future state of the art.

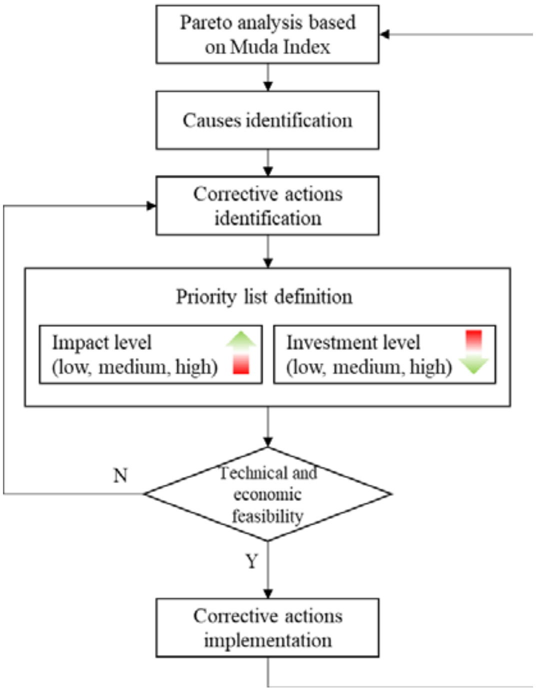

Figure 8. Improvement strategies definition process (Source: Authors)

Table 5. Classification of corrective actions for the resource efficiency improvement

	CORRECTIVE ACTIONS		
ACTIVITY	**VA**	**NVA**	**W**
Processing of compliant products	- Maintain, refurbish and retune equipment - Monitor and optimize process parameters		
More (or faster) production than required (overproduction)			- Optimize production planning - Kanban/Pull
Inventory of products, materials, energy, etc.		- Energy efficient warehouse - Reuse/Recover resources	- Avoid unnecessary storage - Just In Time - Kanban/Pull
Production of non-compliant products (defects)			- Total Quality Management - Poka-Yoke - Six Sigma - Visual Management/Andon
Performing processes that are not required or with inappropriate techniques, oversize equipment, inefficient machinery etc. (overprocessing)			- Choice of more adequate production technology - Replace and retire obsolete equipment - Poka-Yoke
Machinery setup		- Single Minute Exchange of Die - Minimize resources requirements during setup	

Movement of materials or products		- Optimize layout and workflow - Energy efficient transporter and handling system	- Avoid unnecessary movements - Just In Time - 5S
Movements of man or machine		- Optimize layout and workflow	- Avoid unnecessary movements - 5S
Transport of resources		- Avoid unnecessary demand (e.g. too high temperatures or pressures) - Optimize layout - Reuse/Recover resources	- Avoid system losses (e.g. leakages, unfavorable design)
Corrective maintenance			- Total Productive Maintenance
Preventive or predictive maintenance		- Advanced process control	
Waiting, that is no operation is occurring		- Minimize necessary resources requirements in standby mode - Visual Management/Andon	- Avoid unnecessary resources requirements in standby mode - Just In Time - 5S

Source: Authors' compilation based on [35][47][48][49].

4 Case study

The method has been experimented in collaboration with a multinational company, global leader in the sector of appliances for domestic and professional use. In particular, the Italian manufacturing plant that produces ovens and hobs has been involved. This site is subdivided into three areas: Sheet Department (SD), which produces sheet metal semi-finished products; Glazing Department (GD), where the coating of semi-finished parts takes place; Assembly Department (AD), where the semi-finished parts are assembled to realize the final products. The main processes are sheet metal stamping, welding, coating, vitrification and assembly. In this plant, the lean philosophy is deeply rooted, and customer value is one of the main drivers.

4.1 The production plant analysis

The abovementioned plant is an "energy-intensive business" and is therefore obliged to control the energy consumption, as required by article 8 of Legislative Decree no. 102/2014 [50]. Despite the lean philosophy is firmly rooted in the company, there is still no full awareness on the amount of wasted resources and related causes. The goal of the analysis was then defined as "understanding the extent of the main flows of resources absorbed by the production process and their contribution to value, with the final aim to define an action plan for waste elimination/minimization". A static analysis was then performed.

Concerning the resources to map, all the 26 presses of the SD require electricity, compressed air, and water; in addition, the hydraulic presses also require oil. The 3 glazing lines of the GD require water for washing, compressed air, gas and electricity. The AD includes 8 assembly lines for the built-in ovens and a packaging area. The assembly lines are made up of a variable number of stations connected by roller conveyors. Electricity is used for lighting and transport, while compressed air is used for the majority of assembly tools. Robots and conveyors work in the packaging area. This process requires electrical energy, compressed air and natural gas both for the testing phase and the thermo-retraction packaging. Therefore, the focus is settled on the five resources listed in Table 6. Considering the overall annual production of kitchen ovens, also information related to compliant and non-compliant pieces produced, maintenance interventions and stop reports were gathered. The indirect contributions (e.g. maintenance of machines used for ovens and hobs' production) have been allocated according to the production volume.

Table 6. Data processing approach by resource

Resource	Data collection	Data elaboration
Electricity	Direct measurement through network analyzers (HT Instruments PQA824) and portable acquisition instruments	According to the instrument's characteristics, data are automatically or manually read and recorded in a database. These measures may require the presence of the person responsible for electrical systems.
Compressed air	Nominal data from manuals	Consumption derived from compressors flow rate, network pressure, average consumption of each device, and working time: $C_{comp\_air}\left[\frac{m^3}{pc}\right] = \frac{c_{machine}\left[\frac{m^3}{h}\right]}{n_{operations} * n_{pieces}\left[\frac{pc}{h}\right]}$ Compressed air waste calculated as sum of concentrated and distributed pressure drops [51]: $C_{w,comp\_air}\left[\frac{m^3}{pc}\right] = \frac{C_{comp\_air}\left[\frac{m^3}{pc}\right] * p_{drops}\ [Pa]}{p\ [Pa]}$
Water	Nominal data from manuals Water meters	Presses with an open loop water treatment: consumption calculated from heat exchanger nominal data (water flow and operating temperature) and daily working hours: $C_{water}\left[\frac{m^3}{pc}\right] = \frac{c_{water,heat}\left[\frac{l}{h}\right]}{n_{pieces}\left[\frac{pc}{h}\right] * 1000\left[\frac{l}{m^3}\right]}$ Presses with a closed loop water treatment: consumption due to the containment tank replenishment. Its annual flow rate is measured by meters. Glazing lines: consumption measured by meters.
Oil	Nominal data from manuals	Consumption estimated considering the hydraulic oil capacity of a press and the working time in which the oil maintains its viscous properties unaltered: $C_{oil}\left[\frac{l}{pc}\right] = \frac{c_{hydraulic}\ [l]}{t_{viscous\ properties}\ [h] * n_{pieces}\left[\frac{pc}{h}\right]}$
Gas	Gas meters	Consumption measured by meters.

Source: Authors.

All activities of the three departments have been identified and classified in order to properly allocate the resources' consumptions. For this aim, the company's database, containing all internal reports compiled by operators, has been consulted. Each report describes when, where and why an activity is performed. In Table 7, the classification of SD activities is reported as example. NVA activities mainly include material handling, setting, testing and maintenance, while W activities mainly refer to evitable stops, breakdowns and defects.

Table 7. Classification of sheet department activities

VA activity	NVA activity	W activity
- Stamping of compliant steel components for the production of ovens	- Components transfer - Evacuation test - Die load/unload - Die test - Oil tube installation - Performance assessment - Press oil adding - Scheduled maintenance interventions - Regulations - Set up - Supplying - Vacuum	- Blackout - Cleaning - Clogged hopper - Defect - Raw material - Defect - Semi-finished - Delays - Failure - Compressed air tube - Failure - Lubricant - Failure - Die - Failure - Press drawbridge - Failure - Press - Failure - Scraps transporter - Failure - Transfer - Failure - Drain pieces - Meeting - Scheduled breaks - Scraps evacuation - Supply-related problems (lack, delay, etc.) - Warehouse-related problems (mispicks, overstock, etc.)

Source: Authors.

4.2 Results

Collected data allowed calculating all indicators included in the process boxes related to the three departments. The result is the map shown in Figure 9.

The values of CI and MI highlight that SD is the most critical department. Indeed, it requires the more than twice the electricity, which is the most impactful resource (69% of resources total cost), consumed by the other two departments. Contrarily, the highest demand of compressed air (20% of resources total cost) occurs in AD and it is mainly related to cleaning activities. The use of oil (7% of resources total cost) refers exclusively to hydraulic presses of SD. The most of gas consumption is related to the vitrification processes (GD box), where the NVA portion is mainly due to the thermal energy absorbed by the transportation system (supporting system and hooks) used to move the semi-finished parts inside the oven. The W portion, instead, is due to the non-optimal insulation of the oven and the dispersed energy via hot smokes. Finally, the water consumption is mainly due to presses cooling (SD box) and semi-finished parts washing (GD box).

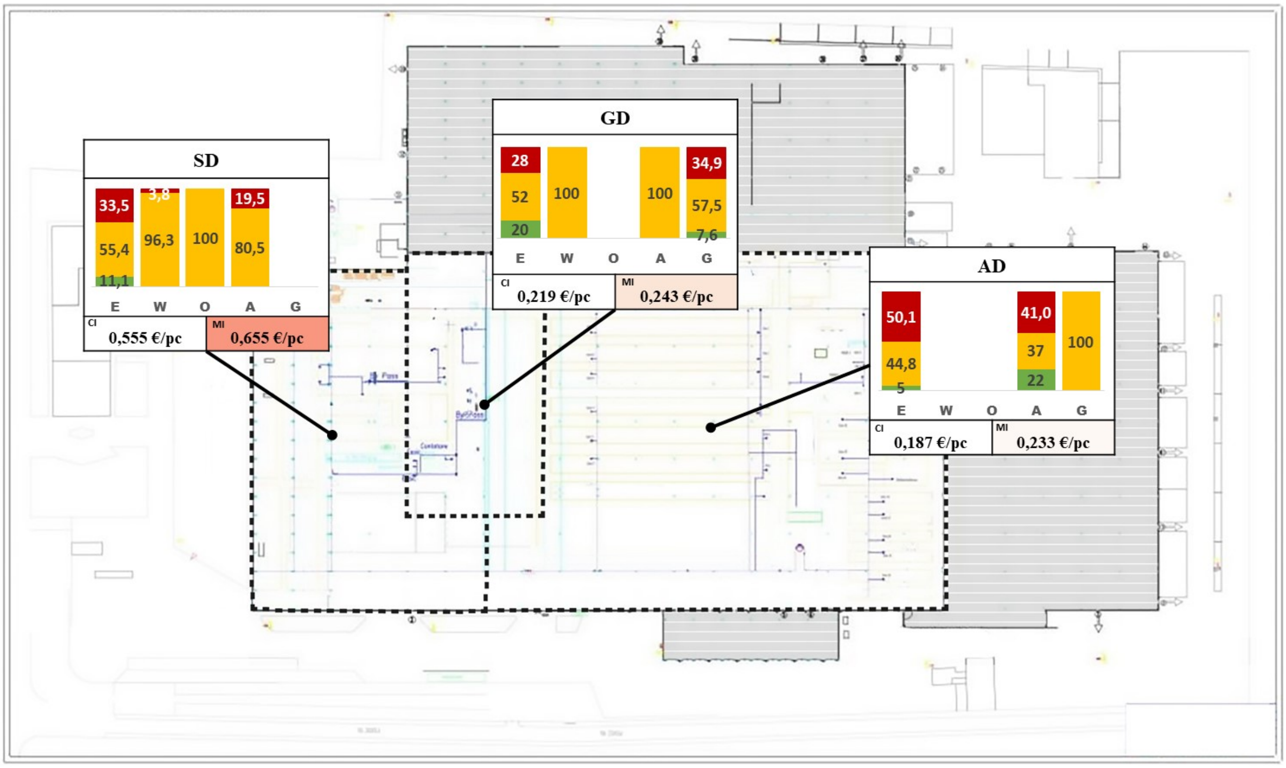

Figure 9. Resources Value Mapping of the whole production plant (Source: Authors' calculation)

Starting from the general results, an in-depth analysis of SD has been carried out. Figure 10 shows the explosion in size of the SD box, with details of the four lines. Starting from the consumption of electric energy, which resulted responsible for 79% of resources costs, a good margin for improvement is observed for Line 1 (L1) that simultaneously has the highest percentages of W energy (more than double in comparison with the others) and the highest percentage of VA energy. Contrarily, NVA activities mainly influence the electricity consumption of Line 2 (L2), Line 3 (L3) and Line 4 (L4). Analyzing the MI values, L4 and L1 are the most critical ones.

As expected, the other resources do not generate value because they are not directly used for pressing steel components. The consumption of oil (12% of resources cost) is completely related to NVA activities, since this resource is only needed for bat movement and die cooling. The most of its consumption is due to L1 and L4.

Compressed air (7% of resources cost) is mainly required by handling systems, consequently, the NVA portion prevails. The wasted amount is related to extra movements that could be avoided. The most of its consumption is once again due to L1 and L4.

L1 and L4 require also the highest quantities of water (totally 2% of resources cost), completely classified as NVA. These lines are composed by mechanical presses cooled by means of water that circulates inside a closed loop circuit. Despite there is not a direct consumption caused by presses operation, part of the water evaporates in the evaporative towers and therefore a water reintegration in the containment tank is necessary. Considering the hydraulic presses included in L2 and L3, instead, the cooling water, after passing within the heat exchangers, is thrown away and not reused (100% NVA).

Overall, L4 and L1 generate the highest resources consumption, with an impact on the related costs (CI) of 52% and 39% respectively. Focusing on activities that do not generate value (MI), their impacts are 53% and 37% respectively.

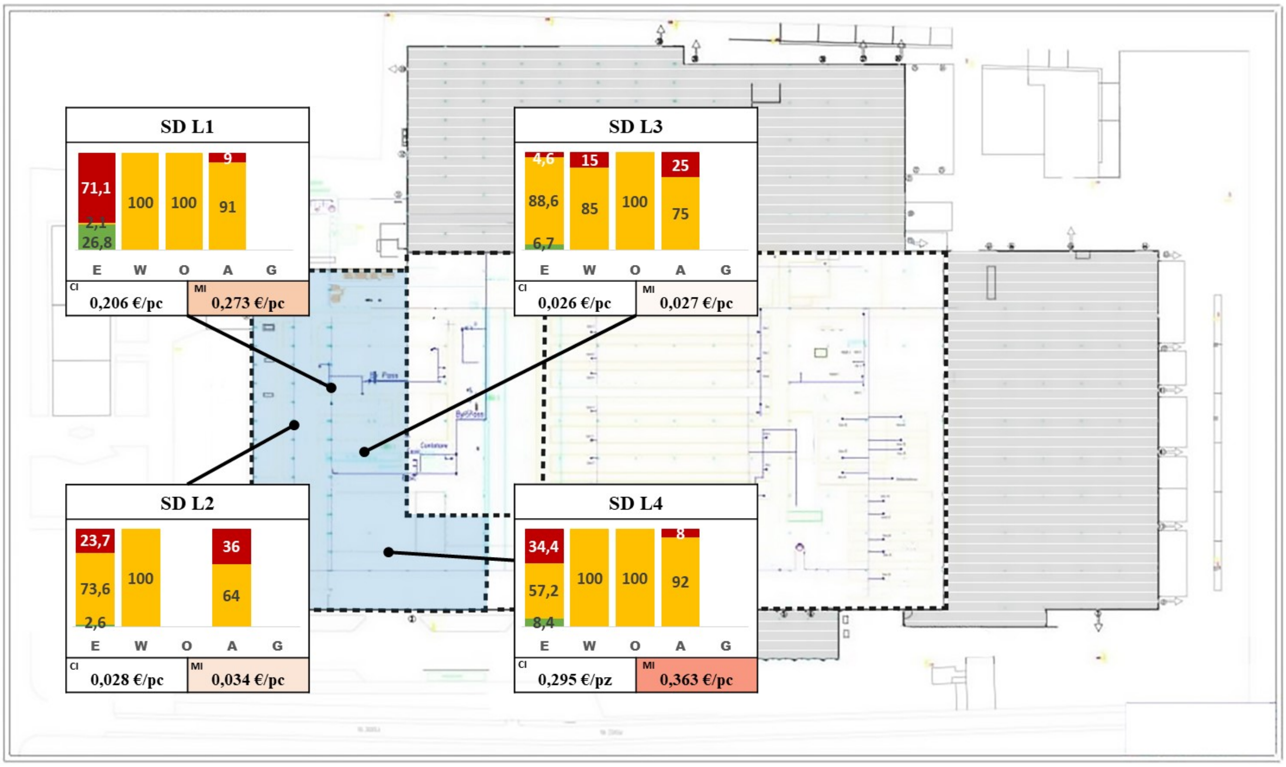

Figure 10. Resources Value Mapping of the sheet department (Source: Authors' calculation)

4.3 The action plan definition

According to the Step5 of the method, a Pareto analysis has been carried out to identify which inefficiencies of SD should be firstly addressed. Inefficiencies have been arranged in a bar graph in decreasing order of importance, by using the MI as metric. Then, the MI cumulative percentage has been calculated and the relative curve has been plotted in the same graph. In order to identify the causes for at least 80% of inefficiencies, a vertical dotted line from the point of intersection between the horizontal dotted line at 80% and the curve to the x-axis (i.e. inefficiencies) has been drawn. The Pareto graph allows focusing the investigation of the main causes and consequently supporting the identification of possible optimization strategies. The VA resources consumption has not been considered since the objective was to evaluate, quantify, and reduce, first of all, the inefficiencies related to W activities, and then those coming from NVA activities. As shown in Figure 11, about the 80% of resources consumption that does not generate value is related to the electricity consumed by L4 and L1 and the compressed air required by L1.

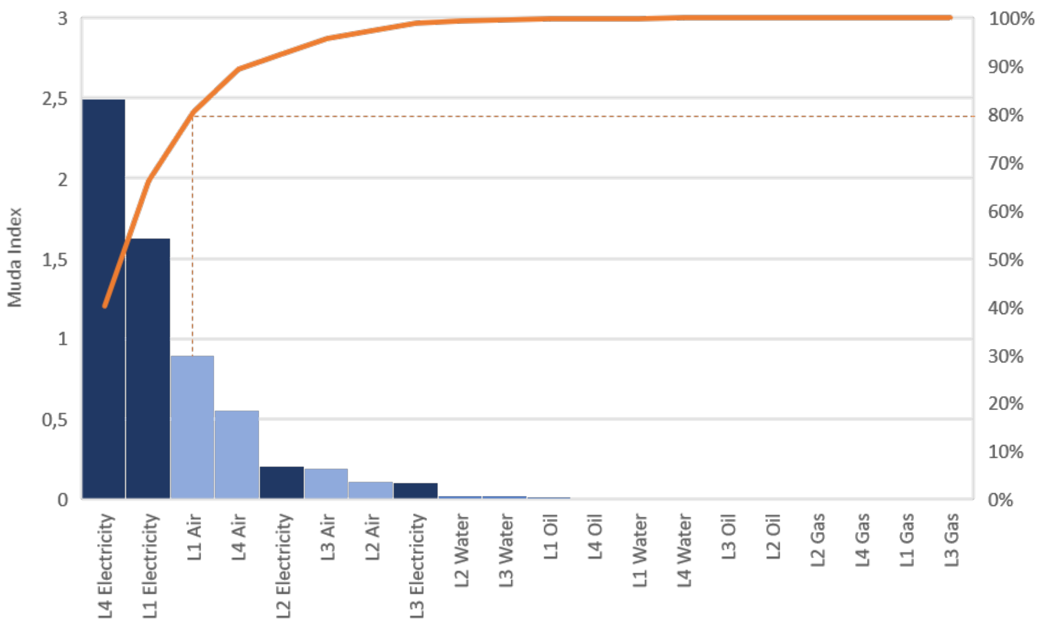

Figure 11. Pareto analysis based on Muda Index (Source: Authors' calculation)

Table 8 summarizes the identified causes of inefficiency and all the possible specific corrective actions that allow improving the lines efficiency in terms of electrical energy and compressed air consumptions. They are prioritized according to their impact on the process efficiency and the required investment.

Table 8. Sheet department action plan according to inefficiency causes

Resource	Cause	Corrective action	Impact/Investment
L4 Electricity (W)	Stand-by mode during idle time	Switch off during idle time	High/Low
L1 Electricity (W)	Stand-by mode during idle time	Switch off during idle time	High/Low
L1 Compressed air (W)	Air losses due to perforated pipes	Pipes replacement	Medium/Low
L1 Compressed air (NVA)	Use of excessive air pressure	Reduce the operating pressure	Medium/Low
L4 Electricity (NVA)	Energy dissipation due to transformers	More efficient transformers	High/Medium
L1 Compressed air (W)	Air losses due to the length and complexity of the distribution lines	Section of compressed air circuit	Low/Low
L1 Compressed air (NVA)	Thermal energy produced by cooling of the compressor is not reused	Recovery of thermal energy for building heating	High/High
L1 Electricity (W)	Faulty components production	Monitoring of process parameters	Medium/Medium
L4 Electricity (W)	Faulty components production	Monitoring of process parameters	Low/Medium
L4 Electricity (NVA)	Energy dissipation due to connections layout	Re-design of connections layout	Low/High
L1 Electricity (NVA)	Energy dissipation due connections layout	Re-design of connections layout	Low/High

Source: Authors.

Considering the electricity, the most of W portions for L1 and L4 lines are related to system-on inactive. The energy loss is due to early starting, stand-by mode during break and delayed switching off. The W portion of

L1 is 71%, 43% of which can be attributed to the stand-by mode during breaks. The average absorption of L1 presses in stand-by mode is approximately 129,7 kW. Considering that the average turn-on time is about 180 seconds with a consumption of about 6,5 kWh, it is easy to verify that it is convenient to turn the press off every time it is inactive. Similarly, the L4 presses cause over 34% of the wasted energy, 12% of it can be adduced to the power consumption in stand-by mode in the 2-hour daily break. Considering the minimum break of 10 minutes, the average standby consumption of one press would amount to 1,47 kWh. As a consequence, turning off all L4 presses can give significant benefits in terms of energy consumption reduction. Additional wastes are due to the production of faulty components and systems failures. The NVA portion of electricity, instead, mainly originates from the energy dissipation due to the high length and complexity of connections, and the use of inefficient transformers.

As far as the compressed air is concerned, in the current situation, the operating pressure is 6 bar. However, looking at the technical characteristics, all the available equipment can work at a minimum pressure of 5 bar. The idea is to reduce the operating pressure from 6 bars to 5 bars, so there would be a reduction of NVA and W energy portions (dependent on pressure drops). Another action could be the recovery of thermal energy produced by compressors for building heating. It would lead to a reduction of consumed methane by co-generators for the production of thermal energy in the winter season. The monitoring of the Specific Energy Ratio (i.e. the energy required for the production of compressed air, measured in kWh/m^3) allowed analyzing the electric energy consumed by compressors and detecting an abnormal night consumption that caused the activation of a second compressor, theoretically not necessary. Going into more detail, it was observed that the abnormal consumption was generated by air losses due to perforated pipes and distribution lines layout.

According to the technical and economic feasibility the first four actions listed in Table 8 have been selected as priorities. Moreover, the section of the compressed air circuit, realizable through a timed solenoid, has been further investigated to estimate possible relapses for the entire plant. It emerged a high impact in terms of air consumption reduction against a low investment.

In order to quantify the potential benefits of the action plan, the implementation of the abovementioned five actions has been simulated and results are summarized in Table 9. The economic savings have been derived on the basis of contracts that the company stipulated with utilities' providers. The environmental savings, instead, have been quantified through a simplified LCA method [52] and using the global warming potential indicator ($kgCO_2eq$). Results show how minimal structural interventions and investments allow to obtain significant gains in economic and environmental terms.

The implementation of machines switching off during pauses does not require any economic investment, but only a correct management of available equipment. These operational corrective actions lead to a saving of about 210 MWh per year, that is 27300 € per year. Considering the plant emissions, a saving of 105 tCO_2eq per year has been estimated.

The pipes replacement and the reduction of the operating pressure from 6 bars to 5 bars allow reducing the air consumptions respectively of about 13% and 6%, which means a total annual saving of 1800 €.

Through the section of the compressed air circuit, the average SER decreases from 0,1269 to 0,1170 with a recovery of 7,8%. Considering an average monthly consumption of compressed air for the entire plant of approximately 1636000 m^3, the potential economic saving with this corrective action is about 2672 € per month.

Table 9. Resource and economic savings derived from the implementation of corrective actions

Implemented corrective action	Annual resource savings	Annual economic saving
L1 switch off during idle time	150 MWh (Energy)	19500 €
L4 switch off during idle time	60 MWh (Energy)	7800 €
Pipes replacement	22000 m^3 (Air)	550 €
Reduction of operating compressed air pressure (L1)	50000 m^3 (Air)	1250 €
Section of compressed air circuit	1400000 m^3 (Air)	32000 €

Source: Authors’ calculation.

Figure 12 shows the map updated according to the action plan. The CI and MI indices highlight that L1 and L4 remain the most critical production lines, even if the corrective actions allow to considerably reduce their resources consumptions. In detail, for L1 and L4 the MI is reduced by 35,5% and 56,5%, while CI is reduced by 23,3% and 46,4%, respectively.

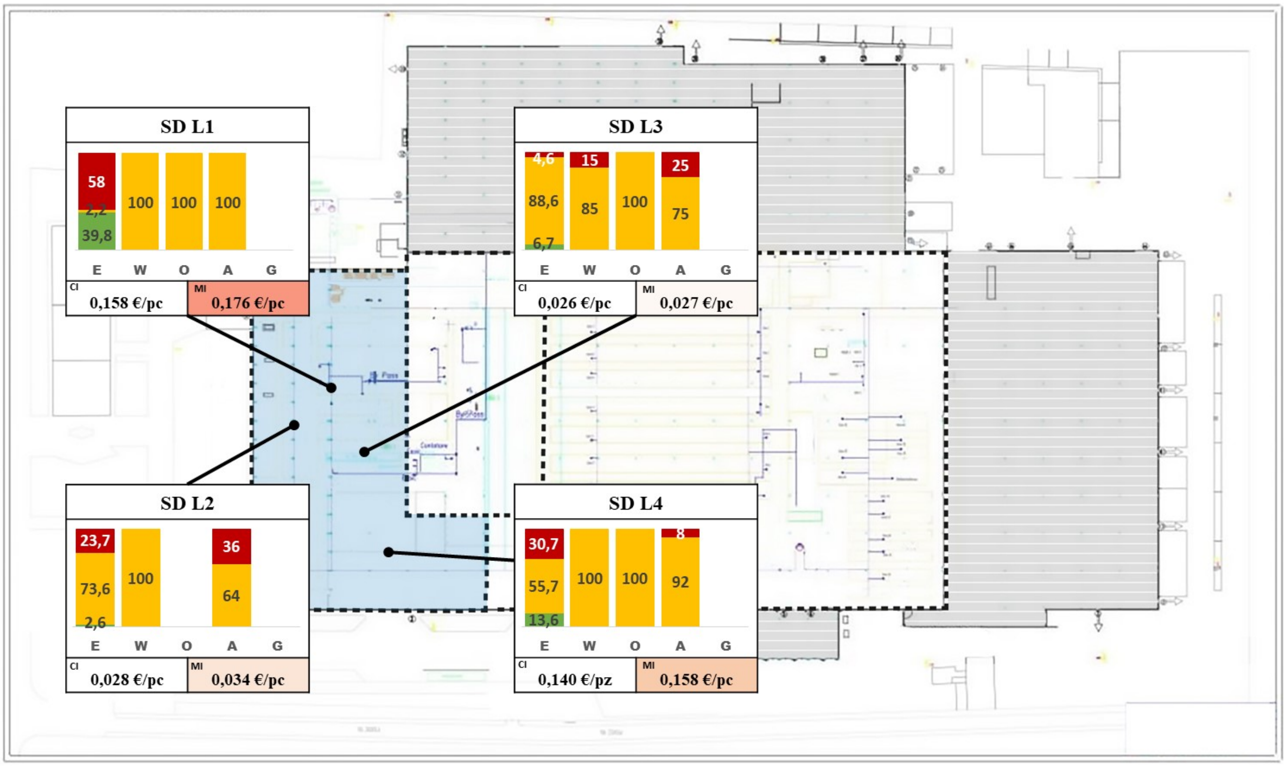

Figure 12. Resources Value Mapping of the sheet department after the action plan implementation (Source: Authors’ calculation)

Finally, a preliminary analysis related to the recovery of thermal energy for building heating has been carried out. Currently the not recovered thermal energy is equal to 38171 kWh per month. Considering an average efficiency of co-generators of 32%, the obtainable saving of thermal energy, and therefore of methane, could be about 12215 kWh, which corresponds to a savings of 1177 Smc of methane, a monthly saving of 423 € and 2421 tCO_2eq. Assuming a constant monthly production, the annual savings could be 5076 € and 29048 tCO_2eq.

Once tackled NVA and W consumptions, also the VA portion has been investigated to identify further inefficiencies. It emerged that the resources' consumption is considerably greater than the theoretical consumptions actually required to execute operations. The main cause is the oversize of some presses, especially belonging to L1. Their replacement is recommended, also considering the shift from hydraulic presses to mechanical ones (medium impact and high investment). In the former, the oil used to transmit energy has to work at maximum pressure. In a mechanical press, instead, the power supplied is maximum only during the die opening and closing. Moreover, hydraulic presses need oil to transmit energy, lubricate and refrigerate mechanical components. So even if the electric presses need water and oil auxiliary systems, the flows of water and fluid necessary for the operation are negligible compared to those of hydraulic presses.

5 Discussion and concluding remarks

As emerged from the literature review, the main novelties of the proposed approach in comparison with the existing literature studies is the procedure to allocate, represent and analyze the resources consumption according to their contribution to value generation (i.e. value added, non value-added and waste activities). Moreover, the graphical representation is innovative compared to traditional models, making the results easier to interpret. The proposed map and KPIs allow quantifying the gap between actual consumption and "optimal consumption", understanding where the reduction of resources' consumption is possible and which optimization strategies are the most suitable.

The implementation of the method in a real industrial context allows appreciating its potentialities and identifying possible weaknesses to be tackled. The case study shows how the analysis was conducted, starting with a general vision of the overall plant consumption and then going into more details for the critical processes (i.e. hierarchical approach). The study focuses on the electricity, water, oil, gas and compressed air flows within the three main departments of the plant, quantifying the resources saving that can be achieved thanks to the implementation of the developed action plan. The latter has been defined starting from the feedbacks derived by analyzing the process boxes, the map and the proposed metrics (i.e. Cost Index and Muda Index). From the analysis it emerges that less of 20% of the consumed resources during the process creates value; this is a typical value for the majority of industrial processes. For example, results show that the total electricity consumed by the production process in some cases is about 7 times bigger than the theoretical quantity required. Even if the theoretical limit cannot be reached, the method implementation allows understanding that the margins of improvement and the achievable benefits are significant, thanks to the waste and non value-added activities' reduction of. However, the effective implementation of proposed interventions will depend on the results of an in-depth feasibility analysis, including their pay-back period.

According to company's stakeholders (i.e. plant manager, energy manager, two process mangers, and lean manger) feedbacks, the method answers the following factory needs:

- Resources' flows and the relative users are easily distinguishable;
- The process box and the map are user-friendly and contain essential data, avoiding infobesity;
- The identification of the most critical areas is faster thanks to the use of meaningful colors and graphical elements;
- Inefficiencies can be identified from different perspectives such as processes, resources, economic impact, wastes, etc.

Therefore, the valid support to the definition of improvement strategies, which is the main challenge for the resources-related assessment methods, and the completeness of the analysis are the two main benefits of the proposed Resources Value Mapping method.

On the other hand, the data acquisition is a critical step, strongly influencing the effort needed for the method implementation and the results accuracy. This limit can be overcome by adopting Industry 4.0 technologies that allow to capture data automatically and with reduced effort, simplify data processing and enable dynamic analyses. Moreover, the activities classification according to value is not an easy task, particularly for those companies that have not already implemented a lean production system. The latter goes beyond the isolated application of lean tools, it is a philosophy that should be shared and supported by all the company stakeholders. The full awareness of mission, pillars, procedures, tools, etc., should be ensured at each company level. Sometimes, this kind of change requires a lot of time and effort, and a change of mentality. Therefore, the effective implementation of the Resources Value Mapping method could require a long-term perspective.

In the next future, the method will be implemented in a software tool to allow the easier and guided application in real industrial contexts, the semi-automatic collection of data (through specific interfaces with company databases and Industry 4.0 technologies), the automatic calculation of the KPIs, as well as the automatic generation of the resource value maps. Additional efforts should be also put to validate and verify the reliability and robustness of the proposed metrics, particularly the Muda Index, in heterogeneous contexts (e.g. different industrial sectors, different processes, different resources). Another important direction of research could be the extension of the method to human resources, including the eighth Muda that refers to underutilized human capital and inadequate training. Furthermore, machine learning algorithms could be developed and implemented in the software tool to support the definition of the action plan, in order to ensure a proper knowledge management and enhancement.

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