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PLANTLCA: A lifecycle approach to map and characterize resource consumptions and environmental impacts of manufacturing plants

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Abstract

The paper presents a lifecycle approach applied to the whole factory plant to characterize primary resource consumptions and environmental impacts for the different processes. The method is based on specific environmental models, defined for each process of a manufacturing plant. The goal is to provide a tangible support to guide decision-making strategies in order to move manufacturing towards sustainability. A case study of a washing machine factory plant has been analyzed to highlight the critical working areas in terms of environmental and energy loads and to support the identification of the corrective actions to increase the overall sustainability.

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1. Introduction

Sustainable Development (SD) is becoming a global goal, determining competitiveness of many companies and manufacturing firms. National and international climate action policies are boosting the SD and the establishment of targets for the reduction of greenhouse emissions and carbon pollution (EC – European Commission, EPA – Environmental Protection Agency, etc.). Currently, there is an increasing consciousness on environmental problems caused by industrial activities and, therefore, the need to reduce the environmental impacts of manufacturing processes and technical facilities. Furthermore, many manufacturing companies combine the concepts related to the environmental and economic sustainability.

As a result, the environmental awareness has brought improvements in terms of environmental and economic performance at the same time [1]. The measurement of the efficiency of material and energy flow conversions is one of the first step towards the quantitative assessment on an economy complying with the principles of SD [2].

In this work, a framework based on factory data collection (IOA – Input-Output Analysis) and lifecycle principles (LCA – Life Cycle Assessment) is proposed to give a picture of the main environmental and energy loads of the different working areas for a generic manufacturing plant. The results can be used to support the decision-making process. Particularly, the assessment results represent a metric to support long-term decisions with the sustainability target.

The goal of this work is to develop a representative environmental model of each process of a manufacturing plant. A methodology for data collection and experimental measurement is proposed as a general tool useful for Life Cycle Inventory (LCI) phase in the case of manufacturing plants and facilities. This model can be used to better understand individual processes, and the areas of highest environmental concerns. More importantly, the assessment results will serve as a mean to compare the environmental performance of alternative manufacturing processes, product designs, and process plans.

The model has been developed for industrial companies oriented to manufacturing and assembly of electronic and mechatronic goods. A washing machine plant is proposed as a

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case study to validate the approach and to give a picture of the current environmental load (AS-IS situation). The step forward is the comparison of the AS-IS situation with the environmental performances of alternative manufacturing and assembly processes and new technologies (TO-BE).

2. State of the art

The implementation of Sustainable Manufacturing (SM) models, means thinking on industrial processes which use natural resources in a responsible manner, promoting the safety and the health of all those involved, and integrating the ecological aspects in the production processes [3].

Lowe and Evans [4] introduced the Industrial Ecology (IE), a multi-disciplinary approach, with emphasis on social sciences, referred to a globally organized closed-cycle economy.

Ayres and Simonis [5] introduced *Industrial Metabolism*, defining the concept of physical flow approach and focusing on manufacturing and industrial systems. In this, the interaction between the ecosystem (plant) and the external world is studied in terms of economical and physical flows [6]. Since that moment, the IE has been mainly focused on production sites and related emissions.

End-of-pipe approach has been traditionally used as a method to address pollution concerns at the point of discharge. End-of-pipe systems have been used for the media treatments such as water, air and soil with, for example, the addiction of filters or the use of other clean-up actions [7]. Since this end-of-pipe approach is often costly and ineffective (environmental problems solved per sector, pollution transfer from one media to another, etc.), industry has increasingly adopted Cleaner Production by reducing the amount of energy and materials used in production processes.

Cleaner production emphasizes a preventive approach to environmental management, taking into account impacts over the whole life cycle of products and services [8]. Many firms are now considering the environmental impact throughout the product’s lifecycle and are integrating environmental strategies into their own management systems [9].

Different methodologies have been developed and customized to overcome the limits of the aforementioned approaches, particularly with the aim to assess the economic and environmental performance of manufacturing plants.

Material flow analysis (MFA) is a widespread methodology for the systematic assessment of flows and stocks of materials within an arbitrarily complex system defined in space and time [10]. MFA has become an integral part of many environmental impact statements/assessments [11]. A major problem of MFA studies is the handling of uncertain or fuzzy data. So far, it is not state-of-the-art to consider uncertainties and their consequences, therefore, valuable information for decision-making gets lost [12].

The Input-Output Approach (IOA) has been developed for a very generic purpose. The fundamental information used in IOA concerns the flows of products (materials, goods, substances, etc.) from each industrial sector, considered as a producer, to each of the sectors, itself and others, considered as consumers [13]. The IOA has been customized to study and to take into account environmental issues (energy consumptions, water and land use, pollution, waste production, etc.) [14]. The IOA has long been recognised as a useful top-down technique to attribute pollution or resource use to final demand in a consistent framework. Nowadays, it is used intensively in the context of environmental economics, environmental LCA, scenario and policy studies, embodied pollution of trade and similar subjects that relate to sustainable production and consumption [15]. For example, more recently, the so called IO-LCA or hybrid-LCA, became more popular within the mainstream of LCA research community [16].

LCA is, currently, the most popular approach and tool used for the environmental assessment of products, services and human activities. A full life cycle perspective means the examination of the environmental impacts of products, processes, facilities or services from resource extraction through manufacture and finally to waste management [17]. However, LCA is a complex science which requires a high degree of expertise and is resource intensive. For manufacturing plants or facilities, the system boundaries should be limited in size, from cradle-to-grave to gate-to-gate (i.e. from raw material processing to transport on different site) which are the physical boundaries of the plant.

In conclusion, the literature review highlights the following limitations. Several approaches are mainly focused on the collection of material flows and input/output of a specific system without defining an analytic method for the assessment of environmental impacts. On the other hand, specific approaches (e.g. LCA) are time-consuming due to the collection and interpretation of large quantity of data coming from a complex system, such as a manufacturing plant, and require a high degree of expertize for the results interpretation and post-processing. This paper aims to answer to these two aspects: firstly, it proposes a method to collect and classify the data in a structured way and, secondly, it defines the way to process the data for the environmental analysis as well as the way to show the results for an easy understanding. A step beyond the state of the art is the definition of a specific model for the manufacturing plant environmental assessment (based on the Industrial metabolism concept) and the definition of the mathematical model for the environmental evaluation.

3. How to analyze the environmental sustainability of a factory plant?

The goal of this paragraph is to describe a method for the environmental impact assessment of manufacturing plants and how the plant can be modelled for a lifecycle analysis.

3.1. Plant System Model

The idea developed and proposed in this work is the evolution of the *industrial metabolism* concept, shifting the viewpoint from the economical side to the production side (material flows and transformations). In particular, the approach consists in considering the plant as a person during its life and to compare the *human metabolism* vs. the *industrial metabolism* (see Fig. 1).

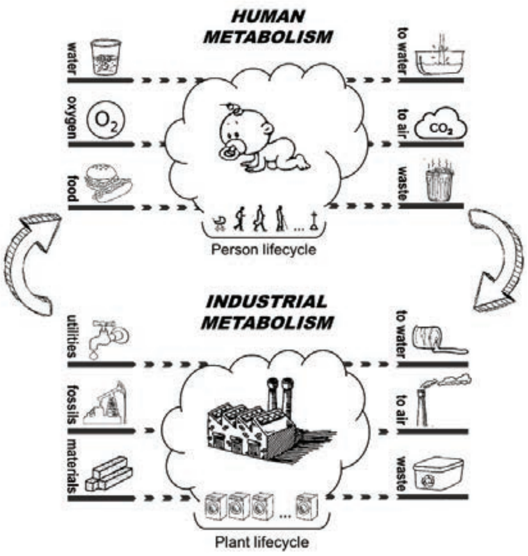

Fig. 1. Parallelism between *human metabolism* and *industrial metabolism* and definition of plant lifecycle.

In the case of *human metabolism*, the person lifecycle is clearly stated from cradle to grave of the person himself. Therefore, the person system boundary is temporally defined in this timeframe. The person growth is considered part of the system because it is the result of the metabolism inputs, (digestion and absorption of nutrients). Emissions to the environment are considered as outputs (digestion scraps).

In the case of the *industrial metabolism*, the plant lifecycle is connected to the product, but the product concept needs a further investigation to fix the boundaries of the system. A general rule is to consider the plant lifecycle limited to a specific product technology, independently from the different product models under manufacturing.

Inside the same product technology, the plant can be built in different ways. Some product components can be internally manufactured or alternatively bought from suppliers. Furthermore, the technology level inside the plant for the same product technologies can be different, based on several aspects, such as investments, plant age, etc.

Starting from this point, the plant system boundary is temporally defined from the birth of a new technology to the end of the same technology. In this timeframe, a focus on specific production periods or manufacturing situations can be done. The plant system boundary, instead, is spatially defined and confined within the walls of the plant (facility). In this way, the plant can be considered as a black box with its I-O flows (see Fig. 1 for industrial metabolism). The plant has in input different items such as Materials, Fossils and Utilities. The output are the different kinds of emissions/pollutions to the environment: to water, to air and to soil (waste).

It is important to understand that the product itself is not considered as a system output because it is the result of the manufacturing process (digestion and absorption of nutrients). Instead, the material scraps are considered as system outputs because they are used during the manufacturing process, but they will not take part of the final product (digestion scraps).

3.2. Methodology for manufacturing plant analyzing

The environmental sustainability analysis of a production plant requires the realization of three fundamental steps. First of all, the necessary I-O fluxes have to be classified and collected. Then, these data have to be processed through specific algorithms to calculate the environmental loads. Finally, an interpretation phase (post-processing) is needed to identify criticalities and set-up optimization strategies. The next sub-sections explain the details for each step.

3.2.1. Data Classification and Collection

The univocal identification of all the necessary fluxes to consider in the analysis is an essential activity to perform for the environmental assessment of a production plant. Following the industrial metabolism concept, all the fluxes related to the plant activities (e.g. production processes, HVAC systems, etc.) have to be considered in the analysis, while all the fluxes directly related to the product have not to be inserted in the calculation model. The following Table 1 reports the detailed classification of the I-O fluxes considered in the proposed approach. This classification is based on previous literature studies about I-O of manufacturing activities (see for example [13][14][18][19]) and on the observation of several case studies regarding different industrial sectors (e.g. household appliances, automotive, textile and shoes, etc.).

Inputs contain all the resources consumed by the different production processes of the factory. They include *Materials*, which are the primary and auxiliary materials used, *Fossils*, which are the fuels used within the plant, and *Utilities*, which are the fundamental supplies commonly used by processes (water, compressed air, etc.). As highlighted above, in the proposed approach Raw Materials are only represented by the scraps generated by manufacturing processes. Thus, the Raw Materials flux can be quantified, measuring (or estimating) the scraps of each manufacturing station, or alternatively can be calculated as the difference between the input materials, bought from suppliers, and the materials which effectively constitute final products.

Except the three main categories (*Materials*, *Fossils* and *Utilities*), input fluxes also include *Transports* and *Maintenance*, which are modelled as a sort of additional inputs used within the factory system boundaries. The first category considers the energy consumption associated to the movements of goods within the factory. In the proposed approach Transports are treated separately from fuels and electricity in order to have a more detailed modelling of the factory fluxes. If only aggregated data about energy consumption are available, transport and energy contributions can be considered together. Maintenance category, instead, considers all the aspects relative both to ordinary and extraordinary maintenance of factory equipment.

Outputs include all the fluxes that exit from the factory boundaries and are not included in final products. This is the case of emissions of substances in the air or liquid emissions or even solid wastes which are successively landfilled.

Table 1. Classification of fluxes

Type of Flux	Main Category	Sub-category	Description
Input	Materials	Raw Materials	Scraps of Input materials generated by the production of the product components (e.g. scraps of PVC, etc.)
		Pure Materials	Accessory materials used by processes (e.g. zinc, chromium, etc.)
		Chemical Agents	Solid or liquid chemical substances used by processes (e.g. phosphoric acid, etc.)
		Gases	Gases used by processes (e.g. Ar, He, etc.)
	Fossils	Fuels	Fossil fuels used by the factory (e.g. methane, diesel, etc.)
	Utilities	Air	Compressed air used by processes
		Electricity	Electricity used by processes with the relative production mix (e.g. EU mix, photovoltaic generation, etc.)
		Water	Water used by processes with its origin (e.g. tap water, river water, etc.)
	Others	Maintenance	Maintenance items (e.g. materials, energy, etc.)
		Transport	Transports internal to the factory plant (e.g. forklift, etc.)
Output	Emissions	Air emissions	Substances emitted into the air by processes
		Liquid emissions	Substances emitted into the wastewater by processes
	Wastes	Industrial wastes	Solid wastes generated by production processes and successively landfilled (e.g. packaging of materials)
		Other wastes	Solid wastes not generated by production processes (e.g. offices, etc.)

Regarding the collection of all the classified fluxes, they can be referred to single manufacturing stations, entire productive lines or factory areas. It depends if the final objective is to have an overall vision of the factory environmental impacts and resource consumptions or if a detailed map is needed. Furthermore, in a real context it could be difficult to have available very specific data about single processes, since it requires the measurement of each I-O flux (e.g. monitoring equipment to measure real-time energy consumptions). Thus, some fluxes can be estimated on the basis of aggregated data (e.g. electricity consumption of productive areas) and considering mean or ideal consumption of single equipment. Obviously, the more precise are the initial data the more significant will be the environmental impact estimations and the consequent optimization strategies.

3.2.2. Data Processing

I-O fluxes represent the primary data directly coming from the factory. However, in order to calculate the environmental impacts, it is necessary to correlate them with secondary data relative to the unitary environmental impacts of each I-O flux, coming from commercial LCA DBs (e.g. *Ecoinvent*).

Concerning each Material flow, two different items contribute to the environmental impact: production and dismantling of materials. Thus, the Materials environmental impact EI_{MAT} is calculated on the basis of the following equation:

$$EI_{MAT} = \sum_{n=1}^{N} (q_n \cdot UEI_{PRO,n} + q_n \cdot UEI_{EoL,n}) \quad (1)$$

where N is the number of different materials used, q_n is the quantity of the *n-th* material, $UEI_{PRO,n}$ is the unitary environmental impact relative to the production of the *n-th* material and $UEI_{EoL,n}$ is the unitary environmental impact relative to the dismantling of the *n-th* material. It is important to restate that the quantities to consider in the calculations are only relative to material scraps, while the materials which follow the Product flow has to be neglected.

The environmental impact relative to Fossils, Utilities Transports, Emissions and Wastes $EI_{FOS,UTI,TRA,EMI,WAS}$ is calculated considering the quantities consumed by each process:

$$EI_{FOS,UTI,TRA,EMI,WAS} = \sum_{p=1}^{P} (q_p \cdot UEI_p) \quad (2)$$

where P is the number of different fluxes, q_p is the quantity of the *p-th* flux and UEI_p is the unitary environmental impact relative to the *p-th* flux.

The contributions relative to Maintenance (EI_{MAI}) can be estimated summing the impacts related to the needed auxiliary materials (e.g. lubricants), components to substitute (e.g. environmental impact of new parts to substitute broken components), and the necessary energy used during maintenance operations (e.g. cleaning). The impacts related to the ordinary maintenance can be calculated considering the maintenance plan, reported in the maintenance manual of each machine, from which it is possible to extract the replacement interval of components. For the extraordinary maintenance, instead, the data used for the calculations are the same considered for the ordinary one, but the replacement interval is estimated on statistical basis.

The arithmetic sum of each contribute represents the final environmental impacts of each process. The overall factory impact can be finally obtained considering the contributions of each process directly (e.g. manufacturing of components) or indirectly (e.g. waste management processes, office activities, etc.) needed for the factory life.

3.2.3. Post-processing

After the impact assessment, the last phase of the approach is represented by the interpretation of results, necessary to "take a detailed picture" of the current plant situation.

Different methods and indicators (both midpoint and endpoint) can be used to assess the impacts of factories. In the proposed approach the following have been chosen:

- Cumulative Energy Demand (CED) [MJ] which represents a good entry point for a lifecycle energy analysis and it is particularly useful as screening indicator [20];
- ReciPe Endpoint [Pt], a damage oriented indicator simple to understand and useful to compare different scenarios in a detailed way [21];
- Climate change [kg CO2 eq] [21], which is the most common indicator to consider the influence of the factory activities on climate changes as the global warming;
- Terrestrial acidification [kg SO2 eq] [21], which is strictly correlated to air emissions;
- Freshwater eutrophication [kg P eq] [21], which is strictly correlated to water emissions;

Other indicators can be used since the approach is general. The choice essentially depends on the typology of the considered factory. For example, in the context of chemical industry, toxicity indicators cannot be neglected.

The proposed approach represents a useful support for companies towards the implementation of sustainable manufacturing principles, which include zero waste, fewer raw materials, optimization of process parameters, infrastructure management, etc. If a firm defines an internal environmental sustainability policy, the quantitative evaluation of resource consumptions and environmental impacts is a necessary step to identify the best corrective actions to implement.

This lifecycle approach can also guide companies during the decision-making process for the refurbishment of productive plants. Comparing alternative technologies to realize the same manufacturing process (e.g. MIG welding vs continuous spot welding), it is possible to choose the most sustainable one, trying to avoid impacts before they occur. These evaluations can be also used for environmental make-or-buy analyses (i.e. to manufacture components internally or to buy them from suppliers equipped with more sustainable technologies).

Concerning standard and regulations, in the last years new documents have been developed with the final scope to protect the environment from the impacts caused by the industrial activities (e.g. emissions to air, water and land, generation of waste, use of raw materials, energy efficiency, noise, etc.) [21]. Also for this purpose, the proposed approach can be very useful to verify the compliance of a company with these standards.

Finally, results of the lifecycle analyses can be used for the optimization of production lines. Following the continuous improvement concept, the scheduling of production processes can be set to maximize resource efficiency and/or minimize environmental impacts, avoiding, for example, waste of energy during stand-by.

4. Case study: a washing machines manufacturing plant

An existing washing machines (WM) factory plant has been analyzed using the proposed approach. The presented plant can be considered as an interesting test case because it includes in-house manufacturing processing, assembly lines, testing laboratories, warehouses, ancillary systems, etc. A general layout of the plant with the main manufacturing areas is described below (Fig. 2).

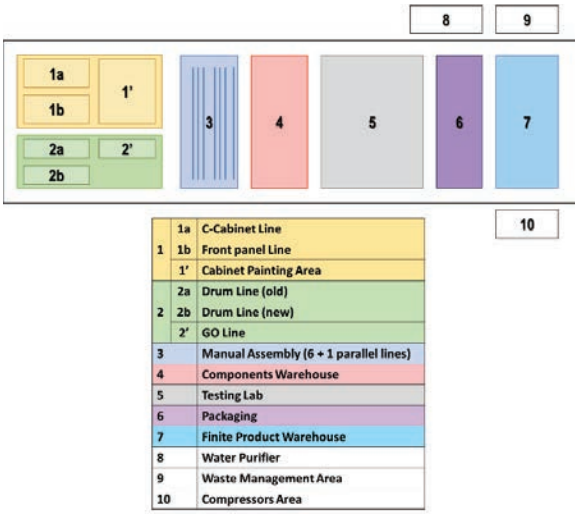

Fig. 2. General WM manufacturing plant layout.

The goal of the analysis is to assess the environmental impacts of the manufacturing plant and to make a picture of the factory with the identification of the critical working areas in terms of pollution and energy demand.

4.1. Plant data collection

As a first step of the approach application, an I-O analysis has been performed. A data collection example for the *C-Cabinet line* (1a) and the *Front panel line* (1b) is depicted in Fig. 3.

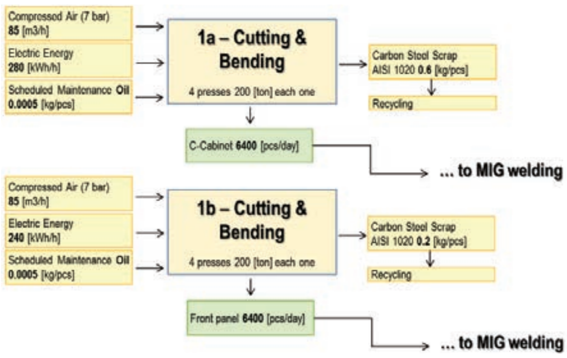

Fig. 3. I-O analysis examples for the Cutting & Bending process of *C-Cabinet line* and *Front panel line*.

The functional unit considered for the analysis is a standard manufacturing day with a production rate of 6400 WM/day. The analysis has been conducted for each area of the factory plant and related to the defined functional unit. The system boundaries are limited within the walls of the plant and include the waste scenarios for the scraps (from gate to grave). For instance, steel scraps are recovered by a consolidated system of collection and material recycling.

4.2. Data processing and results interpretation

The lifecycle analysis has been done using a dedicated LCA software tool (*SimaPro 8.1*) and secondary flow datasets coming from the *Ecoinvent 3.1* repository. Two different LCIA methods have been used for the impact assessment calculation: the ReCiPe midpoint and the Cumulative Energy Demand (CED). An overall picture of the results concerning the Climate Change midpoint indicator is proposed in Fig. 4.

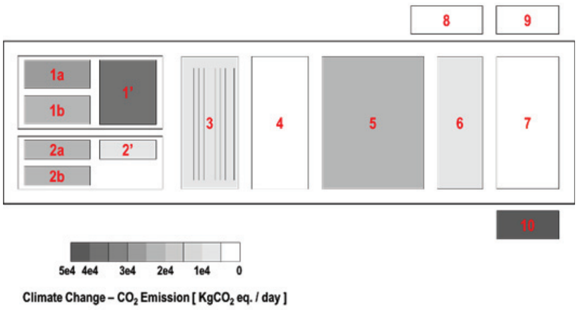

Fig. 4. Contoured map of the plant for the Climate Change indicator.

The *Cabinet Painting Area* (1') and the *Compressors Area* (10) are the most critical areas of the plant considering the CO_2 emissions. The two areas can be considered as a target for possible alternative technologies with the aim to reduce the environmental impacts and improve the overall plant sustainability. The analysis can be used as a tool for the plant change management actions focusing on sustainability.

5. Conclusions

The proposed approach, based on industrial metabolism and LCA, allows to quantitatively assess the lifecycle impacts of industrial plants. A hierarchical model is used to map the I-O fluxes of each manufacturing process or line, production area or working site. The results coming out from the estimations represent a fundamental feedback for companies to identify the most critical areas in terms of resource consumptions, scraps or pollutant emissions. The approach can be used to compare alternative technologies or to perform environmental make-or-buy analyses. Quantitative indicators will guide the decision-making process towards the definition of effective improvement strategies.

Future works will be focused at first to verify the approach robustness through the application in different industrial sectors. Then, the implementation in a software tool will help companies in the environmental sustainability estimation.

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