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ANALISI DI SOSTENIBILITA' AMBIENTALE DEI PROCESSI INDUSTRIALI

Abstract

Il lavoro di questa tesi si propone come introduttore e suggeritore di una serie di tecniche, strumenti e pratiche di monitoraggio e controllo degli aspetti ambientali legati al ciclo aziendale. Lo strumento attualmente in uso oggi nelle imprese, che funge da guida nella ristrutturazione in ottica ambientale delle proprie attività è l'LCA, sul quale si basa l'approccio delle 6R e le strategie di sviluppo suggerite: REDUCE, REMANUFACTURING, REUSE, RECOVER, RECYCLE, REDESIGN. L'obiettivo di fornire alle imprese strumenti utili in ottica sostenibile viene affrontato inquadrando le diverse analisi condotte nella tesi all'interno di due linee guida fondamentali: controllo dei costi e valutazione dell'impatto ambientale allo stesso tempo. Dunque, l'obiettivo è duplice e complesso: il solo traguardo morale non è sufficiente alle imprese per rimanere competitive. Dunque, costi e impatto ambientale diventano obiettivi alla pari anche se a volte apparentemente contrastanti.

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CICLO

XXVIII

ENVIRONMENTAL SUSTAINABILITY ANALYSIS OF INDUSTRIAL PROCESSES

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Index

Figures' index

Tables' index

Introduction

“Industry” is synonymous with one of the essential components of the process of civilization, and therefore indicates a phenomenon whose beginning can be traced back to about ten thousand years ago. “Industrialization” is considered a key component of the industrial revolution that is, a phenomenon that began to manifest itself at the most three centuries ago and from which descends the present world.

On the other hand, the industry has not yet emancipated from a double terrible finality that accompanied his birth: the first products industry were at once weapons and tools. Flints of the Early Pleistocene roughly machined served, in all probability, either to kill or to tear the animals; since then the same craftsman, the same worker, the same lab, the same workshop produced, separately or together, weapons and tools, swords and plows, tanks and tractors, missiles and space crafts. Moreover, often the weapon preceded the instrument. Recently, the production of work tools and consumer goods, for the volume that reached, has come to transform the industrial waste in dangerous poisons for humans and the environment. In addition, more or less short time away looms the danger of seeing the rapid development of industry land to paralysis due to the scarcity of natural resources [1].

It is of human the ability, the experience and the knowledge to limit the environmental damage caused by this important and fundamental industrialization process, so that the humanity can continue innovating, progressing and discovering, but also “living”.

Hence, the growing and urgent attention to the worldview of sustainability in its three dimensions social, economic and environmental. The “industry” is the factor that most influences the sustainable balance of the world: on one side, it causes civilization, culture, knowledge. Development of skills and innovation with all that implies as better education, specificities of educational paths aimed at an easier and directed entry into the working world. Aggregation of the old villages in towns, cities, metropolis. All these implications and many others have been and will be directed by the industrialization phenomenon that has seen changing the world in a very short time. On the other hand, industrialization has led the world in a truly critical environmental situation. Therefore, the man had the ability to upset the world, both negatively and positively. However, it is necessary a global disaster to understand when react and addresses the progress in the right direction. It is what is happening from an environmental perspective. In particular, the industrial sector plays an important role in the global economy (Energy Sectorial Consumption: 52% industrial, 14% residential, 7% commercial, 27% transport) [2]. So it becomes important monitoring its environment impact which increases from year to year and which is one of the most relevant percentage that determines the global pollution.

In this work, the problem of industrial processes sustainability is addressed from different points of view employing several case studies, experimental and real ones. The taken approach will give theoretical explanations related to research carried out so far in this area and, at the same time, will prove empirically what are the steps to take to address the production activities towards sustainability.

Therefore, in the first chapter the sustainability issue will be widely exposed, explaining the beginnings of the terminology and the first activities undertaken from this point of view. The discussion will focus on the organs that have the task to monitor this issue and the established global targets by the Nations. Finally, ample space to the issue of sustainability in industries will be given: how companies seek to transform their production in a sustainable direction and what are the macro strategies and activities undertaken for this purpose.

The second chapter will expose widely the macroeconomic aspect of the environmental choices made by companies. It is true, in fact, that a company has interest in monetization of all its activities. Therefore, it is necessary to show that converting the production in a sustainable direction is suitable not only under an environmental point of view but also in an economic one. As evidence of this, this paper offers several empirical tools available to draw conclusions. In the second chapter, the company's macro-economic aspect will address. An evaluation model of environmental costs already known in the literature will be considered, the Environmental Management Accounting (EMA). It will be applied to a real business case related to a manufacturing company, leader in the world in mechanical material production (SKF). The results provided by such a model are not exhaustive in practice for companies. Therefore, a serious of performance indexes will be added in order to give information that is more accurate to the companies that decide to take the way of environmental sustainability.

In the third chapter, the issue of sustainability in business is dealt from a microeconomic point of view. In fact, if the macroeconomic side is important to understand how the company is positioned in in the environmental context, referring to factors such as human resources, research & development, production plant size. On the other hand, it is essential to analyze the processes from below. Therefore, it is important to understand whether a production process generates too much production waste going to significantly raise the level of pollution; or if there is an excessive use of lubricants or if the machines are obsolete and so the energy consumption are excessive. All these factors become part of a detailed cost model that quantifies the emissions of CO_2 generated by the finished products production, monetizing them. The model is comprehensiveness and universality and this is a fundamental aspect for a company. It is independent from where the company is located. It can consider *m* raw materials to realize *n* output product. Therefore, this model goes beyond all theoretical model known in literature, incorporating in it all possible aspects interesting for a company. This model is applied to two case studies: an experimental case and a real one. The first is conducted at the technical laboratories of Mechanical, Energy and Management Engineering Department (DIMEG) of University of Calabria. It provides for the calculation of the *industrial full cost* for an aluminum profile achieved through the innovative Incremental Sheet Forming Process (SPIF). The second case is referred to the production of industrial bearings for the company SKF. For both outputs will be carried on a sensitivity analysis in order to better understand which factors most affect the increase of environmental costs.

In the fourth chapter, the focus is on the comparison between traditional and innovative production processes. Often it is convinced that new technologies bring only benefits. In reality it is not always so. Therefore, a chapter that enters in the details of the new manufacturing process for 3D molding, which goes to replace old processes for chip removal or molding with die. It will be widely exposed the new production process in its various forms. Finally, it will be considered the production of a piece with traditional molding and with Additive Manufacturing. It will be assumed an optimum amount of production and analyzed the results. The second study case considered regards the comparison between Incremental Forming and Stamping of sheet metal. In addition, here, a sensitivity analysis will be conducted to better understand what are the influential factors from the environmental costs point of view.

Finally, in the fifth chapter, the recycling issue is dealt with. In the production chain, in fact, the last step, waste disposal, is today one of the most urgent factors for today's population. The pollution has now reached exaggerated level and the waste produced by manufacturing firms contribute significantly to this factor. It has been noticed, however, that in many cases it is possible to recover the discarded material in different ways. Indeed, it is often cheaper to produce from recycled materials and not turn to the extractive industries. In this chapter, a case of this type will be presented, taking into consideration a food containers aluminum manufacturer.

Chapter 1

Sustainability: the secret ingredient of the new millennium

“Sustainability” *is the ability to be maintained at a certain rate or level* [3].

“Sustainable development” *is development that meets the needs of the present without compromising the ability of future generations to meet their own needs* [4].

The principle of ***“The Three Pillars of Sustainability”*** *says that for solving the complete sustainability problem all three pillars of sustainability must be sustainable. The pillars are social, environmental, and economic sustainability* [5].

The previous lines contain the key official definitions related with the sustainability concepts and, consequently, with the sustainable activities worldwide.

In the following chapter, sustainability definition is going to be more thoroughly exposed. From the birth of the concept of sustainability to date, we will retrace the milestones of sustainable development throughout the world, focusing on the industrial sector, of our interest. We will try to understand how the sustainability concept has gradually transformed the companies’ behavior and as it often coincides with the inexpensiveness one for them.

1.1. Sustainability and its promoter: UN

The first time that attention was drawn to the need to preserve natural habitats to produce a sustained improvement in living conditions for all was in the UN Conference on the Human Environment in Stockolm in 1972.

The United Nations (UN) is the principal initiator and driver of sustainable development at the international level. It is an intergovernmental organization established on 24 October 1945 with the aime to promote international co-operation. Its objectives include: maintaining international peace and security, promoting human rights, fostering social and economic development, protecting the environment, and providing humanitarian aid in cases of famine, natural disaster, and armed conflict. UN established various specialized agencies to fulfill its duties. Some best-known agencies are the International Atomic Energy Agency (IAEA), the Food and Agriculture Organization (FAO), the United Nations Educational, Scientific and Cultural Organization, (UNESCO), the United Nations Children's Emergency Fund (UNICEF). A number of UN agencies and programmes are active in one or more areas of sustainable development, such as the UN Environment Programme (UNEP), the International Labour Organization (ILO), the World Health Organization (WHO) and the UN Development Programme (UNDP). Furthermore, it exists the High Level Political Forum on sustainable development (HLPF) with the aim to implement the sustainable development and strengthen the international governance.

But what is meant by *sustainable development*?

The official definition of <<*sustainable development*>> was published in 1987 with the Brundtland Report by UN. Really, first of all, the sustainability problem born some time before from issues such as deforestation and natural landscape changing. In addition, the oil crises in 1970s and the following energy one stimulate to reflect on the excessive dependence on fossil fuels of the world economy and the need of having to turn to other forms of energy sources. Since this moment, expressions as <<*ecology*>> and <<*energy saving*>> start to enter the common vocabulary. In 1972, the Club of Rome published its report on «The Limits to Growth», which attracted enormous attention in the climate of the Stockholm Conference. It is now that in the international debate the issue of unsustainability of a development model that considers the planet as an inexhaustible mine of resources at our disposal enters with force. Exactly in this year, 1972, the first UN conference on sustainability issues.

The UN milestones in sustainable development are the following [6]:

- 1972: UN Conference on the Human Environment, Stockholm;
- 1987: Brundtland Report;
- 1992: UN Conference on Environment and Development, Rio de Janeiro;
- 1997: Rio+5 Conference, New York;
- 2002: UN World Summit on Sustainable Development, Johannesburg;
- 2012: Conference on Sustainable Development Rio+20.

In 1992, 172 nations met in Rio de Janeiro at the United Nations Conference on Environment and Development (UNCED), to seek solutions to issues such as poverty, the growing gap between industrialized and developing countries, and growing environmental, economic and social problems. Here, Environmental conservation and social and economic development were all accorded equal weight.

Fig. 1.1: Economy, Social and Environmental Sustainability [7]

The participating countries signed three agreements and two conventions. Among theese, the *Agenda 21*, a global action plan for the 21st Century, divided into four sections: Social and economic dimension, Conservation and management of resources for development, Strengthening the role of major groups and Means of implementation.

The Rio+5 Conference was the first comprehensive status review of work to implement the UNCED's agreements. This Conference aimed to revive and strengthen commitment to sustainable development, ascertain failures and identify the reasons in each case, recognize achievements, set priorities and determine problems that had not been addressed sufficiently in Rio.

The objective of the World Summit on Sustainable Development (WSSD) was to examine the implementation of resolutions made at the conference in Rio, with a particular focus on Agenda21. Problems such as social justice, dialogue between cultures, health and development were given greater weight than at the previous summits in Stockholm (1972) and Rio de Janeiro (1992). Furthermore, a clearer link was drawn between poverty and the state of the environment.

The international community wished to renew its political commitment to sustainable development, assess the progress to date and the gaps remaining in the implementation of the decisions made during previous conferences, and identify solutions to new challenges. The outcomes of the conference are recorded in the final fifty-page document entitled "The Future We Want”. The main outcomes are the following:

- a landmark decision has been taken in order to launch a process to define the sustainable development goals;
- the Rio document urges states to implement a green economy as an integral part of their sustainable development policy;
- a high-level political forum for sustainable development will be launched, replacing the current Commission on Sustainable Development;
- the United Nations Environment Programme (UNEP) will be strengthened.

By the UN Conferences of 1992, 2002 and 2012, the 2030 Agenda was established on 25 September 2015, in order to end poverty, protect the planet, and ensure prosperity for all as part of a new sustainable development agenda was adopted. Each goal has specific targets to be achieved over the next 15 years. In the 2030 Agenda are defined the 17 sustainable development goals to transform the world [8]:

- G1: End poverty in all its forms everywhere.

- G2: End hunger, achieve food security and improved nutrition and promote sustainable agriculture.
- G3: Ensure healthy lives and promote well-being for all at all ages.
- G4: Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all.
- G5: Achieve gender equality and empower all women and girls.
- G6: Ensure availability and sustainable management of water and sanitation for all.
- G7: Ensure access to affordable, reliable, sustainable and modern energy for all.
- G8: Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all.
- G9: Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation.
- G10: Reduce inequality within and among countries.
- G11: Make cities and human settlements inclusive, safe, resilient and sustainable.
- G12: Ensure sustainable consumption and production patterns.
- G13: Take urgent action to combat climate change and its impacts.
- G14: Conserve and sustainably use the oceans, seas and marine resources for sustainable development.
- G15: Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss.
- G16: Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels.
- G17: Strengthen the means of implementation and revitalize the Global Partnership for Sustainable Development.

Fig. 1.2: Sustainable Development Goals [8]

1.2. Sustainability in industrial context

Industry is central to the economies of modern societies and an indispensable motor of growth. It is essential to developing countries, to widen their development base and meet growing needs. Many essential human needs can be met only through goods and services provided by industry. The production of food requires increasing amounts of agrochemicals and machinery. Beyond this, the products of industry form the material basis of contemporary standards of living. Thus all nations require and rightly aspire to efficient industrial bases to meet changing needs. Industry extracts materials from the natural resource base and inserts both products and pollution into the human environment. It has the power to enhance or degrade the environment; it invariably does both.

Observing historical trend of industrial sector, there is a high grow of manufacturing sector production until 1973 with slight slowdown in the next ten years: especially manufacturing industry is more subject to this surge, followed by mining one, with the consequent increase of the environmental pollution. In subsequent years, this trend is reversed simultaneously with the more attention on environemtal impact: the industries start to produce more with less while the light industry takes greater importance [9].

In the light of the studies conducted on the pollution level of the planet, which is too high and not more manageable if it continues to grow at this rate, it is evident that measures to reduce, control, and prevent industrial pollution will need to be greatly strengthened. If they are not, pollution damage to human health could become intolerable in certain cities and threats to property and ecosystems will continue to grow. Fortunately, the past two decades of environmental action have provided governments and industry with the policy experience and the technological means to achieve more sustainable patterns of industrial development. At the beginning of the 1970s, both governments and industry were deeply worried about the costs of proposed environmental measures. Some felt that they would depress investment, growth, jobs, competitiveness, and trade, while driving up inflation. Such fears proved misplaced. A 1984 survey by OECD (Organisation for Economic Co-operation and Development) of assessments undertaken in a number of industrial countries concluded that expenditures on environmental measures over the past two decades had a positive short term effect on growth and employment as the increased demand they generated raised the output of economies operating at less than full capacity. The benefits, including health, property, and ecosystem damages avoided, have been significant. More important, these benefits have generally exceeded costs.

However, to develop more sustainable societies, industries need to better understand how to respond to environmental, economic and social challenges and transform industrial behavior. The industrial world should follow a more environmentally and economically sustainable future for all manufacturing with a resilient industrial sector adapting to uncertain future conditions and operating their businesses in ways that do not compromise the needs of future generations. So it becomes important carrying out effective interdisciplinary research that delivers ideas, knowledge and solutions in management practice, technology and policy to create lasting impact for the whole manufacturing sector. To make this, some fundamental steps could be the following:

- Understanding factory performance and developing tools to drive effective reductions in the use of resources;
- Providing the systems and tools to design and manage the next generation of factories;
- Providing frameworks for sustainable business models;
- Enabling and driving sustainable industrial policy development.

Firms involved in food processing, iron and steel, non-ferrous metals, automobiles, pulp and paper, chemicals, and electric power generation - all major polluters have borne a high proportion of the total pollution control investment by industry. Such costs provided a strong incentive for many of these industries to develop a broad range of new processes and cleaner and more efficient products and technologies. In fact, some firms that a decade ago established teams to research and develop innovative technologies to meet new environmental standards are today among the most competitive in their fields, nationally and internationally. Waste recycling and reuse have become accepted practices in many industrial sectors. Innovative products and process technologies are also currently under development that promise energy- and resource-efficient modes of production, reducing pollution and minimizing risks of health hazards and accidents. Not only have these industries become more efficient and competitive, but many have also found new opportunities for investment, sales, and exports. Looking to the future, a growing market for pollution control systems, equipment, and services is expected in practically all industrialized countries.

1.3. Strategies for Sustainable Industrial Development

Industrial growth is widely seen as inevitably accompanied by corresponding increases in energy and raw material consumption. In the past two decades, however, this pattern appears to have fundamentally changed. As growth has continued in the developed market economies, the demand for many basic materials, including energy and water, has levelled off; in some cases, it has actually declined in absolute terms. All this has been possible thanks to the sustainable development strategies undertaken by companies in order to limit pollution from the analysis of the entire life cycle of the product/service.

In fact, industry and its products have an impact on the natural resource base of civilization through the entire cycle of raw materials exploration and extraction, transformation into products, energy consumption, waste generation, and the use and disposal of products by consumers. These impacts may be positive, enhancing the quality of a resource or extending its uses. Or they may be negative, as a result of process and product pollution and of depletion or degradation of resources.

In particular, the Life Cycle Assessment (LCA) scheme is represented in figure 1.3.

Fig. 1.3: Life Cycle Assessment

LCA is a systematic set of procedures for compiling and examining the inputs and outputs of materials and energy and the associated environmental impacts directly attributable to the functioning of a product or service system throughout its life cycle. It is a technique for assessing the potential environmental aspects and potential aspects associated with a product (or service), by [10]:

- compiling an inventory of relevant inputs and outputs,
- evaluating the potential environmental impacts associated with those inputs and outputs,
- interpreting the results of the inventory and impact phases in relation to the objectives of the study.

Life-cycle assessment has emerged as a valuable decision-support tool for both policy makers and industry in assessing the cradle-to-grave impacts of a product or process. Three forces are driving this evolution. First, government regulations are moving in the direction of "life-cycle accountability;" the notion that a manufacturer is responsible not only for direct production impacts, but also for impacts associated with product inputs, use, transport, and disposal. Second, business is participating in voluntary initiatives which contain LCA and product stewardship components. Third, environmental "preferability" has emerged as a criterion in both consumer markets and government

procurement guidelines. Together these developments have placed LCA in a central role as a tool for identifying cradle-to-grave impacts both of products and the materials from which they are made.
Summarizing, LCA is today the basis of the company's business restructuring in a sustainable direction: it suggests at what stage of a product/service life cycle must act in order to pursue the corporate goal of "sustainability".

The next step is to understand which strategy to undertake on the basis of the results obtained from LCA analysis, with the help of 6R's approach (fig. 1.4) [11]:

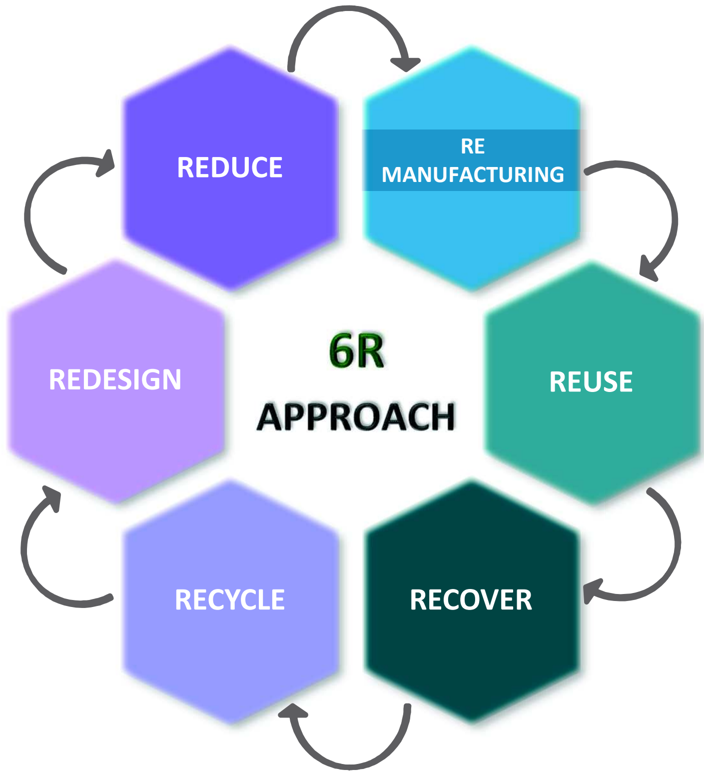


Fig. 1.4: 6R Approach

Six the activities which could change, if applied, the pollution history of the world:

- REDUCE: The first and most effective component of the waste hierarchy is reducing the waste created. Consumers are encouraged to reduce their waste by purchasing in bulk, buying items with less packaging and switching to reusable instead of single-use items. Businesses can adopt manufacturing methods that require fewer resources and generate less waste. In addition to benefiting the environment, these efforts often offer consumers and businesses the financial incentive of lower expenses in purchases.

- REMANUFACTURING: The production process should adapt to the new sustainable trends, creating more streamlined and reusable products, resulting from the redesign and reuse activities. Therefore, the new production chains must be able to work recycled and recyclable raw material, not use indirect raw material with a high environmental impact and consume less energy.
- REUSE: Despite efforts to reduce the amount of waste generated, consumers and businesses still create substantial waste. The U.S. Environmental Protection Agency (EPA) estimates that in 2013, Americans generated about 254 million tons of trash [12]. Much of this waste can immediately be reused to minimize the strain on the environment and municipal waste management. For example, consumers can refill a purchased bottle of water with water from home to minimize the number of plastic bottles being discarded. Consumers have a financial incentive here as well, as municipal water is far cheaper than bottled water.
- RECOVER: If it is not possible use the decommissioned product as it is discarded, a suitable alternative is to use its parts to realize something else.
- RECYCLE: When waste is eventually discarded, segregating items for recycling from other waste is important. Recyclables include glass, newspaper, aluminum, cardboard and a surprising array of other materials. Lead, for example, has one of the highest recycling rates because of laws requiring the recycling of lead-acid batteries.
- REDESIGN: It is foundamental re-design the good or service in a more sustainable way, considering the recyclable materials that could be used to make the product and the need to reduce the amount of raw material used in production (in order to facilitate the next reduce activity).

The six activities described are linked by a cyclic relation.

To define the strategy which a company have to pursue to become more sustainable, it is improtant to choose basing on two main aspects togheter: costs and environmental impact (fig. 1.5).

Fig. 1.5: 6R Approach between Cost and Environmental Impact Assessment

The core of the 6R approach is to consider all the six “R” activities under the dual profile of costs and environmental impact. In fact, for companies, it is essential to quantify and monetize all the aspects concerning it: only in that way it can do the appropriate considerations for own business. To make this, two are the cost levels considered in a company: macroeconomic and microeconomic ones.

In a company, *macroeconomic considerations* are the study of the behavior of the whole (aggregate) enterprise with its different economic activities. It is concerned primarily with the forecasting of company income, through the analysis of major economic factors that show predictable patterns and trends. These factors include taxes, depreciation for equipment, human resource, research and development investments and other aspects.

At *microeconomic level*, the considerations are different and become more varied and complex as the level of detail lowers. Therefore, the study is referred to individual units of an enterprise (such as a human resource, a product, or a factory line) and not of the aggregate business ones (which is the domain of macroeconomic level). It is primarily concerned with the single factors as the various cost rates of a goods, how the single rates could influence the total product cost and so what actions the decision makers must take.

In the light of the above, the economic and environmental analysis, at enterprise level, must be conducted in two respects: microeconomic and macroeconomic ones (fig. 1.6).

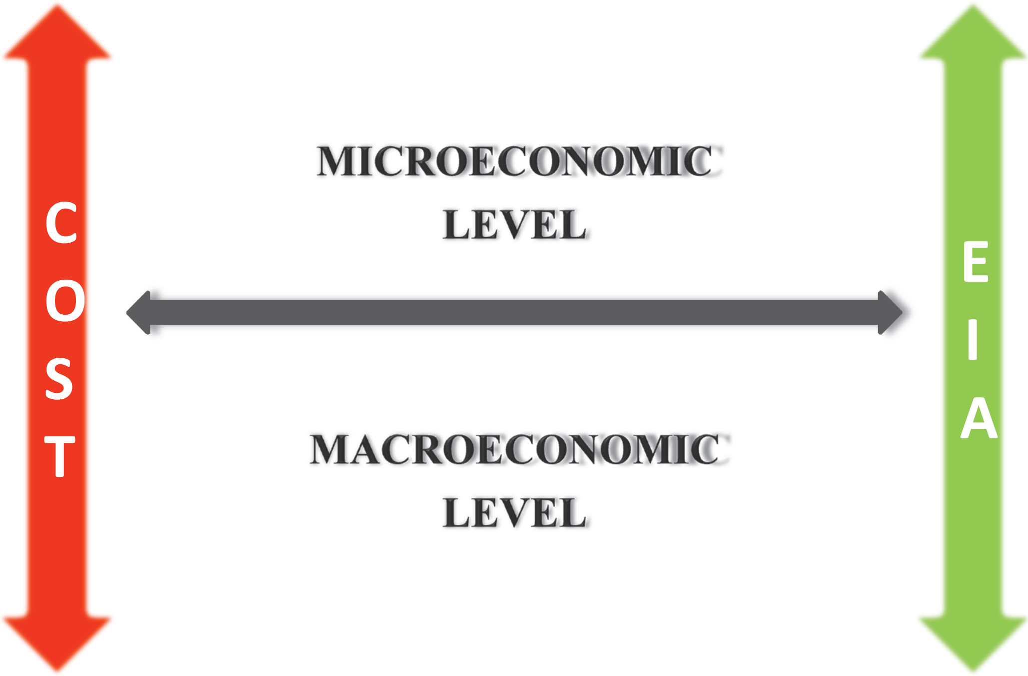


Fig. 1.6.: Microeconomic and macroeconomic level of analysis

The two different approach will first be dealt at a theoretical level and then be presented by a real case.

The macroeconomic analysis will be conducted through the Environmental Management Accounting (EMA) method, devised by *Christine Jasch,* who wrote about it in 2003 [13], enriching it with a set of performance indexes appropriately formulated.for this method, a case study will be introduced in order to better understand the method application end the suggestions proposed.

Moreover, the problem will be discussed through a microeconomic model to calculate the environmental cost. This model has been formulated by the research group of Mechanical, Energy and Management Engineering Dipartment (DIMEG) research. For this important tool to, two cases of study will be implemented and analysed.

The macroeconomic point of view will be presented in the chapter 2. Information about microeconomic analysis will be explained in chapter 3 of this thesis.

Chapter 2

Green and Competitive: the macroeconomic point of view

"The need for regulation to protect environment gets widespread but grudging approval: widespread because everyone wants a livable planet, grudging because of the lingering belief that environmental regulations erode competitiveness".

Corporate social responsibility has evolved through the years. Much more than doing charity work, most companies are now implementing green measures because they just have to do: it improves corporate image, shows they care and it is what customers demand. Companies believe that *"it is their responsibility to do so"*. The companies have undertaken many eco-works: improve energy efficiency, making products and services more sustainable, calculate their carbon footprint, and, very important, the increase in companies reporting on sustainability. The reasons for going green are not a one-way thing: companies are not adapting sustainability practices just because they are concerned about the environment but because it benefits them too, and in a great way.

Several tools are used for this purpose: environmental accounting systems, performance indexes, cost evaluation models. This chapter and the next will proposed methods to monitor the companies' sustainability level.

2.1. Macroeconomic analysis: Environmental Management Accounting

To obtain the whole perception of the enterprise environmental situation, several authors designed important methods to monitor sustainability enterprise issues and many companies adopted important actions in order to improve their sustainability performances; the last actions, in particular, were performed for economic returns [14], but also for imagine coming back and for consumer perception purposes [15]. At macroeconomic level, environmental cost models were introduced in conjunction with environmental certification systems. The ISO 14001 standard contemplates procedures for managing and reducing environmental impacts through the Environmental Management Systems (EMSs), which can be implemented in every country in the world [16]. The Eco-Management and Audit Scheme (EMAS) technique, similar to ISO method, is designed to obtain changes in relation with environmental performance and it is available, furthermore, in Europe [15]. The GRI Sustainability Reporting Guidelines offers Reporting Principles, Standard Disclosures and an Implementation Manual for the preparation of sustainability reports by organizations. In 2001, the United Division for Sustainable Development published the Environmental Management Accounting Procedures and Principles, together with guide and checklists for its applications, in order to present the concepts of EMA method. *Christine Jasch* wrote about this innovative method in 2003 [13]: it represents an approach that provides for the transition of data from financial accounting, cost accounting and mass balance in order to improve the environmental corporation situation.

2.1.1. Environmental Management Accounting

As the author suggests, the EMA method considers the material flow as a money flow. Accordingly, it is important not only to monitor the financial situation of the enterprise, but also to understand the intrinsic mechanisms of the enterprise, like material and machine use, energy consumption and/or other important characteristics. To do this, a complete scheme like the one reported in fig. 2.1, can be used. All dimensions involved in environmental accounting are included. The model is a matrix where the lines are the cost/revenue items, incurred by the firm, and the columns represent the origin of them.

Environmental media Environmental cost/expenditure categories	Air/Climate	Waste water	Waste	Soil/ Groundwater	Noise/ Vibration	Biodiversity/ Landscape	Radiation	Other	Total
a. Waste and emission treatment									
a.1. Depreciation for related equipment									
a.2. Maintenance and operating materials and services									
a.3. Related personnel									
a.4. Fees, taxes, charges									
a.5. Fines and penalties									
a.6. Insurance for environmental liabilities									
a.7. Provisions for clean-up costs, remediation									
b. Prevention and environmental management									
b.1. External services for environmental management									
b.2. Personnel for general environmental management activities									
b.3. Research and development									
b.4. Extra expenditure for cleaner technologies									
b.5. Other environmental management costs									
c. Material purchase value of non-product output									
c.1. Raw materials									
c.2. Packaging									
c.3. Auxiliary materials									
c.4. Operating materials									
c.5. Energy									
c.6. Water									
d. Processing costs of non-product output									
Σ Environmental expenditure									
e. Environmental revenues									
e.1. Subsidies, awards									
e.2. Other earnings									
Σ Environmental revenues									

Fig. 2.1: Environmental expenditure/costs and revenue/earnings [17]

Accordingly, with the previous table, the difference between the total environmental expenditures and the total environmental revenues gives the final measurement of the enterprise sustainability. The result is a ***delta***(Δ), which indicates how much sustainable is the analyzed company:

$$\Delta = \sum ENVIRONMENTAL\ EXPENDITURE - \sum ENVIRONMENTAL\ REVENUES \quad (1)$$

The model so implemented produces a measurement (Δ), which does not provide useful information to understand the weaknesses. Several studies were carried out about the direct link between EMA implementation and the improvement of environmental corporate characteristics [18] [19] [20]. All case studies confirmed the goodness of EMA method, as presented in the state of the art. However, the information provided by the EMA method is a good starting point to obtain more detailed and useful data for business economic purposes. In order to highlight the aspects that need to be improved, a relation between the EMA result (Δ) and other quantitative parameters has to be created. Consequently, the proposed work aims to overcome this important limit, giving some guidelines oriented to get useful the information generated from EMA model. As widely known from the literature [21], there are not absolute key performance indexes for evaluating enterprise behaviour. Since each firm consists of different conditions and characteristics, a universal form for the performance measurement can not be defined. Before designing the right KPIs, which have to be used, the context and the available information need to be evaluated. Starting from the basic and the well-known performance indexes, the appropriate ones will be created.

According to that, in the present work the Environmental Management Account will be applied to a complex case study characterised by a multi-site reality; subsequently, some performance considerations, based on original indexes, will be customised in order to analyse the multi-plant company in a more homogeneous way. The proposed approach is not related to the case study, but can be applied to analyse and understand how the environmental issues are performed in multi-plant and multi country companies.

THE CASE STUDY

To proceed with the analysis, an industrial leader company, operating in bearings and seals manufacturing, mechatronics, services and lubrication systems, is considered. A multi plants structure, with plants, warehouses, business units and sells channels placed all over the world characterizes it. To simplify the analysis and better focus on the method, only the Italian bearings manufacturing plants are studied. For these plants, the balance data sheets are available and they contain all information useful to implement the EMA method.

Fig. 2.2 reports the Italian sites of the company; the dimension of each plant is different and is proportional with the dimension of the icons on the map.

Fig. 2.2: Italian manufacturing plants

Many balance information and data sheet about the company and about its units are available (for the year 2014) even if it is often necessary to introduce some hypotheses in order to implement the method chosen for the analysis in the correct way.

For sake of simplicity, in the case study here analysed, the distinction among the possible cost/revenue item origins is not considered. There will be only one column in the matrix, the total one. For each Italian plant (considering a numeration going from the biggest plant to the smallest one), the model is applied providing the results summarised in Table 2.1.

Table 2.1: Environmental expenditure/costs and revenue/earnings for the case study

Environmental cost/expenditure categories [K€]	**Plant 1**	**Plant 2**	**Plant 3**	**Plant 4**	**Plant 5**	**Plant 6**	**Plant 7**
Plant dimension [m^2]	236.685	75.579	57.900	24.045	19.996	15.153	11.100
1. Waste and emission treatment	**1.708,5**	**1.077**	**2.678**	**1.783**	**424,5**	**259**	**79,8**

1.1. Depreciation for related equipment	384,7	105,3	82,8	34,4	29,2	22,7	17,1
1.2. Maintenance and operating materials and services	76,93	21,06	16,55	6,87	5,83	4,53	3,41
1.3. Related personnel	775	575	1.650	1.275	150	75	25
1.4. Fees, taxes, charges	322,49	164,12	356,2	113,05	113,04	57,08	8,41
1.5. Fines and penalties	-	-	-	-	-	-	-
1.6. Insurance for environmental liabilities	73,39	198,2	572,66	308,62	126,4	99,97	25,87
1.7. Provisions for clean-up costs, remediation	66	13,4	0	45,4	0	0	0
2. Prevention and environmental management	**8.758,5**	**3.043**	**3.045**	**3.044**	**3.042**	**3.042**	**3.042**
2.1. External services for environmental management	1,457	1,081	3,102	2,397	0,282	0,140	0,001
2.2. Personnel for general environmental management activities	214	214	214	214	214	214	214
2.3. Research and development	8.543	2.828	2.828	2.828	2.828	2.828	2.828
2.4. Extra expenditure for cleaner technologies	-	-	-	-	-	-	-
2.5. Other environmental management costs	-	-	-	-	-	-	-

3. Material purchase value of non-product output	**39.312**	**46.408**	**27.177**	**11.005**	**3.125,5**	**5.075**	**1.845**
3.1. Raw materials	18.128	14.001	16.960	6.101	2.173	4.398	375
3.2. Packaging	0	0	0	0	4,862	0	0
3.3. Auxiliary materials	812	386	197	0	817	182	0,870
3.4. Operating materials	641	0	1.355	0	55,38	0	7,2
3.5. Energy	17.977	8.752	8.624	4.886	1.293	638	1.455
3.6. Water	1.754	65	41	18	74	21	3
4. Processing costs of non-product output	**31.013**	**15.232**	**30.653**	**6.689**	**6.683**	**4.819**	**40,82**
Environmental expenditure	**80.792**	**65.760**	**63.550**	**6.689**	**10.462**	**13.195**	**5.007**
5. Environmental revenues (-)	**114.264**	**15.085**	**21.554**	**4.858**	**2.453**	**1.566**	**357**
5.1. Subsidies, awards	-	-	-	-	-	-	-
5.2. Other earnings	114.264	15.085	21.554	4.858	2.453	1.566	357
Environmental revenues	**114.264**	**15.085**	**21.554**	**4.858**	**2.453**	**1.566**	**357**
Δ	**- 33.472**	**50.674**	**41.996**	**17.663**	**8.009**	**25.002**	**4.650**

Below, the detailed explanation of all highlighted lines in Table 2.1, according with the available explicit information about the company and the assumption or inferences made.

a. Waste and emission treatment

a.1 Depreciation for related equipment

In the “related equipment” are included the cost of the useful tools installed by the company in the last years with the aim of becoming more sustainable. Specifically the installation aims to monitor, to automate, to control and to reduce CO_2 emissions. The main tools are:

- Permanent and mobile CO_2 emissions monitoring tools (one each 100 m^2);

- Infrared thermograph tool for each plant; intelligent lightings (one each 10 m^2);

- Automatic ignition tool in presence of a transportation trolley (one each 10 m^2);

- High energy efficiency trolley battery (one each 100 m^2);

- Pressure controllers for the power of the elevators (one each 100 m^2);

- Methane system replacement with a new technology (only for plant 2);

- Compressed air activation and illumination automation (one each 100 m^2);

- Compressed air tool replacement with a new technology (only for plant 3).

These investments belong to the under “general and particular equipment” item in the company report: so the depreciation rate is 10%.

a.2 Maintenance and operating materials and services

Also for this item, a percentage of the investment made for waste and emission treatment equipment is considered. It is equal to 2% of the total amount.

a.3 Related personnel

The available data does not give this value so it has been estimated as the ratio between the raw material waste and the annual work salary.

a.4 Fees, taxes, charges

As required by law, it is necessary to have two environmental supervisors to monitor the correct environmental behavior of the company. The related cost is equal to 50.000 € for each unit and allocated to each plant based on the percentage of the produced waste. Moreover, the rate related with certifications, obtained to ensure an efficient behavior of the company, is included here. This rate changes according with the plant dimension and its performances.

a.5 Fines and penalties

The company is very performing in environmental area; thus, the value of this item is null, as inferable from its reports.

a.6 Insurance for environmental liabilities

These costs include the company funds for environmental risk, equal to 1.406.000€ for the Italian sites. Based on the ratio between solid waste produced and raw material introduced, this amount is allocated to each plant

a.7 Provisions for cleanup costs, remediation

In this area, the asbestos disposal costs for plant 1, 2 and 4 are included.

b. Prevention and environmental management

b.1 External services for environmental management

This item is composed of the training costs for the “related personnel”. It includes also the cost of the no-working time because of the training.

b.2 Personnel for general environmental management activities

For each plant there are two persons related with environmental activities: the Energy Manager and the Sustainable Manager. Moreover, in each country, where manufacturing plants are settled, as in Italy, an Environmental Health and Safety (EHS) Country Coordinator works. In each plant, a number of 2,14 persons is allocated with a unitary salary equal to 100.000€.

b.3 Research and development

This item is not expressed in the available company reports, but has been calculated considering that in the biggest plant, 5 on 70 R&D employees are full-time engaged on sustainability aspects. More in particular, for each plant, the 0,2% of personnel is committed in environment R&D area and its cost is elaborated allocating the total R&D cost based on person’s distribution.

b.4 Extra expenditure for cleaner technologies

This item should include those environmental expenditures, which have not been included before, but which the company pays for.

b.5 Other environmental management costs

Equal to zero for the investigated case study.

c. Material purchase value of non-product output

The selected enterprise is very careful to environment issues. Accordingly, in this area it is possible to compare the percentages of material recycled on the total one (in "material" all the following 3.x items are included). Here, the costs attributable to that part of the output, which is scrap and not product, is summarized.

c.1 Raw materials

Among the different outputs of the production process (grinding scarfs, production metal scraps, turning chips and other metal scraps), only the first one is not very recycled. To quantify this value, the purchase cost of the metal used to manufacture the output (steel 52100) is considered.

c.2 Packaging

The plants totally recycle the packaging, which includes "paper, carton, and plastic container". Plant 5 is the only exception since it does not recycle the plastic container.

c.3 Auxiliary materials

Among auxiliary materials there are the oils used as lubricant during the production. These could not be recycled and their cost is estimated according to their purchase cost.

c.4 Operating materials

In this area, there are "electrical and electronic equipment", "used oils" and "tools". For each one and for each plant there are different recycling percentages, all of them valued at their own purchase cost.

c.5 Energy

The energy consumed in each plant is not renewable. Therefore, its cost has to be totally considered according to the energy purchase cost.

c.6 Water

Water consumption was considered according to the local purchasing cost.

d. Processing costs of non-product output

To estimate the process costs for non-output product, a double allocation is made. According to the company balance sheet, related with the considered working year, the total production cost for Italian plants is firstly subdivided among the plants, according with the total raw material quantity purchased by them. Subsequently, for each plant, only a percentage of the production cost is added: the rate between the waste quantities on raw material one.

e. Environmental revenues

e.1 Subsides, awards

This amount is null because the Italian plants do not collect any monetary award.

e.2 Other earnings

The earnings obtained by the company are based on the commercialization of its waste with a sell price equal to the 50% of the purchase cost. Among the non-product output sold there are grinding scarfs, production metal scraps, other metal scraps, turning chips, paper and carton, plastic container, electrical and electronic equipment, used oils and buildings material, in different quantity for each plant.

Below, a complete overview to understand what the environmental situation of the company is.

Fig. 2.3: Environmental company situation

As shown in Fig. 2.3, the first plant is the better one: its Δ has a negative value. This indicates that the revenues from environmental activities give a gain bigger than the expenditures. This is an important result since it means that the plant is efficient and it benefits from the adoption of a sustainability behavior.

For the other plants, observing the presented values on the table is not enough; in fact, it could seem that the plant 7 is the best one, among the last six in the table, but it is also the smallest plant and this explains why the value is low. This observation leads to understand that this simple balance, given by Δ value, is not adequate to give a right and appropriate evaluation of the environmental situation of a multi-plant company. For this reason, the company should provide a set of performance indexes in order to go over the first level analysis, by considering the same from the network point of view.

PERFORMANCE INDEXES AND RESULTS

As announced in the second section, in a company an excellent management system does not exist since the optimization of one objective is often in opposition with other important company issues. In that case, a trade-off could be defined in order to obtain the best solution in relation with the company purpose.

Accordingly, a set of appropriate indexes is here provided, with the aim of giving the possibility to evaluate contemporary more aspects of the company behavior. In the following analysis, there is not the observation on Plant 1 because of its already high level of performance.

First, the presented work proposes three simple key performance indexes: I_1, I_2 and I_3. They are formulated considering already known measurement of performance:

- Productivity measured on the number of employees working in production area;
- Plant dimension in term of square meter;
- Input quantity of raw material entered into the production cycle.

All of those were considered in relation with the EMA application output (Δ).

Index 1: $$I_1 = \frac{\Delta}{number\ of\ employees} \quad (2)$$

Table 2.2: Index 1

	Plant 2	**Plant 3**	**Plant 4**	**Plant 5**	**Plant 6**	**Plant 7**
Number of employees	354	347	502	143	88	178
Δ	50.674	41.996	17.663	8.009	25.002	4.650
I_1	**143,15**	**121,03**	**35,19**	**56,01**	**284,11**	**26,13**

The Δ value expresses the company losses. Dividing this value for the number of employees is an expression of the quantification of their individual loss. Looking at Table 2, Plant 7 seems to be the better. Anyway, in this plant, the quantity of raw material in input (as company report suggests) is smaller than the other; therefore, the I_1 indicator does not allow getting a good perception of the plant performances.

Index 2:
$$I_2 = \frac{\Delta}{plant\ dimension} \tag{3}$$

Table 2.3: Index 2

	Plant 2	**Plant 3**	**Plant 4**	**Plant 5**	**Plant 6**	**Plant 7**
Plant dimension [m²]	75.579	57.900	24.045	19.996	15.153	11.100
Δ	50.674	41.996	17.663	8.009	25.002	4.650
I_2	**0,67**	**0,73**	**0,73**	**0,40**	**1,65**	**0,42**

In this case, the rate represents the loss for each square meter of the plant. Thus, Plant 5 gets the best performance. In addition, here, it is not possible to give an absolute evaluation, because of the other plant characteristics.

Index 3:
$$I_3 = \frac{\Delta}{input\ raw\ material} \tag{4}$$

Table 2.4: Index 3

	Plant 2	Plant 3	Plant 4	Plant 5	Plant 6	Plant 7
Input Raw Material [ton]	5.771	3.988	1.614	3.945	3.592	117
Δ	50.674	41.996	17.663	8.009	25.002	4.650
I_3	**8,78**	**10,53**	**10,94**	**2,03**	**6,96**	**39,75**

With the third index, Plant 5 provides the best performance. On the contrary, the Plant 7, which had a good position for I_2 (the second), is here the worst.

The following histogram summarizes all the three indexes.

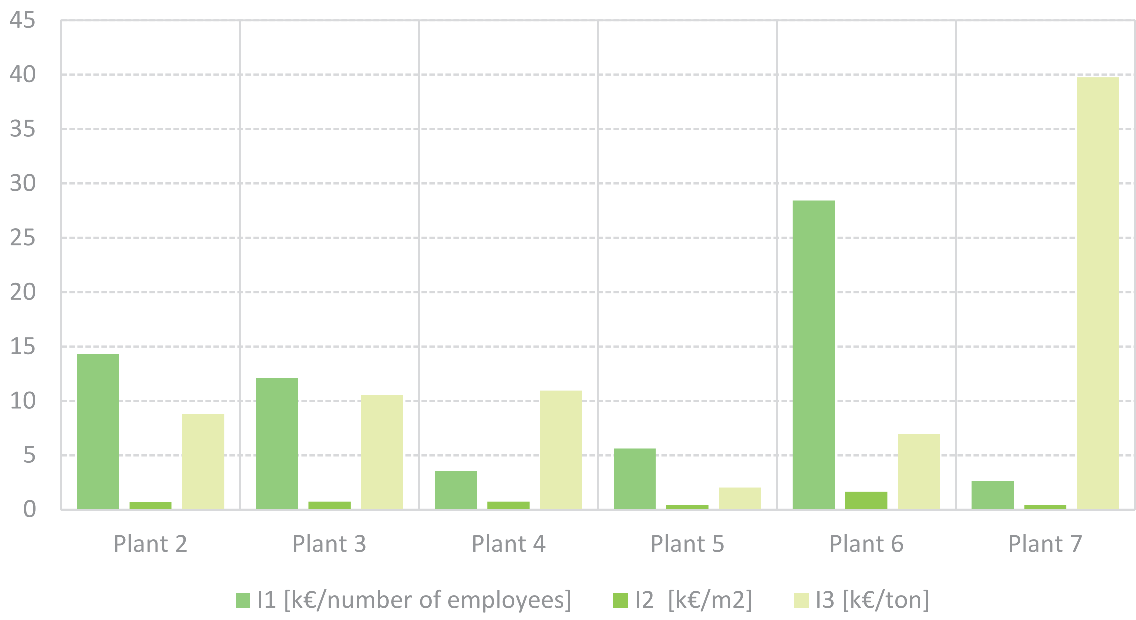


Fig. 2.4: I_1, I_2 and I_3 distribution

It is clear that the indicators here presented are not adequate to give a complete and plausible explanation of the company situation. Each one gives a different plant picture and it is not possible to establish which the plant with the best performances is. In conclusion, the simple key performance indicators, as productivity in its different expressions, are is not sufficient to give a real judgment for a multi plants enterprise, because they do not link the performance evaluations to each other.

Accordingly, more complex and complete indexes have to be customized.

The next two indexes, I_4 and I_5, involve the Δ parameter trying to consider all the factors influencing the firm environmental performances, as suggested by *Christine Jasch*.

Index 4: $$I_4 = \frac{\Delta}{input\ raw\ material / number\ of\ employees} \qquad (5)$$

Table 2.5: Index 4

	Plant 2	Plant 3	Plant 4	Plant 5	Plant 6	Plant 7
Input Raw Material [ton]	5.771	3.988	1.614	3.945	3.592	117
Number of employees	354	347	502	143	88	178
Δ	50.674	41.996	17.663	8.009	25.002	4.650
I_4	**3.109,5**	**3.655**	**5.494**	**289,6**	**612,5**	**7.075**

With I_4, the enterprise dimension is quantified through the rate between the input raw material and the number of employees, without considering the plant dimension, in terms of square meters.

Index 5: $$I_5 = \Delta * \left(plant\ waste / input\ raw\ material \right) \qquad (6)$$

Table 2.6: Index 5

	Plant 2	Plant 3	Plant 4	Plant 5	Plant 6	Plant 7
Input Raw Material [ton]	5.771	3.988	1.614	3.945	3.592	117
Plant Waste [ton]	378,14	755,17	164,72	165,37	118,74	1
Δ	50.674	41.996	17.663	8.009	25.002	4.650
I_5	**3.320**	**7.952**	**1.803**	**336**	**826,5**	**40**

This index expresses an efficiency measurement for each plant, based on the quantity of waste generated in proportion to the input of raw material.

The following figure summarized results:

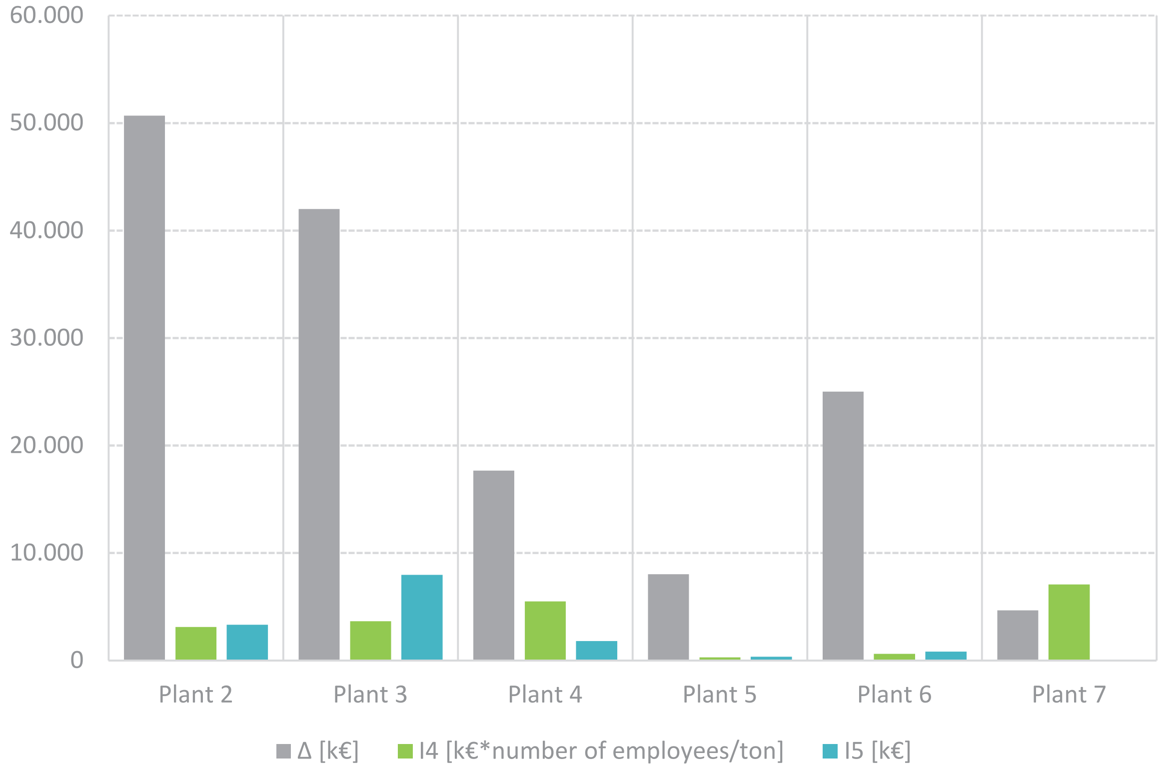


Fig. 2.5: Δ, I_4 and I_5 distribution

These values could be considered more objective than the previous indexes, because consider all that parameters which characterize the enterprise, as the number of employees or the quantity of raw materials processed or the level of produced waste.

Based on the previous histogram, it is evident how the delta indications are often very different from the KPIs. From a comparison between Plant 2 and Plant 7, the following considerations: Plant 2 has a very high delta and this could suggest, according to EMA method, that it is less powerful than Plant 7 which has a delta very small. Actually, I_4 indicates the Plant 7 has a disproportionate relationship between labor and raw material processed: the number of employees is too high compared to the incoming raw materials. This demonstrates that just the delta is not able to provide an objective and totally correct interpretation of the business situation.

Finally, the result is that Plant 5 provides the best performances, in relation with the features considered, while Plant 3 is the worst one. Plant 5 has the size factor (I_4) and the production efficiency (I_5) values lower than the others. Moreover, Plant 3 has high value of both Δ and customized KPIs. Naturally, the proposed method allows performing a sort of classification among the different plants, but at the corporate level, each company should specify its environmental targets determining an appropriate trade-off according to its needs and skills.

Chapter 3

Green and Competitive: the microeconomic point of view

"Microeconomics is the social science that studies the implications of individual human action, specifically about how those decisions affect the utilization and distribution of scarce resources." [22]

In this chapter, this generic concept will be referred to the company reality. In fact, nowadays industries are submit to new legislation and regulations requests imposing more efficiency of the production processes; this means think to the process in a sustainable way. In this context, it becomes very important to estimate additional environmental costs to bear. At the same time, the need to define a global, unique and integrated model, which is independent from the process types, and from the production country is more pressing. With this perspective, here a microeconomic model, product, process and country independent, which includes the environmental rate into the product unit cost, will be presented. It gives the firms an accurate instrument allowing them to estimate the environmental costs connected with their production in a simple and correct way, so to have a realistic view of the true total environmental internal costs. Two kind of cases study will be presented in order to better understand the method's utilization.

3.1. Microeconomic analysis: a model for estimating the environmental costs in a production system

In the first chapter of this work, the difference between the two types of approaches used to address the problem of industrial processes sustainability has been extensively dealt. In this chapter, the attention will be focused on microeconomic considerations.

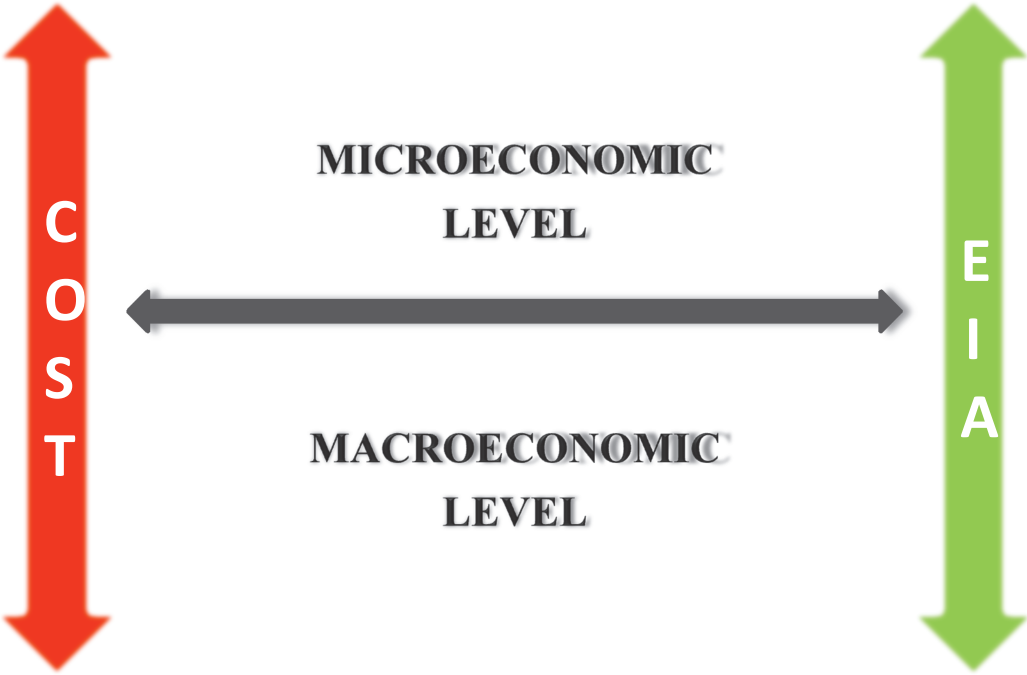


Fig. 3.1: Microeconomic and macroeconomic level of analysis

The need to define a global, unique and integrated model, which is independent from the process types and from the production country, is more pressing in a social and business context in which the knowledge and the monetization of environmental expenditure that companies held up assumes a strategic relevance. In literature, different are the formulations or partial models, which propose a solution for the evaluation of production and environmental costs, associated with an output product. However, a worldwide recognized index, which allows having a standard and complete measurement of all costs included the environmental ones, does not exists. In fact, strong simplification or the focus on specific case study characterize the preliminary attempts already proposed (*Duflou et al.*, 2012 [23], *Branker et al.*, 2011 [24], *Gutowski et al.*, 2006 [25]). In this study, the idea behind the model is to create a cost function, which overcomes the limitation of a single process or of a specific product configuration, making it available to every type of product, production and country.

In literature, there are many models for the evaluation of environmental costs for a production process but for all of them there are initial hypothesis or they are limited to investigate specific cost sources. Below, the explanation of the already known studies conducted, useful for the new model.

Energy consumption and *GHG emissions* are the most investigated factors from the scientific community and five studies are particularly worth of note.

Rajemi et al. (2010) [26] estimated the energy consumption for a machining process. Their model estimates the total energy consumed during manufacturing as the sum of five rates of energy cost:

$$E = E_1 + E_2 + E_3 + E_4 + E_5$$

where E_1 is the setup energy, E_2 is the energy absorbed during the process, E_3 is the energy consumed during the tool change, E_4 and E_5 are the energy used for tools and raw materials production respectively.

Anderberg et al. (2010) [27], who divided the process energy in direct and indirect rates, proposed another important distinction in energy classification. *Rahimifard et al.* (2010) [28], instead, considered direct energy as the sum of theoretical energy and supporting auxiliary energy. Finally, *Abele et al.* (2005) [29] estimated the total energy demand during the process equal to:

$$\mathrm{E_{total}} = \mathrm{E_{theoretical}} + \mathrm{E_{additional}} + \mathrm{E_{periphery}}$$

Where $\mathrm{E_{theoretical}}$ is the theoretical needed energy, which represents the minimum energy demand of the production process, and $E_{additional}$ and $E_{periphery}$ stand for the additional energy demands of the machine tool and peripherals respectively.

One of the most used method for the evaluation of *GHG emissions* is the Carbon Emission Signature (CES) one, proposed by *Jeswiet and Kara* (2008) [30]. It directly connects the process energy with carbon emissions and allows quantifying carbon emissions during the manufacturing phase through the product of energy consumption and CES factor. The last quantifies carbon emission considering the weighted sum of used primary sources (coal, natural gas, oil). As regards the GHG emissions during the machine tool lifecycle *Cao et al*. (2012) [31] presented an interesting model in which the total GHG emissions is the sum of all rates of GHG emissions emitted during single steps of a machine tool lifecycle (manufacturing, assembly, use, transportation, recycling).

Other microeconomic cost models estimate the environmental costs from two perspective of costs: cost model based on CO_2 emissions and cost model based on waste production and disposal. *Branker et al*. (2011) [24] quantified the production cost C_p as the following sum:

$$C_p = C_m + C_s + C_l + C_t + C_{MD} + C_{MID} + C_{ED} + C_{EA} + C_{env}$$

where C_m, C_s, C_l, C_t are the manufacturing, the setup, the leisure and the tool change costs respectively; C_{MD} and C_{MID} are the direct and indirect material costs; C_{ED} and C_{EA} are the cost rates due to direct and auxiliary energy and C_{env} is the environmental cost.

For the last factor, the authors used the LCA method in which the environmental cost (C_{env}) is the product of the total CO_2 of the process (P_{CO_2}) and the carbon cost/price (k_{CO_2}), which is a country dependent coefficient:

$$C_{env} = P_{CO_2} \cdot k_{CO_2}$$

P_{CO_2} is the sum of the different portions associated to the energy (E_{CO_2}), the use of coolant (CO_{CO_2}) and lubricant (LO_{CO_2}), the tool production and disposal (TL_{CO_2}), the emissions intensity (CH_{CO_2}) and the CO_2 emissions for material production (M_{CO_2}), as reported below:

$$P_{CO_2} = E_{CO_2} + CO_{CO_2} + LO_{CO_2} + TL_{CO_2} + CH_{CO_2} + M_{CO_2}$$

Da Silva and Amaral (2009) [32] proposed a cost model based on lifecycle assessment and activity based costing principles. This methodology quantifies environmental cost basing on waste and disposal costs of the production process stages, so determining which of them have the greatest environmental impact.

The existing cost models are penalized by the absence of an integrated approach: while *Branker et al.* (2011) [24] exclusively considered the environmental cost based on the quantification of the total *CO_2*, *da Silva and Amaral* (2009) [32] focused their attention on waste generation and disposal costs, neglecting all the other environmental rates. In the same way, the studies measuring the impact of consumed energy are related to specific application fields, whereas the company need of a general way to quantify the total energy for changing process steps and machine tool types. Finally, in the studies previously proposed, just one raw material type comes in, whereas the reality is more different.

Therefore, it appears mandatory changing the way to establish environmental costs.

In fig. 3.2, a qualitative schematization of the product cost decomposition so that the companies could have the possibility to evaluate the incidence of environmental aliquots on the total cost product.

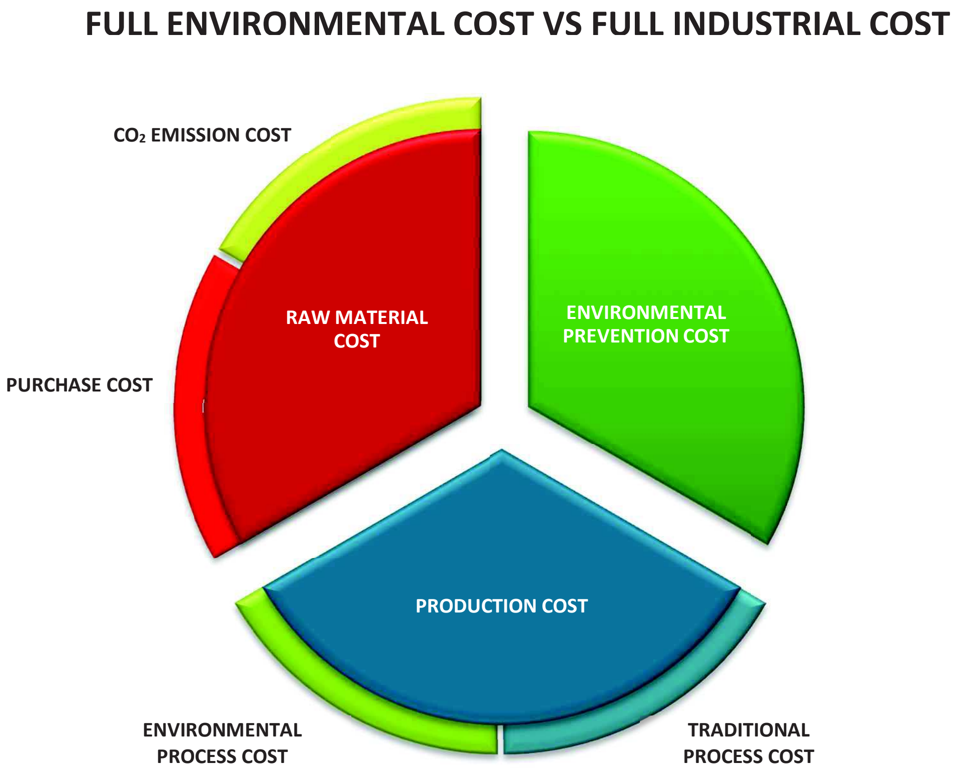


Fig. 3.2: Qualitative decomposition of full industrial cost in cost items

Therefore, three are the method at the base of this work:

- Life Cycle Assessment, as proposed by *da Silva and Amaral* (2009) [32], which explores the environmental impact of a material from generation to disposal;
- Environmental Management Accounting, firstly presented in *Development, United Nations Division for Sustainable* (2001) [33], which suggests the cost items imputable to environmental impact;
- Activity Based Costing [34], which allows allocating the activity costs to the output product.

3.1.1. The microeconomic model

The model following explained will be available for the firms to evaluate the impact of total environmental costs on the total cost of production. The assumptions behind are:

- The production is *discrete* and the input/output material quantities are known;

- The *machinery* are already *available*, so that purchasing costs for new machineries do not have to be considered;
- Just a *single output product* is realized. According to that, the model considers the p^{th} output product. Obviously, all traditional production costs will be considered allocated to each output product, based on conventional criteria of costs allocation [34].
- The model is *process and materials independent*, so it can work in every kind of industrial production characterized by more production processes and more raw materials; according to that, there will be n production processes and $m + t$ raw materials.
- The model is *country independent*, since it includes the use of indexes, which take into account the nation where the process takes place.

The model basic idea is to start from the estimation of *full industrial cost* and to include into the final value the environmental aliquots. Fig. 3.3 reports the breakdown structure of the above-mentioned cost.

Fig. 3.3: Full industrial cost breakdown structure

According to the proposed approach and for making the company more sustainable and competitive, following the model for evaluating the incidence of environmental costs on full industrial costs is presented. Basing on that, the company can program any production process improvements.

THE MODEL FOR FULL INDUSTRIAL COST

For sake of clearness, below the indexes introduced in the manuscript:

- J is the set of *n* production processes, with $j = 1, \dots, n$;
- I is the set of m indirect raw materials, with $i = 1, \dots, m$;
- D is the set of t direct raw materials, with $d = 1, \dots, t$;
- L is the set of w wastes, with $l = 1, \dots, q$ for liquid wastes, $l = q + 1, \dots, s$ for solid wastes and $l = s + 1, \dots, w$ for gas wastes.

As well known the *full industrial cost* ($C_{full\ industrial}$) includes two classes of cost: *production costs*, related to the manufacturing steps, and *direct costs*, that are all the other costs directly correlated to the output (i.e. direct raw materials, packaging, etc.).
However, an estimation of environmental rate useful to have a complete idea of total production costs has not been yet included. According to that, a review of the full industrial cost of the p^{th} output product is represented:

$$C_{full\ industrial_{p^{th}}} = C_{production_{p^{th}}} + C_{RM_{direct_{p^{th}}}} + C_{environmental_{prevention_{p^{th}}}} \quad (1)$$

where the single terms will be explained in the following.
For sake of simplicity, hereinafter the subscript p^{th} will be neglected, referring all upcoming expression to the p^{th} output product.
According to Eq. 1, $C\_production$ $[€/pce]$ *is the total production cost for the p^th output product*, given by the sum of each production cost ($C_{production_{PROCESS}}{}^{j}$) of the *n* involved processes:

$$C_{production} = \sum_{j=1}^{n} C_{production_{PROCESS}}{}^{j} \quad (2)$$

The next equation is a general way to express the *total production costs for process j* [24]:

$$C_{production_{PROCESS}}{}^{j} = C_{setup}{}^{j} + C_{unproductive}{}^{j} + C_{manufacturing}{}^{j} + C_{RM_{indirect}}{}^{j} + C_{TOT_{tool}}{}^{j} + C_{energy}{}^{j} + C_{environmental_{PROCESS}}{}^{j} \quad (3)$$

While the first six rates of Eq. 3 are the traditional production costs, the last one, $C_{environmental_{PROCESS}}{}^{j}$, represents the environmental costs endorsed by the company connected with the process *j*. Moreover, in spite of [24], Eq. 3 includes just indirect raw materials, which depends from the applied process; vice versa, it does not consider the direct raw materials because the same could be involved in more transformation processes. According to that, the direct raw material rate is included directly in the full industrial cost (see Eq. 1).

Before to explicate all the rates of Eq. 3, it is necessary to introduce the *management cost of process j* (${C_{management_{PROCESS}}}^j$) as the sum of four terms: the *depreciation cost* for machinery j, the *labor cost* for process j, the *ground cost* where the machinery j is placed and the *maintenance cost* for machinery j.

Now, based on the estimation of ${C_{management_{PROCESS}}}^j$, the terms in Eq. 3 can be defined as follows:

- ${C_{setup}}^j$ is the *setup cost for process j* [$€/pce$], expressed as the product between the management process cost and the *setup time* [min/pce], ${T_{setup}}^j$:

$$ {C_{setup}}^j = {C_{management_{PROCESS}}}^j * {T_{setup}}^j \tag{4} $$

- ${C_{unproductive}}^j$ is the *unproductive time cost for machinery j* [$€/pce$], given by the product of the management process cost and the *unproductive time* [min/pce], ${T_{unproductive}}^j$:

$$ {C_{unproductive}}^j = {C_{management_{PROCESS}}}^j * {T_{unproductive}}^j \tag{5} $$

- ${C_{manufacturing}}^j$ is the *manufacturing cost for process j* [$€/pce$], which general formulation consists by the product between the management process costs and the *manufacturing time for process j* [min/pce], ${T_{manufacturing}}^j$:

$$ {C_{manufacturing}}^j = {C_{management_{PROCESS}}}^j * {T_{manufacturing}}^j \tag{6} $$

- ${C_{RM_{indirect}}}^j$ is the *indirect raw materials cost used for process j* [$€/pce$], like lubricant, refrigerant and others; this cost is obtained as the sum of all the *m* indirect materials costs given by the product between the unit purchasing cost (${Cu_{purchaseRM_{indirect}}}^i$, [$€/(material\ unit)$]) and the used quantities in the *j* process (${UQ_{RM_{indirect}}}^{ij}$, [$(material\ unit)/pce$]), with $i = 1, \dots, m$,:

$$ {C_{RM_{indirect}}}^j = \sum_{i=1}^{m} {Cu_{purchaseRM_{indirect}}}^i * {UQ_{RM_{indirect}}}^{ij} \tag{7} $$

- ${C_{TOT}}_{tool}^{\ j}$ represents both the *tool cost and the cost of the tool change for process* j [$€/pce$]. A general way to quantify this rate is reported in the following equation:

$$ {C_{TOT}}_{tool}^{\ j} = {C_{management}}_{PROCESS}^{\ j} * \frac{{T_{tool}}_{change}^{\ j}}{{pcs_{tool}}^{j}} + \frac{{C_{tool}}^{j}}{{pcs_{tool}}^{j}} \tag{8} $$

where ${T_{tool}}_{change}^{\ j}$ [min] is the time for tool changing on process j, ${pcs_{tool}}^{j}$ [pce] is the number of produced pieces with the same tool on machinery j and ${C_{tool}}^{j}$ [€] is the tool cost.

- ${C_{energy}}^{j}$ is the *cost of energy consumed during the process j* [$€/pce$]. According to *Branker et al.* (2011), this term can be derived like the sum of the energy aliquots consumed both during manufacturing step, ${C_{energy}}_{manufacturing}^{\ j}$, and not-productive time, ${C_{energy}}_{additional}^{\ j}$. While the first amount is influenced by the process parameters, the other one depends on the energy used to keep the machinery ready-to-use. The ${C_{energy}}^{j}$ can be so measured:

$$ \begin{aligned} {C_{energy}}^{j} &= {C_{energy}}_{manufacturing}^{\ j} + {C_{energy}}_{additional}^{\ j} \\ &= {C_{electricity}}_{country} * \left({E_{manufacturing}}^{j} + {E_{additional}}^{j}\right) \\ &= {C_{electricity}}_{country} * {E_{TOT}}_{machinery}^{\ j} \end{aligned} \tag{9} $$

where ${C_{electricity}}_{country}$ is the electricity cost dependent on production country [$€/kJ$], ${E_{manufacturing}}^{j}$ is the manufacturing energy consumed during the production on machinery j [kJ/pce] and ${E_{additional}}^{j}$ is the additional energy consumed during the not-productive time of machinery j [kJ/pce].

- ${C_{environmental}}_{PROCESS}^{\ j}$ is the *environmental production cost for process j* [$€/pce$]. This kind of cost strictly depends by the process characteristics and it could be defined as follows [32]:

$$ {C_{environmental}}_{PROCESS}^{\ j} = $$

$$ {C_{environmental}}_{{WASTE}_{disposal}}^{\ j} + {C_{environmental}}_{CO_2 PROCESS}^{\ j} \tag{10} $$

where ${C_{environmental}}_{{WASTE}_{disposal}}^{\ j}$ is the *waste disposal cost for process j* [$€/pce$], measured considering the aliquots of liquid, solid and gaseous wastes (further details are reported in Appendix 1); ${C_{environmental}}_{CO_2 PROCESS}{}^{j}$ is the *cost due to the CO_2 emissions during the process j* $[€/pce]$.

According to the study proposed by *da Silva and Amaral* [32], following the calculation of the last cost:

$$ {C_{environmental}}_{CO_2 PROCESS}{}^{j} = {CO_2}_{PROCESS}{}^{j} * K_{CO_2 country} \tag{11} $$

where ${CO_2}_{PROCESS}{}^{j}$ $[kg_{CO_2}/pce]$ is the CO_2 quantity emitted during the process j and $k_{CO_2 country}$ $[€/kg_{CO_2}]$ is a country coefficient which takes into account where the production happens and allows to make the model country independent. In Appendix 2, the detailed explanation of the *CO_2* quantity emitted during the process j.

The second term of the full industrial cost, reported in Eq. 1 is the *total direct raw materials cost,* $C_{RM_{direct}}$ [€], given by the sum of all materials used to manufacture the p^th output product (in direct raw materials are included packaging materials too). Follows, fixing $d = 1, \dots, t$ the index of the raw materials, the total cost is:

$$ C_{RM_{direct}} = \sum_{d=1}^{t} {Cu_{RM_{direct}}}^{d} * {IQ_{RM_{direct}}}^{d} \tag{12} $$

Where:

- ${IQ_{RM_{direct}}}^{d}$ is the *input quantity of d-th direct raw material* $[(material\ unit)/pce]$ used during the production process;
- ${Cu_{RM_{direct}}}^{d}$ is the *unit cost of the d-th direct raw material*, given by the sum of two rates: the first is the direct raw materials purchasing cost, ${Cu_{purchaseRM_{direct}}}^{d}$ $[€/(material\ unit)]$ and the second is the environmental impact cost that each unit quantity of *d-th* material generates during its primary production, ${Cu_{environmental}}_{CO_2 RM_{direct}}{}^{d}$ $[€/material\ unit]$. The equation is here reported:

$$ {Cu_{RM_{direct}}}^{d} = {Cu_{purchaseRM_{direct}}}^{d} + {Cu_{environmental}}_{CO_2 RM_{direct}}{}^{d} \tag{13} $$

Obviously, to make the model country independent, the right way to measure the environmental impact cost, ${Cu_{environmental}}_{CO_2 RM_{direct}}{}^{d}$, has to consider the country where the primary production happens. According to that, the last cost can be quantified as the following product:

$$ {Cu_{environmental}}_{CO_2 RM_{direct}}{}^{d} = {EF_{RM}}^{d} * K_{CO_2 country} \tag{14} $$

where ${EF_{RM}}^{d}$ is the emission factor or CO_2 quantity emitted to produce each unit of direct raw material d $\left[kg_{CO_2}/material\ unit\right]$ and $K_{CO_2 country}$ is the country coefficient which converts the CO_2 quantity emitted for the primary production in cost $[€/kg_{CO_2}]$ [35].

Finally, the last term of the Eq. 1 is the *environmental prevention cost,* $C_{environmental_{prevention_{p^{th}}}}$ $[€/pce]$, which is independent by the process. It constitutes a fundamental part of the full industrial cost, contributing to increase it based on the investment that a company sustains to reduce the impact of its production. Among the environmental costs there are: costs for waste and emission treatment (i.e. depreciation for related equipment, maintenance and operating materials, etc.), cost for prevention and environmental management (i.e. research and development, external services for environmental management, etc.) and others; all these costs compose the total environmental prevention cost met by a company, $C_{TOT_{environmental_{prevention}}}$. Up to now, it does not exist a unique formula to estimate *environmental prevention cost* because it depends to the enterprise strategy and the activities carried out to prevent environmental impact. Actually, the general idea followed by companies, which put more attention on sustainability aspects, is to firstly quantify all total costs and then to rightly allocate them on the realized products. Naturally, they have to properly choose an accurate cost driver based on their own characteristics and products typology. More in particular, in the present study, the cost driver referred to the p^{th} output product is fixed equal to the sum of CO_2 emitted by all the direct raw materials and by all the production processes used to manufacture the p^{th} output product, as reported in the following equation which terms have been already introduced:

$$COST\ DRIVER_{p^{th}} = \sum_{d=1}^{t}\left({EF_{RM}}^{d}{}_{p^{th}} * {IQ_{RM_{direct}}}^{d}{}_{p^{th}}\right) + \sum_{j=1}^{n} {CO_{2_{PROCESS}}}^{j}{}_{p^{th}} \quad (15)$$

Accordingly, the fraction of total environmental prevention cost to attribute to the p^{th} product is:

$$C_{environmental_{prevention_{p^{th}}}} = \frac{C_{TOT_{environmental_{prevention}}}}{\sum_{p} COST\ DRIVER_{p}} * COST\ DRIVER_{p^{th}} \quad (16)$$

The model for full environmental cost

It is comparing the incidence of environmental costs on production cost for an output product that the company can make detailed evaluation on their sustainability. Therefore, following the components of *full environmental cost*:

- *environmental costs of the process*, which includes environmental cost of waste disposal and environmental cost of CO_2 emission during the production processes;
- *environmental cost of CO_2 emission by direct raw materials*;
- *environmental prevention cost*;
- and *environmental cost of waste generation*.

$$C_{full\ environmental} = \sum_{j=1}^{n} C_{environmental_{PROCESS}}{}^{j} + \sum_{d=1}^{t} \left(Cu_{environmental_{CO_2RM_{direct}}}{}^{d} * IQ_{RM_{direct}}{}^{d} \right) + C_{environmental_{prevention}} + C_{WASTE_{generation}} \quad (17)$$

where the first three aliquots have been already defined in the previous model (Eq. 10, Eq. 12, Eq. 16), whereas, the last aliquot is the *environmental cost of waste generation*, not yet included in the model and useful to calculate the quantity of production costs loses for waste generation. The simplest way to evaluate this term is based on the idea to multiply the direct production cost (i.e. manufacturing cost, energy cost and raw material purchase cost per piece) for a inefficiency index, as follows:

$$C_{WASTE_{generation}} = \omega * \left\{ \left[\sum_{j=1}^{n} \left(C_{manufacturing}{}^{j} + C_{energy}{}^{j} \right) \right] + \left[\sum_{d=1}^{t} Cu_{purchaseRM_{direct}}{}^{d} * IQ_{RM_{direct}}{}^{d} \right] \right\} \quad (18)$$

The coefficient ω is the *inefficiency factor* of the production which depends on the ratio between output quantity, $OQ_{RM_{direct}}{}^{d}$, versus input quantity, $IQ_{RM_{direct}}{}^{d}$, both ones valued at purchasing cost, $Cu_{purchaseRM_{direct}}{}^{d}$, as shown in the following Eq. 19:

$$\omega = 1 - \frac{\sum_{d=1}^{t} OQ_{RM_{direct}}{}^{d} * Cu_{purchaseRM_{direct}}{}^{d}}{\sum_{d=1}^{t} IQ_{RM_{direct}}{}^{d} * Cu_{purchaseRM_{direct}}{}^{d}} \quad (19)$$

For sake of clearness, in fig. 3.4 there are the single rates that compose the full environmental cost.

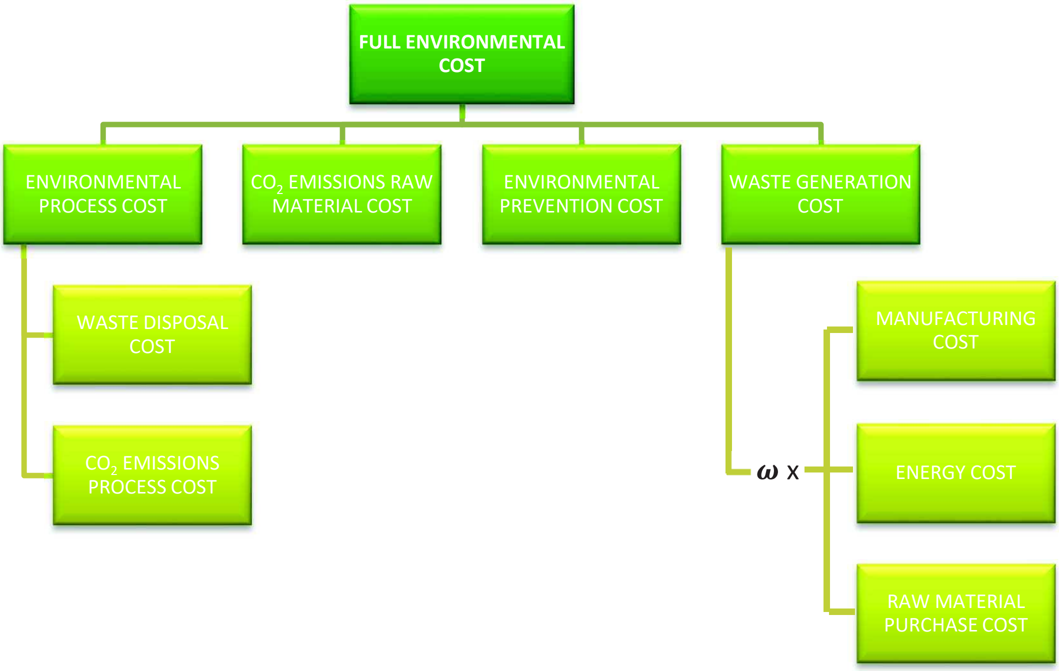


Fig. 3.4: Full Environmental Cost breakdown structure

CASE STUDY A: an environmental analysis of ISPF

The proposed microeconomic model estimates the impact of environmental costs during an output production, in order to have a right perception on how much cost rates are spent for environmental issues. An innovative forming technology, called Incremental Sheet Forming (ISF) has been used as case study to test the model [36]. Unlike stamping process, the ISF does not use expensive dies to manufacture a blank but the deformation is obtained by the action of a punch driven by a CNC machine [37]. Furthermore, a hemispherical punch and a general-purpose clamping frame complete the equipment, as represented in Figure 3.5. The above-mentioned process can be applied in different fields such as rapid prototyping, medical sector, architectural industry, aerospace and marine, etc. [38].

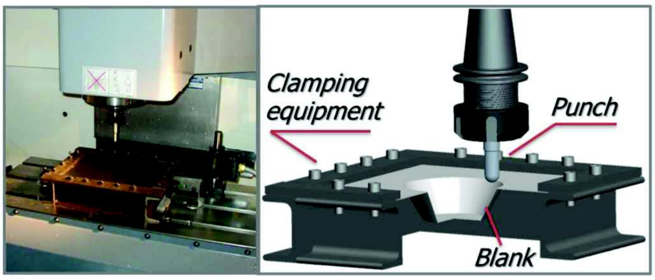


Fig. 3.5: Incremental Sheet Forming equipment

Case hypothesis

The first hypothesis is that CNC milling machine used to perform the ISF process is already available; the second one concerns the production aim which consists in the manufacturing of a truncated pyramid made by AA5754 sheet, 1 mm thick. The component dimensions are respectively: 200 mm in length and 40 mm in height. The process parameters are fixed and equal to 3 m/min for feed rate and 1 mm for tool depth step. As a consequences, the third hypothesis is that just one direct raw material (i=1), a single manufacturing step (j=1) and one output product (p=1) are considered. Finally, due to the company small dimension, the management on matter of environmental prevention supplies only one training course per year.

Model application

The first aliquot that composes the full industrial cost (Eq. 1), customized according to the previous hypotheses for ISF process, is reported below:

$$C_{production_{PROCESS}} = C_{setup} + C_{unproductive} + C_{manufacturing} + C_{RM_{indirect}} + C_{TOT_{tool}} + C_{energy} + C_{environmental_{PROCESS}} \quad (20)$$

To estimate this cost both the *management process cost* and the *time study* were evaluated. Firstly, a *management process cost* equal to 0,35 €/min was estimated, including depreciation, labor (one skilled worker for 8h/day), area availability and maintenance. Secondly, as concerns the duration of *manufacturing time*, a whole work shift was experimentally observed in order to measure and estimated average times for manual and semiautomatic steps (i.e. loading, working, cutting and unloading). The cost estimation is synthesized in Table 3.1.

Table 3.1: Setup cost, unproductive cost, manufacturing cost

SETUP, UNPRODUCTIVE AND MANUFACTURING DATA	SYMBOLOGY	VALUE	UOM
Management process cost	$C_{management_{PROCESS}}$	0,35	€/min
Setup time	T_{setup}	0,5	min/pce
Unproductive time	$T_{unproductive}$	2	min/pce
Manufacturing time	$T_{manufacturing}$	14,8	min/pce

Setup cost	$\mathbf{C_{setup}}$	**0,175**	**€/pce**
Unproductive cost	$\mathbf{C_{unproductive}}$	**0,702**	**€/pce**
Manufacturing cost	$\mathbf{C_{manufacturing}}$	**5,22**	**€/pce**

As regards the indirect raw materials cost, $C_{RM_{indirect}}$, the use of cooling system directly provided by the CNC milling machine was considered and quantified during both the shape manufacturing and the cutting steps, according to *Anghinelli et al.* [39]. The final cost is detailed in Table 3.2.

Table 3.2: Indirect raw materials cost

INDIRECT RAW MATERIALS DATA	SYMBOLOGY	VALUE	UOM
Lubricant purchase unit cost	$\mathrm{Cu}_{\mathrm{purchaseRM}_{\mathrm{indirect}}}^{\mathrm{lubricant}}$	0,01	€/ml
Input lubricant quantity	$\mathrm{IQ}_{\mathrm{RM}_{\mathrm{indirect}}}^{\mathrm{lubricant}}$	13,9	ml/pce
Indirect raw material cost	$\mathbf{C_{RM_{indirect}}}$	**0,14**	**€/pce**

The total tool cost, $C_{TOT_{tool}}$, includes the cost due to the tool supplying (which consists of raw material and manufacturing) and the cost associated to the change tool time. All the terms are summarized in Table 3.3.

Table 3.3: Total tool cost

TOTAL TOOL DATA	SYMBOLOGY	VALUE	UOM
Management process cost	$\mathrm{C}_{\mathrm{management}_{\mathrm{PROCESS}}}$	0,35	€/min
Change tool time	$\mathrm{T}_{\mathrm{tool}_{\mathrm{change}}}$	2	min
Tool cost	$\mathrm{C}_{\mathrm{tool}}$	7,20	€
Parts produced with the tool	$\mathrm{pcs}_{\mathrm{tool}}$	50	pce
Total tool cost	$\mathbf{C_{TOT_{tool}}}$	**0,16**	**€/pce**

The total energy required to address the ISF process was also monitored during the whole working time, following the same approach already proposed in *Ambrogio et al.* [40]. The manufacturing energy refers to the process executed with a feed rate of 3 m/min, a speed rotation of 300 r.p.m. and a depth step of 1 mm. The measured values are reported in Table 3.4:

Table 3.4: Energy cost

TOTAL ENERGY DATA	SYMBOLOGY	VALUE	UOM
Additional energy	$\mathrm{E}_{\mathrm{additional}}$	450	kJ/pce
Manufacturing energy	$\mathrm{E}_{\mathrm{manufacturing}}$	2.856	kJ/pce
Electricity cost	$\mathrm{C}_{\mathrm{electricity}_{\mathrm{country}}}$	2,00	€/kWh
Energy cost	$\mathbf{C}_{\mathbf{energy}}$	**1,84**	**€/pce**

The last aliquot of production process cost is the *environmental process cost,* $C_{environmental_{PROCESS}}$: it depends on the cost for waste disposal and the cost for CO2 emissions. In the present case study, just one solid waste is produced by the process, which consists of the blank resulting by the cutting operation [39]. As concerns the cost due the CO2 emissions, $C_{environmental_{CO_2 PROCESS}}$, the percentages dependent by both coolant use and energy consumption were firstly quantified for the case study and then valued by means of the country coefficient $K_{CO_2 country}$ [24]. In agreement with the Copenhagen climate summit held in December 2010, a carbon price equal to 12,40 €/ton$_{CO2}$ is hypothesized (*BBC News*, 27 January 2013). Starting by the last and taking into account the aluminum emission factor, a $K_{CO_2 country}$ equal to 0,13 €/kg$_{CO2}$ is stated for the specific case study. Both the single rates and the final addition for the $C_{environmental_{PROCESS}}$ are detailed in Table 3.5.

Table 3.5: Process environmental cost

ENVIRONMENTAL DATA	SYMBOLOGY	VALUE	UOM
Solid waste quantity	y^{lj}	0,0025	kg/pce
Solid waste processing total cost	$\mathrm{C}_{\mathrm{solidW}_{\mathrm{disposal}}}$	3,00	€/kg
Waste disposal cost	$\mathbf{C}_{\mathbf{environmental}_{\mathbf{WASTE}_{\mathbf{disposal}}}}$	**0,08**	**€/pce**
Coolant use CO2 quantity	$\mathrm{C0}_{\mathrm{CO}_2}$	41,067	g$_{CO2}$/pce
Energy consumption CO2 quantity	$\mathrm{E}_{\mathrm{CO}_2}$	376,9	g$_{CO2}$/pce

Process CO2 quantity	$\mathrm{C0}_{2_{\mathrm{PROCESS}}}$	417,97	g_{CO2}/pce
CO2 cost coefficient (country of production)	$\mathrm{K}_{\mathrm{CO}_2\mathrm{country}}$	12,40	€/ton_{CO2}
Cost process CO2 emissions	$\mathrm{C}_{\mathrm{environmental}_{\mathrm{CO}_2\mathrm{PROCESS}}}$	0,005	€/pce
Environmental process cost	$\mathbf{C}_{\mathbf{environmental}_{\mathbf{PROCESS}}}$	**0,082**	**€/pce**

For sake of clearness, the production cost value is summarized in Table 3.6.

Table 3.6: Production process cost

ALIQUOTS	SYMBOLOGY	VALUE	UOM
Setup cost	$\mathrm{C}_{\mathrm{setup}}$	0,175	€/pce
Unproductive cost	$\mathrm{C}_{\mathrm{unproductive}}$	0,702	€/pce
Manufacturing cost	$\mathrm{C}_{\mathrm{manufacturing}}$	5,22	€/pce
Indirect raw material cost	$\mathrm{C}_{\mathrm{RM}_{\mathrm{indirect}}}$	0,14	€/pce
Total tool cost	$\mathrm{C}_{\mathrm{TOT}_{\mathrm{tool}}}$	0,16	€/pce
Energy cost	$\mathrm{C}_{\mathrm{energy}}$	1,84	€/pce
Environmental process cost	$\mathrm{C}_{\mathrm{environmental}_{\mathrm{PROCESS}}}$	0,082	€/pce
Production cost	$\mathbf{C}_{\mathbf{production}_{\mathbf{PROCESS}}}$	**8,31**	**€/pce**

According to Eq. (1), the second important aliquot useful to evaluate full industrial cost is the *direct raw materials cost,* $C_{RM_{direct}}$. To quantify this, the input quantity, $IQ_{RM_{direct}}$, and the direct raw material unit cost, $Cu_{RM_{direct}}$, were firstly calculated following the approach proposed in the model and then multiplied between them. The summary of these aliquots is reported in Table 3.7.

Table 3.7: Direct raw material unit cost

DIRECT RAW MATERIAL DATA	SYMBOLOGY	VALUE	UOM
Emission factor	EF_{RM}	10,47	kg_{CO2}/kg

Conversion ratio for CO_2 emissions	$K_{CO_2 country}$	12,40	€/ ton$_{CO2}$
CO2 emission for RM production cost	$Cu_{environmental CO_2 RM_{direct}}$	0,13	€/kg
Direct raw material purchase cost	$Cu_{purchase RM_{direct}}$	4,00	€/kg
Direct raw material unit cost	$\mathbf{Cu_{RM_{direct}}}$	**4,13**	**€/kg**
Direct raw material input quantity	$IQ_{RM_{direct}}$	0,155	kg/pce
Direct raw material cost	$\mathbf{C_{RM_{direct}}}$	**0,64**	**€/pce**

Finally, due to the initial hypotheses, the *environmental prevention cost*, $C_{environmental_{prevention}}$, becomes a simple partition by realized pieces number rather that an allocation based on emissions of CO_2, as proposed by the general model in Eq. (16). For further details, see Table 3.8.

Table 3.8: Environmental prevention cost

ENVIRONMENTAL PREVENTION DATA	SYMBOLOGY	VALUE	UOM
Annual training course cost	$C_{TOT_{environmental_{prevention}}}$	5.000	€/y
Pieces produced	COST DRIVER	8.000	Pce/y
Environmental prevention cost	$\mathbf{C_{environmental_{prevention}}}$	**0,62**	**€/pce**

Finally, the *full industrial cost* for the investigated case study is reported in Table 3.9.

Table 3.9: Full industrial cost

FULL INDUSTRIAL RATES	SYMBOLOGY	VALUE	UOM
Production cost	$C_{production_{PROCESS}}$	8,31	€/pce
Direct raw material cost	$C_{RM_{direct}}$	0,64	€/pce
Environmental prevention cost	$C_{environmental_{prevention}}$	0,62	€/pce
Full industrial cost	$\mathbf{C_{full_{industrial}}}$	**9,58**	**€/pce**

The *total environmental cost* has been estimated with a similar procedure. It is the sum of four environmental aliquots (see Eq.17). Concerning the *environmental cost of waste* *generation*, $C_{WASTE_{generation}}$, the inefficiency factor ω was firstly derived by means of both input and output raw material quantities valued at the purchasing unit cost. The values are reported in Table 3.10.

Table 3.10: Environmental cost of waste generation

WASTE GENERATION DATA	SYMBOLOGY	VALUE	UOM
Direct RM input quantity	$IQ_{RM_{direct}}$	0,160	Kg/pce
Direct RM output quantity	$OQ_{RM_{direct}}$	0,135	Kg/pce
Direct RM purchase cost	$C_{purchaseRM_{direct}}$	4.00	€/Kg
Inefficiency factor	**ω**	**0,16**	**-**
Manufacturing cost	$C_{manufacturing}$	5,22	€/pce
Energy cost	C_{energy}	1,84	€/pce
Direct RM purchase cost per piece	$C_{purchaseRM_{direct}} * IQ_{RM_{direct}}$	0,62	€/pce
Waste generation cost	$\mathbf{C_{WASTE_{generation}}}$	**1,23**	**€/pce**

So, all the aliquots that compose the *full environmental cost* are displayed in Table 3.11.

Table 3.11: Full environmental cost

FULL ENVIRONMENTAL ALIQUOTS	SYMBOLOGY	VALUE	UOM
Environmental process cost	$C_{environmental_{PROCESS}}$	0,082	€/pce
RM production CO_2 emissions cost	$Cu_{environmental_{CO_2 RM_{direct}}}$	0,13	€/Kg
Direct RM input quantity	$IQ_{RM_{direct}}$	0,160	Kg/pce
Environmental prevention cost	$C_{environmental_{prevention}}$	0,62	€/pce
Waste generation cost	$C_{WASTE_{generation}}$	1,23	€/pce
Full environmental cost	$\mathbf{C_{full_{environmental}}}$	**1,95**	**€/pce**

Finally, by comparing the results reported in Table 3.9 and Table 3.11, it is worth of notice that the incidence of the environmental cost on the full industrial for the investigated case study one is about 20%. A representation of the single aliquots incidence is graphically displayed in Figure 3.6.

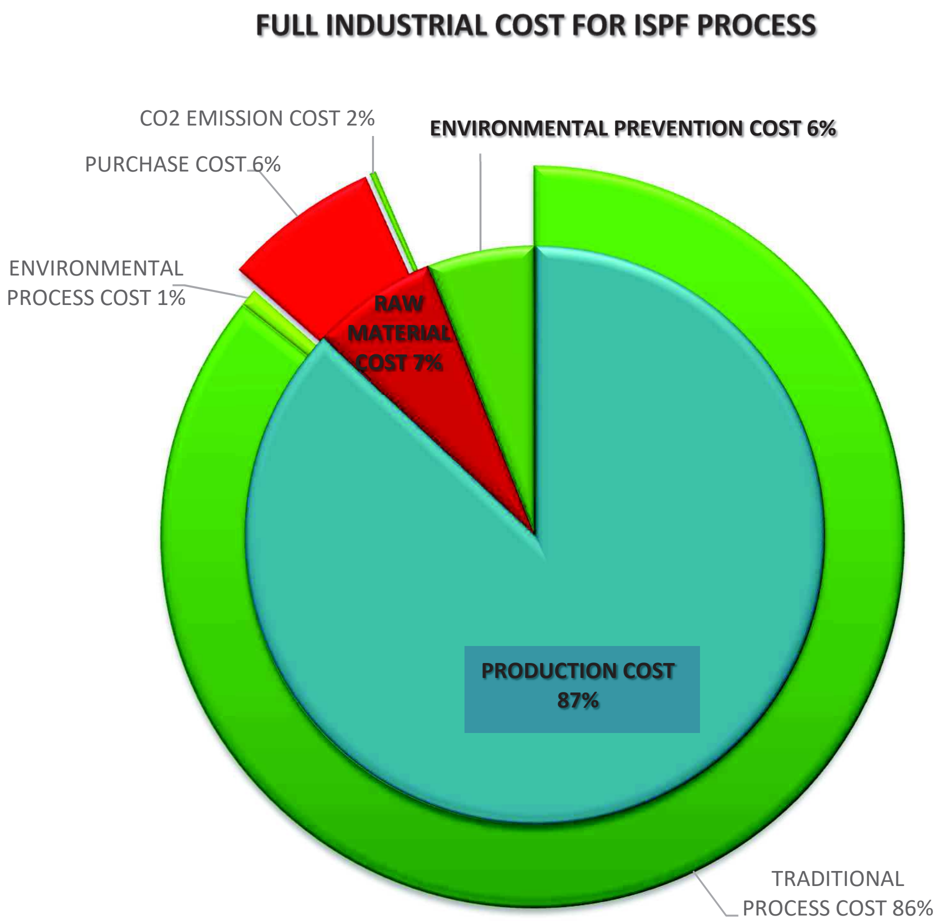


Fig. 3.6: Full industrial cost for ISPF process (percentage composition)

Here the percentage due to the waste generation is not reported being already included both in the production cost and in the raw material cost. However, the analysis of the single terms highlights that the cost of waste generation represents the high inefficiency from an environmental point of view; so a *"sustainable re-engineering"* of ISF process should start from the waste optimization.

Despite this result was obtained for ISF process, it confirms that the environmental rates can not be neglect in a robust analysis of the industrial costs.

Sensitivity analysis

To definitely asses which source of the full industrial cost strongly influences the growth of the environmental rate, a sensitivity analysis was also pursued to complete the study and to understand as the incidence of environmental aliquot changes for changing process conditions. More in detail, taking into account that energy consumption and waste generation change for changing of process time and blank geometry respectively [41], a wide experimental plane was executed introducing a variability as reported in the following:

- three different shape dimensions (classified as small, medium and large) and two 3D profiles (i.e. frustum of cone and frustum of pyramid) were evaluated for understanding the impact of geometrical factors on environmental cost;
- two tool depth steps (i.e. 0,25 and 1mm) and two feed rates (i.e. 3 and 30m/min) were performed.

The completely investigated conditions are reported in the following table.

Table 3.12: Experimental plane

	CONE			**PYRAMIDE**		
DS 0,25 mm – FR 3 m/min	small	medium	large	small	medium	large
DS 0,25 mm – FR 30 m/min	small	medium	large	small	medium	large
DS 1 mm – FR 3 m/min	small	medium	large	small	medium	large
DS 1mm – FR 30 m/min	small	medium	large	small	medium	large

Each configuration was executed three times, in order to determine average values for energy consumption and manufacturing time; after that, both full and environmental costs were quantified and compared. The main comparisons and related results are summarized in the following figures. Figure 3.7 highlights the comparison between the two 3D-profiles; it reports the investigated costs and the relative percentage incidence, measured as the ratio between the full environmental cost and full industrial one. As it can be observed, the incidence of the environmental rate on the full industrial cost decreases increasing the shape dimension; this result can be ascribed to the fact that the percentage of waste quantity and, as a consequence, the incidence of the cost for waste generation is higher when small components are produced. On the other side, no significant differences are observed for changing 3D profile, except that derived by the longer manufacturing time required to manufacture a pyramidal shape [41].

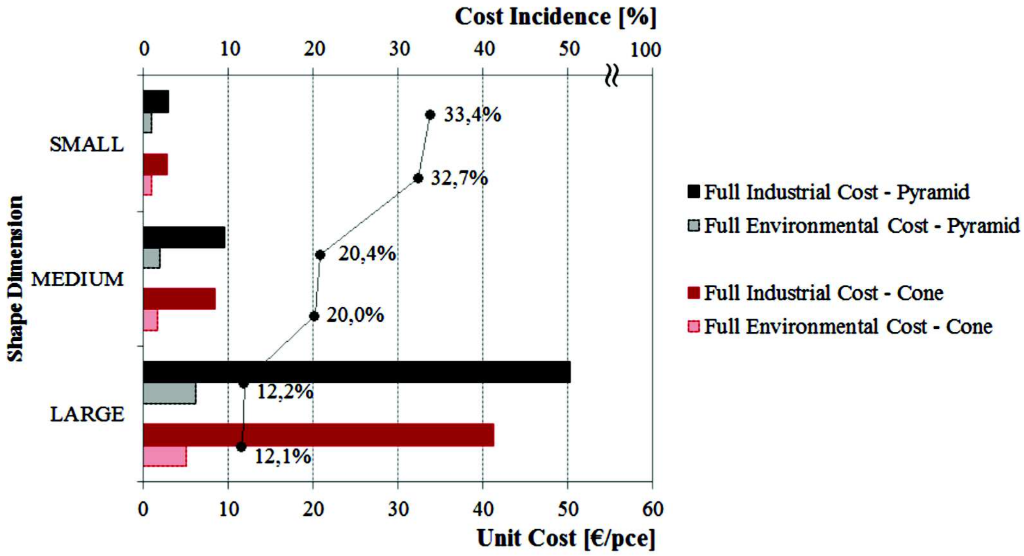


Fig. 3.7: Full industrial cost vs Full Environmental cost changing 3D profile (feed rate = 3 m/min, depth step = 1 mm)

Figure 3.8 reports the comparisons between the investigated costs at the varying of process feed rate: as highlighted, the incidence of environmental cost decreases increasing the process speed, due to the compression of manufacturing cost and time, while is quite constant (about 2%) for all the investigated geometry dimensions.

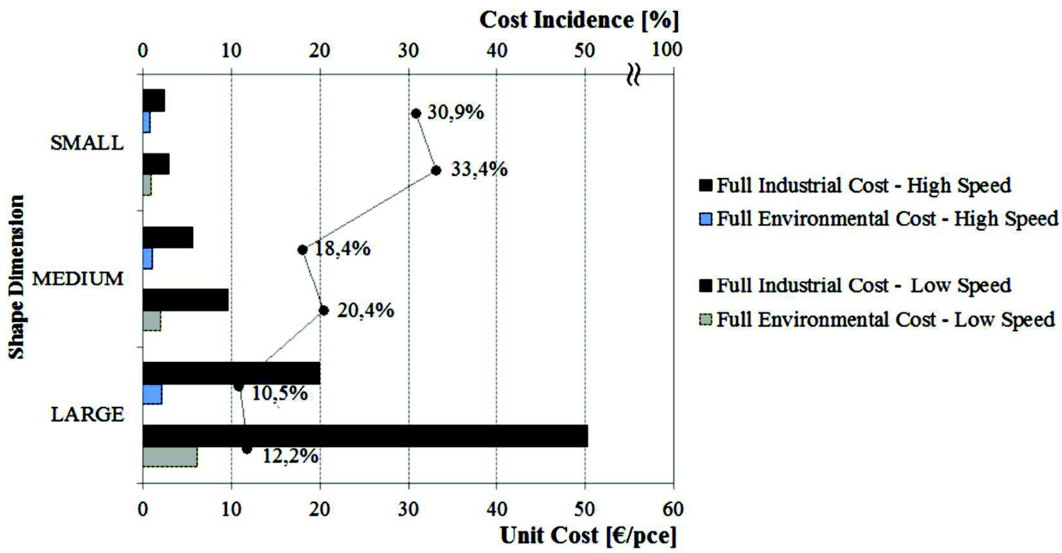


Fig. 3.8: Full industrial cost vs Full environmental cost for changing feed rate (frustum of pyramid, depth step=1mm)

Finally, Figure 3.9 shows the comparison at the varying of tool depth step for frustum of pyramid, executed with a feed rate of 3 m/min. As it is easy to understand, a low depth step determines longer manufacturing time and energy consumption; for this reason, the incidence of environmental rate is higher when a depth step of 0,25mm is used. However, this effect is more significant on the manufacturing of small components with respect to the large ones (about 4% vs. less 1%) due to the nonlinear trend of the environmental prevention cost. More deeply, a lower tool depth step implies less part produced annually; this reduction is more significant for small components (up to 70%) that for large ones (about 50%), due to the high repetition of the unproductive phases.

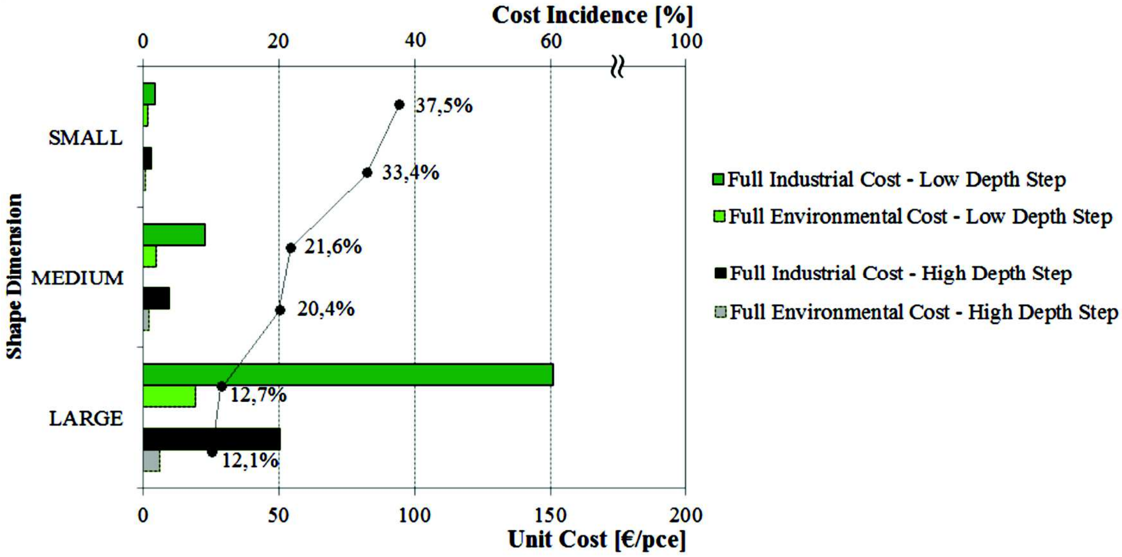


Fig.3.9:Full industrial cost vs Full environmental cost for changing depth step(frustum of pyramid,feed rate=3m/min)

Results discussion and conclusion

The goal of this chapter was to construct a microeconomic model able to consider all kind of industrial costs held up by a firm to realize an output product, including also environmental cost, which constitute today a substantial part of industrial costs. To do that, more different models have been considered and starting to these, a compact and original one has been created in order to consider all possible factors influencing a production process. The final model results fully "general purpose" since it can be applied to all product typologies, independently by the number or by the type of production processes that are required to realize the output product, as well as the country where the processes took place.

Different aspects have been considered to construct the expression of full industrial cost. Some of these are given by the traditional costs, which a company supports to produce an output product (i.e. costs of setup, unproductive, manufacturing, tool, and energy, indirect and direct raw materials). Others additional terms constitute the novelty of the proposed controlling approach and are related to environmental issues (i.e. environmental costs of process and raw material, cost of waste disposal, environmental costs of prevention, etc.).

The second step of the presented study was aimed at determining an accurate measurement of environmental rate in order to establish its incidence on the full industrial cost. To make this, different cost items were considered, such as the environmental prevention cost or the environmental cost of waste generation.

Finally, an application was given, testing the model on the features of ISF production process. This analysis allows deriving two important results:

1. the incidence of environmental cost is on average the 20%, where the main part is due to the waste generation. According to that, an environmental process re-engineering of ISF should consider the cost drop dependent from this item;
2. a wrong choice of the process parameters or the design constrains could determine an increase of the environmental cost incidence up to the 40%. The last occurrence makes the production completely unsustainable and suggest to the process owner the necessity to find alternative and more performing production technologies.

Concluding, the proposed microeconomic model allows driving the decision maker toward more complete and efficient solution, becoming a winning strategy for businesses in period of high environmental pressure as today.

CASE STUDY B: an environmental analysis of bearing production by SKF

The second case study of this work considers a Swedish company, leader in the bearings manufacturing sector, the SKF.

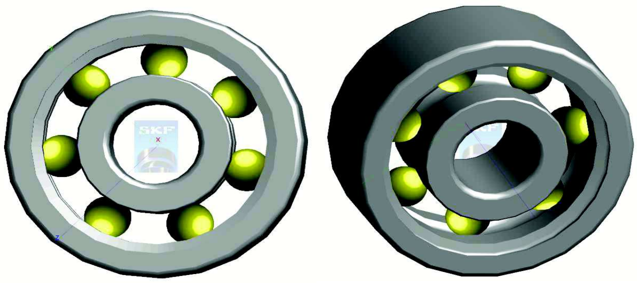


Fig. 3.10 Example of SKF bearing

Relying on the study of the company's production process and on industrial bearings production knowledge, the production cycle has been supposed as represented in the following fig. 3.11.

Fig. 3.11: SKF bearings production process

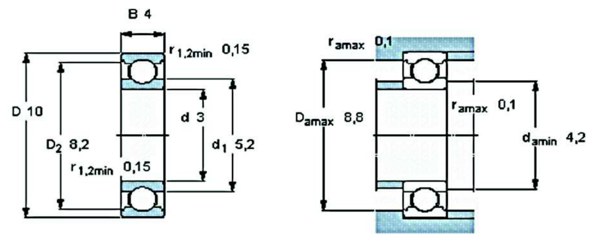
Proceeding similarly to the case study A, the sensitivity analysis has been realized on three different radius dimension, as following.

Table 3.13: Bearings diameters analyzed

DIAMETER	TECHNICAL DATA SHEET
D1 = 10 mm	see below
D2 = 100 mm	see below
D3 = 1000 mm	see below

D1 = 10 mm

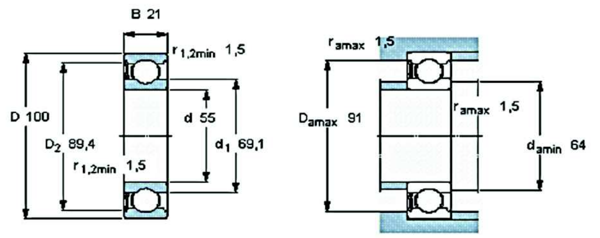
Dimensioni principali d	D	B	Coefficienti di carico base dinamico C	statico C_0	Carico limite di fatica	Velocità di riferimento: Velocità di riferimento	Velocità limite	Massa
mm			kN		kN	g/min		kg
3	10	4	0,54	0,18	0,007	130000	80000	0,002



Fattori di calcolo
k_r 0,025
f_0 7,5

D2 = 100 mm

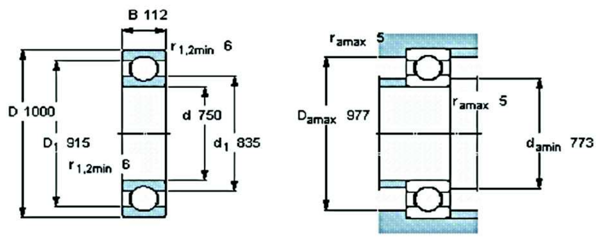
Dimensioni principali d	D	B	Coefficienti di carico base dinamico C	statico C_0	Carico limite di fatica	Velocità di riferimento: Velocità di riferimento	Velocità limite	Massa
mm			kN		kN	g/min		kg
55	100	21	46,2	29	1,25	-	4300	0,61



Fattori di calcolo
k_r 0,025
f_0 14

D3 = 1000 mm

Dimensioni principali d	D	B	Coefficienti di carico base dinamico C	statico C_0	Carico limite di fatica	Velocità di riferimento: Velocità di riferimento	Velocità limite	Massa
mm			kN		kN	g/min		kg
750	1000	112	761	1800	25,5	1000	850	255



Fattori di calcolo
k_r 0,02
f_0 17

For the previous three different bearings, full industrial cost and full environmental cost have been estimated. The results are reported in the following table, in which the incidence of environmental cost on industrial cost is evidenced with a red box:

Table 3.14: Sensitivity analysis (diameter changing)

Diameter [mm]	$C_{FULL\ INDUSTRIAL}$	$C_{FULL\ ENVIRONMENTAL}$	
10	1,06	0,06	**6%**
100	25,09	0,76	**3%**
1.000	7.690,2	49,31	**1%**

Below, the graphic representation of previous results.

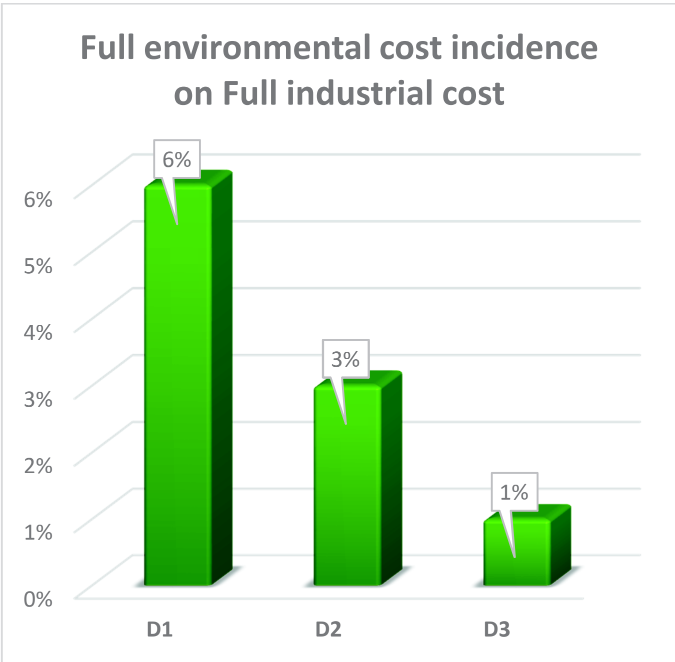


Fig. 3.12: Environmental cost incidence on Full industrial cost

Figure 3.12 demonstrates with evidence how the full environmental cost is more incident on smaller bearings rather than the biggest.

In correspondence with the industrial cost increment, the environmental rate influence decreases until to become next to nothing. This event is, probably, due to the high production cost of the piece with a greater diameter for which the environmental costs constitute only a minimum rate, little relevant on the total cost. For the other two versions (D1 and D2) does not happen the same thing.

As test of true, in the following figures, the trend of production costs and raw material costs for the three kind of output can be observed. It is clear the break between the first two bearing measures production costs and the greatly increased cost for the D3 dimension.

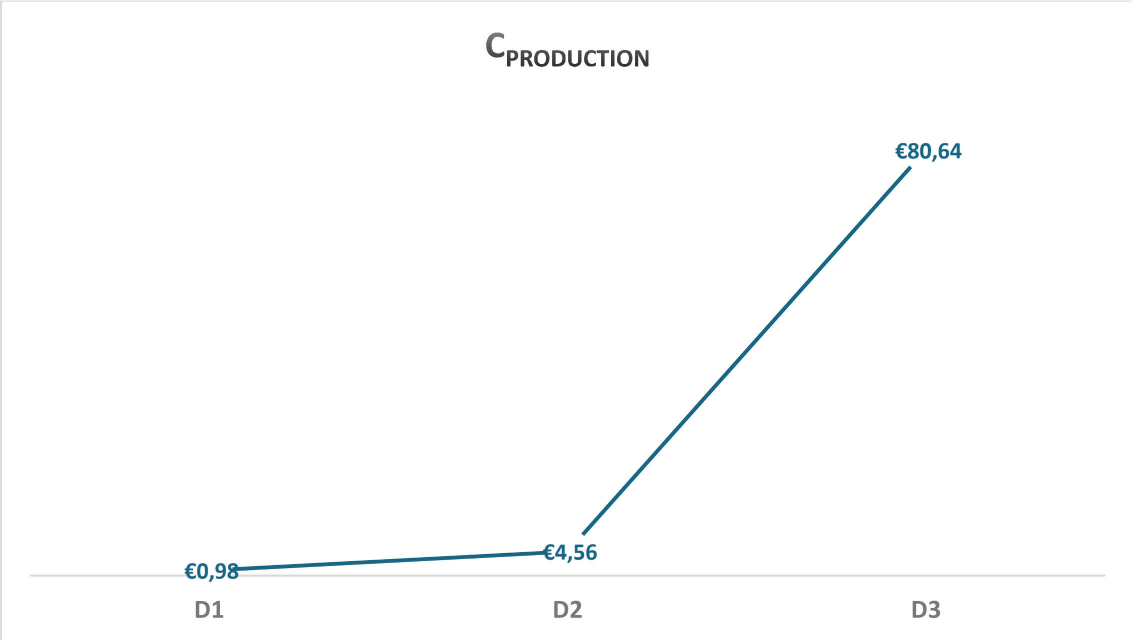


Fig. 3.13: $C_{PRODUCTION}$ trend for the three analyzed dimensions

Fig. 3.14: $C_{RM\ DIRECT}$ trend for the three analyzed dimensions

Therefore, it is clear that a company will act primarily on the smaller bearing production if it wants to reduce environmental cost.

Chapter 4

Additive Manufacturing: the real breakthrough

Scientific research has made great strides over the past decade in the field of industrial processes. The development of technology and the smart systems has quadrupled the possibility of growth in the industrial field, generating great results not only in relation with the process costs but also about the important goal of environmental sustainability.

In this great context, Additive Manufacturing (AM) technology (or 3D printing) comes in preponderantly, offering new perspectives and new question marks, which have not yet given a definitive answer. However, the aerospace industry employs it because of the possibility of manufacturing lighter structures to reduce weight. Additive manufacturing is transforming the practice of medicine and making work easier for architects. Anyway, there is still a lot of work and research to be accomplished before additive manufacturing technologies become a standard in the manufacturing industry because not every commonly used manufacturing material can be handled. Therefore, the study of hybrid processes, that allow the fusion of 3D printing advantages with the traditional manufacturing processes ones, increases. The continuous and increasing growth experienced since the early days and the successful results up to the present time agree with optimism for an AD significant place in the future of manufacturing.

4.1. Redesign and Remanufacture: two activities closely linked

The activities aimed at realization of a good depend on each other so tight: the production process is organized according to the output design. As well as the industrial outputs are the result of a market research, to capture consumer's needs. As well as the type of good realized establishes the marketing policy to adopt for selling it. All the activities are so closely connected generating a continuous cycle allowing spontaneous innovation.

The modern world market is more and more careful to environmental factors whether for ethical and image issues, and for an economic one. Thus, in a company, the whole production cycle is thought putting the environmental sustainability as common denominator of all activities. In the 6R approach, explained in the first chapter of this study, all the manufacturing activities involved in the "sustainable rethinking cycle" production are highlighted.

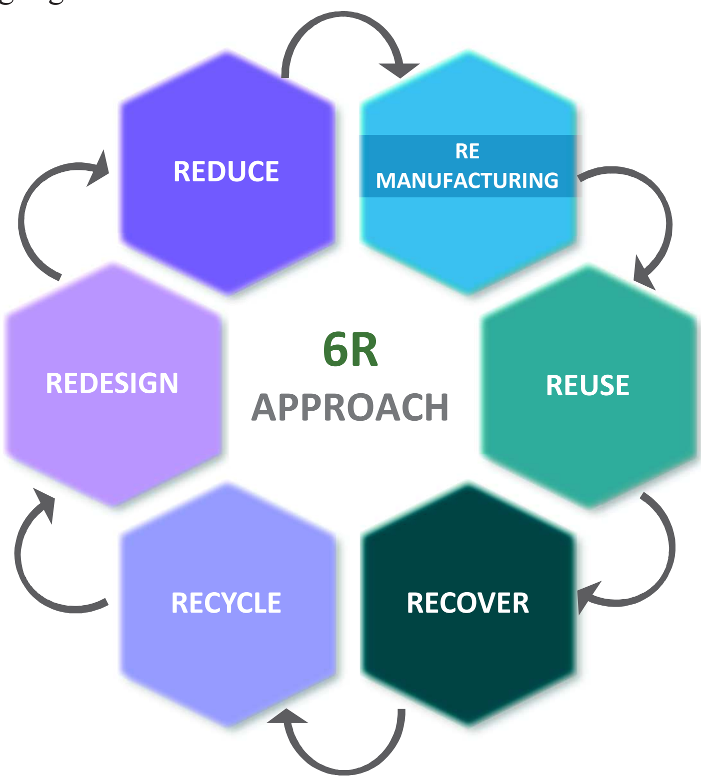


Fig. 4.1: 6R Approach

Of course, the first activities considered in this sustainability oriented renewal process are “redesign”, “reduce” and “remanufacturing”, which compare at the beginning of the production process of a good. “Reuse”, recover” and “recycle” are the actions allowing working at the end of the production chain.

More in particular, in this chapter the attention will be addressed to redesign and remanufacturing activities, which influence each other.

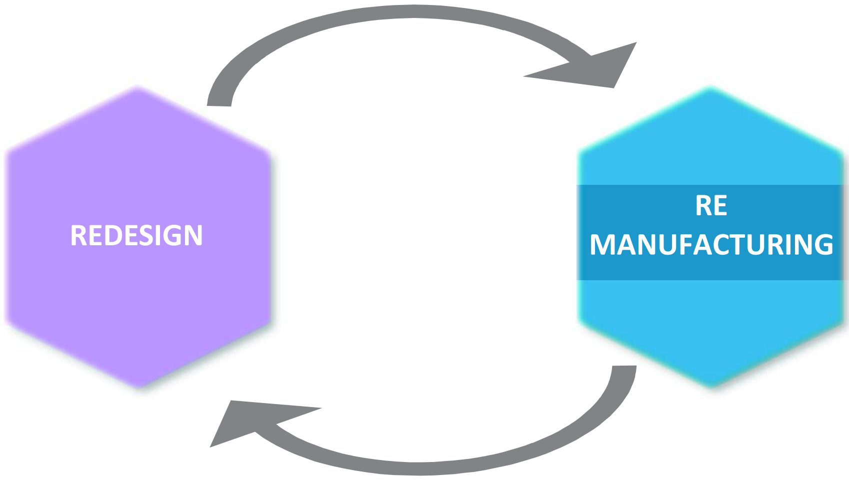


Fig. 4.1 Redesign and Remanufacture link

In the production chain, the output redesign is a very important step. First of all, it is important to clearly define what is the goal to achieve, not only taking into account the consumers' needs but also searching the output characteristics useful to get the desired scope and to observe the needs of economic efficiency (material, production process, transport type) and environmental sustainability, increasingly incumbent for modern industries. At the same time, program the production of a good means considering the output characteristics together with the most economic and sustainable kind of manufacturing process.

4.2. Remanufacturing: traditional and innovative processes in comparison

Technological innovation allows introducing frequently new alternatives to traditional production methods. They give similar outputs to the previous ones but with better economic and environmental performance. However, not always the rule "the newest is better" is valid. In fact, many are the studies conducted with the aim to compare traditional and innovative production processes on real or experimental cases of study.

Following, a detailed exposition on two important comparisons: the traditional Stamping process with the innovative Incremental Sheet Forming one and the Additive Manufacturing with Machining.

4.2.1. Additive Manufacturing and Machining processes

Additive manufacturing (AM) is the "process of joining materials to make objects from 3D model data, usually layer upon layer" [42]. It is also known as rapid manufacturing [43] or rapid prototyping [44]. Unlike conventional manufacturing techniques such as machining and stamping that fabricate products by removing materials from a larger stock or sheet metal, additive manufacturing creates the final shape by adding materials. It has the ability to make efficient use of raw materials and produce minimal waste while reaching satisfactory geometric accuracy [42-44]. Using additive manufacturing, a design in the form of a computerized 3D solid model can be directly transformed to a finished product without the use of additional fixtures and cutting tools. This opens up the possibility of producing parts with complex geometry that are difficult to obtain using material removal processes. As such, it is unnecessary to consider design for manufacturing and assembly (DFM/DFA) principles in product design, which is conducive to design innovation. AM enables environmental friendly product design as well. Unlike traditional manufacturing processes that place many constraints on product design, the flexibility of AM allows manufacturers to optimize design for lean production, which by its nature eliminates waste [45]. In addition, Additive Manufacturing's ability to construct complex geometries means that many previously separated parts can be consolidated into a single object. Furthermore, the topologically optimized designs that AM is capable of realizing could increase a product's functionality, thus reducing the amount of energy, fuel, or natural resources required for its operation [46].

The development of additive manufacturing technology started in the 1980s [47]. Significant progress has been made since then, and there is an expectation that additive manufacturing technology can revolutionize the manufacturing industry and provide various benefits to the society. These benefits include:

- Healthcare products customized to the needs of individual consumers, which is expected to significantly improve population wellbeing.
- Reduced raw material usage and energy consumption, which is a key contribution to environmental sustainability.
- On-demand manufacturing, which presents an opportunity to reconfigure the manufacturing supply chain to bring cheaper products to consumers faster while utilizing fewer resources.

AM technology consists of three basic steps:

1. A computerized 3D solid model is developed and converted into a standard AM file format such as the traditional standard tessellation language format [48] or the recent additive manufacturing file format [49].
2. The file is sent to an AM machine where it is manipulated, e.g., changing the position and orientation of the part or scaling the part.
3. The part is built layer by layer on the AM machine.

Different AM processes build and consolidate layers in different ways. Some processes use thermal energy from laser or electron beams, which is directed via optics to melt or sinter (form a coherent mass without melting) metal or plastic powder together. Other processes use inkjet-type printing heads to accurately spray binder or solvent onto powdered ceramic or polymer. Major AM processes are briefly summarized as follows:

- *Fused deposition modeling (FDM)*. The patent for FDM (US Patent 5121329) was awarded on June 9, 1992, but the technique was described earlier in Crump [50]. Liquid thermoplastic material is extruded from a movable FDM head and then deposited in ultra-thin layers onto a substrate. The material is heated to 1 °C above its melting point so that it solidifies almost immediately after extrusion and cold welds to the previous layers. The materials used have since been expanded to include wax, metals, and ceramics [44]. Machines with two nozzles have also been developed, one for part material and the other for support material that is cheaper and breaks away from the part without impairing its surface [51]. A good variety of materials can be used in FDM and the part accuracy can reach ±0.05 mm. FDM equipment has a compact size, and the maintenance cost is low. However, FDM has some disadvantages, e.g., the seam line between layers, the required supports, long build time, and delamination caused by temperature fluctuation [52].
- *Inkjet printing (IJP).* Inkjet is a non-impact dot-matrix technology originally developed for printing 2D images. Its origin can be traced to the late nineteenth century and the first patent (US Patent 2566443) for practical inkjet device was awarded on September 4, 1951 [53]. IJP uses liquid phase materials, or inks, that consist of a solute dissolved or dispersed in a solvent. A fixed quantity of ink in a chamber is ejected from a nozzle through a sudden, quasi-adiabatic reduction of

the chamber volume via piezoelectric action. The ejected droplet falls under action of gravity until it impinges on the substrate and then dries through solvent evaporation. Printing of a 3D part involves the use of pre-patterned substrates at multiple layers of processing. Various types of materials have been used in IJP to produce a variety of products including solar cells, sensors, and thin-film transistors [54]. IJP can achieve faster response and just-in-time customization. Its disadvantages include fragile print heads (that is prone to clogging or blockage) and expensive ink cartridges.

- *Laminated object manufacturing (LOM)*. The patent for LOM (US Patent 4752352) was awarded on June 21, 1988. A simpler process was presented in Feygin and Hsieh [55]. LOM use adhesive-coated sheet materials. The adhesive, which can be pre-coated onto materials or be deposited prior to bonding, allows the sheets to be attached to each other. 3D parts are then manufactured by sequentially laminating and cutting 2D cross-sections. The cutting is done using laser beam where its velocity and focus is adjusted so that the cutting depth corresponds exactly to the thickness of the layer, thus avoid damaging the underlying layers. A variety of materials can be used, including paper, metals, plastics, fabrics, synthetic materials, and composites. The LOM process is inexpensive and no toxic fumes are generated. It can also be automated with little operator attention. However, LOM has some Z-axis accuracy problems which results in dimensional stability issues. It may generate some internal cavities which affect product quality. In addition, postproduction time is needed to eliminate waste and in some cases secondary processes are required to generate accurately functional parts [56].
- *Laser engineered net shaping (LENS)*. The LENS technology was originally developed at Sandia National Laboratories in collaboration with Pratt & Whitney and then licensed to Optomec Inc. in 1997 [57]. The patent (US Patent 6046426) was awarded on April 4, 2000. With LENS, a part is fabricated by focusing a high-powered laser beam onto a substrate to create a molten pool in which metal powder particles are injected to build each layer. The substrate is moved beneath the laser beam to deposit a thin cross-section to create the desired geometry. Consecutive layers are sequentially deposited to build a 3D part. With appropriate control of fabrication parameters, desired geometric properties (accuracy and

surface finish) and material properties (strength and ductility) of a part can be achieved [58]. LENS can be used to repair parts as well as fabricate new ones. It does not require secondary firing operations. However, LENS still needs postproduction process and the part must be cut from the build substrate. It also has a rough surface finish, which may require machining, or polishing.

- *Stereolithography (SLA)*. The patent for SLA (US Patent 4575330) was awarded on March 11, 1986 and the technique was publicized in Hull [59]. SLA uses a photosensitive monomer resin and a UV laser to build parts one layer at a time. It requires support structures to attach the part to the build platform. On each layer, the laser beam traces the cross-section of the part on the surface of the liquid resin to solidify the pattern. The build platform is then lowered in order to coat the part thoroughly. It is then raised to a level such that a blade wipes the resin, leaving exactly one layer of resin above the part. The part is then lowered by one layer and left until the liquid has settled to ensure an even surface before the next layer is built [60]. Once the part is completed, the support structures may be removed manually. SLA is particularly suitable in the manufacturing industry as it lessens the time it takes for a prototype part to be produced and can achieve a good surface finish. The main limitation of SLA is that the product size is relatively small, roughly no larger than a 2-foot cube. Another disadvantage is the cost. The photopolymer and the machine have very high costs. Also, the materials used in SLA are relatively limited compared to other AM processes [61].
- *Selective laser sintering (SLS)*. The patent for SLS (US Patent 4863538) was awarded on September 5, 1989, but the process was described earlier in Deckard and Beaman [62, 63]. SLS uses a high power laser to fuse small particles of the build material (polymers, metals, ceramics, glass, or any material that can be pulverized). The fabrication powder bed is heated to just below the melting point of the material to minimize thermal distortion and facilitate fusion to the previous layer. Each layer is drawn on the powder bed using the laser to sinter the material. The sintered material forms the part whilst the un-sintered powder remains in place to support the structure and may be cleaned away and recycled once the build is complete. SLS offers the freedom to quickly build complex parts that are more durable and provide better functionality over other AM processes. No post curing is required, and the build time is fast. However, SLS operation is

complicated as many build variables need to be decided. The achievable surface finish is not as good as that from SLA, and the material changeover is difficult [56].

- *Three-dimensional printing (3DP)*. The patent for 3DP (US Patent 5204055) was awarded on April 20, 1993, but the work was reported earlier in Sachs et al. [64]. 3DP functions by the deposition of powdered material on a substrate that are selectively joined using a binder sprayed through a nozzle. The material is first stabilized through misting with water droplets to avoid excessive disturbance when the binder hits it. Following the sequential application of layers, the unbound powder is removed. The part may be further processed by subjecting it to a firing at high temperature to further strengthen the bonding. This process may be applied to the production of metal, ceramic, and metal/ceramic composite parts. 3DP offers the advantage of speedy fabrication and low materials cost [65]. In fact, it is probably the fastest of all AM processes. However, there are some limitations, such as rough surface finish, size limitation, and high cost.

Note that the AM process of solid ground curing (SGC) ceased to be used in 1999 [43] and hence is not included in the previous summary. The disappearance of SGC is because the production system was very complex and therefore suffered from high initial and operating costs.

Compared to conventional manufacturing processes, AM processes have the following perceived advantages:

- *Material efficiency*. Unlike conventional subtractive manufacturing where large amount of materials need to be removed, AM uses raw materials efficiently by building parts layer by layer. Leftover materials can often be reused with minimum processing.
- *Resource efficiency*. Conventional manufacturing processes require auxiliary resources such as jigs, fixtures, cutting tools, and coolants in addition to the main machine tool. AM does not require these additional resources. As a result, small manufacturers that are close to customers can make parts. This presents an opportunity for improved supply chain dynamics.
- *Part flexibility*. Because there are no tooling constraints, parts with complex features can be made in a single piece. In other words, there is no need to sacrifice

part functionality for the ease of manufacture. In addition, it is possible to build a single part with varying mechanical properties (flexible in one part and stiffer in another part). This opens up opportunities for design innovation.

- *Production flexibility.* AM machines do not require costly setups and hence is economical in small batch production. The quality of the parts depends on the process rather than operator skills. As such, production can be easily synchronized with customer demand. In addition, the problems of line balancing and production bottlenecks are virtually eliminated because complex parts are produced in single pieces.

However, AM technology still cannot fully compete with conventional manufacturing, especially in the mass production field because of the following drawbacks [66]:

- *Size limitations*. AM processes often use liquid polymers, or a powder comprised of resin or plaster, to build object layers. These materials render AM unable to produce large sized objects due to lack of material strength. Large-sized objects also often are impractical due to the extended amount of time need to complete the build process.
- *Imperfections.* Parts produced using AM processes often possess a rough and ribbed surface finish. This appearance is due to plastic beads or large-sized powder particles that are stacked on top of each other, giving the product an unfinished look.
- *Cost.* AM equipment is considered an expensive investment. Entry-level 3D printers average approximately $5,000 and can go as high as $50,000 for higher-end models, not including the cost of accessories and resins or other operational materials.

Researchers have been working on improving AM processes to overcome the abovementioned drawbacks. Nonetheless, it is unlikely that AM technology will make traditional manufacturing processes obsolete. However, it is reasonable to expect that AM processes will play an increasingly important role in manufacturing as a complementing technology. In fig. 4.3, an imagine representing AD process.

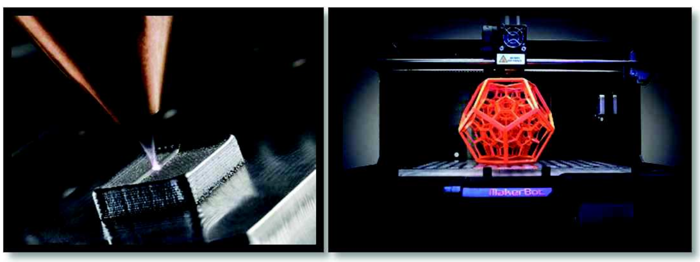


Fig. 4.3: Additive manufacturing process

Explained the main features of the AM technology, it is necessary to put it in comparison with the traditional machining process. In Table 4.1 the main differences.

Table 4.1: AM processes and Manufacturing in comparison [67]

Technique	**Acronym**	**Raw material**	**Energy consumed**	**Fixture and tooling**	**Laser used**	**Solid residues**	**Liquid residues**	**Aerosol residues**	**Disposal**
Machining		Steel, aluminum, alloy	Mechanical energy	Yes	No	Tool scrap, chips	Fluid mix (cutting, cooling)	Tool particulate, fluid vapor	Landfill, recycling
Stereo lithography	Sla	Liquid photopolymer	Uv laser beam	No	Yes	Small amount of resin, removed supports	No	No	Incineration, landfill
Selective laser sintering	Sls	Nylon, metal, ceramic, paraffin wax	High power Laser beam	No	Yes	Material chips	No	No	Incineration, landfill, recycling
Fused deposition modeling	Fdm	Nylon, abs, ceramic, investment casting	Heat	No	No	Material chips, removed supports	No	No	Incineration, landfill, recycling
Laser engineered net shape	Lens	Metal, binder	High power Laser beam	No	Yes	Material chips	No	No	Incineration, landfill, recycling
Laminated object manufacturing	Lom	Paper, polymer, metal, ceramic	High power Laser beam Heat	No	Yes	Material chips	No	No	Incineration, landfill, recycling
Inkjet printing	Ijp	Liquid materials, ink	Piezoelectric nozzle	No	No	Microchips, removed supports	No	No	Incineration, landfill, recycling
Three-dimension printing	3dp	Metal, ceramic, binder	Piezoelectric nozzle, heat	No	No	Material chips, removed supports	No	No	Incineration, landfill, recycling

Now, it is necessary to quantify the differences between the two kinds of processes in order to understand what the best technique to use is. Serres et al. [68] carried out an environmental assessment of direct additive laser manufacturing (CLAD, Construction Laser Additive Directe in French) process, with a life-cycle inventory as large as possible and to compare its environmental impact with conventional machining. The experimental results showed that the total environmental impact was much greater in the case of machining. CLAD process is much more environmentally friendly, with an impact reduction of about 70 %. Comparative studies were carried out in LENS [69] and Direct Metal Deposition [70, 71] with similar results. However, comparing with conventional manufacturing processes, AM processes have their unique features in terms of system complexity and operating style. AM has clear advantages in terms of environmental impact, its energy consumption far exceeds that of casting.

In the two following figures, an overview of the energy consumption of the two industrial processes considered, AM and Machining. Fig. 4.4 shows the different power levels during the productive mode of an EOSINT P760 machine tool (AM). Fig. 4.5 illustrates a typical power profile of a turning process [72, 73].

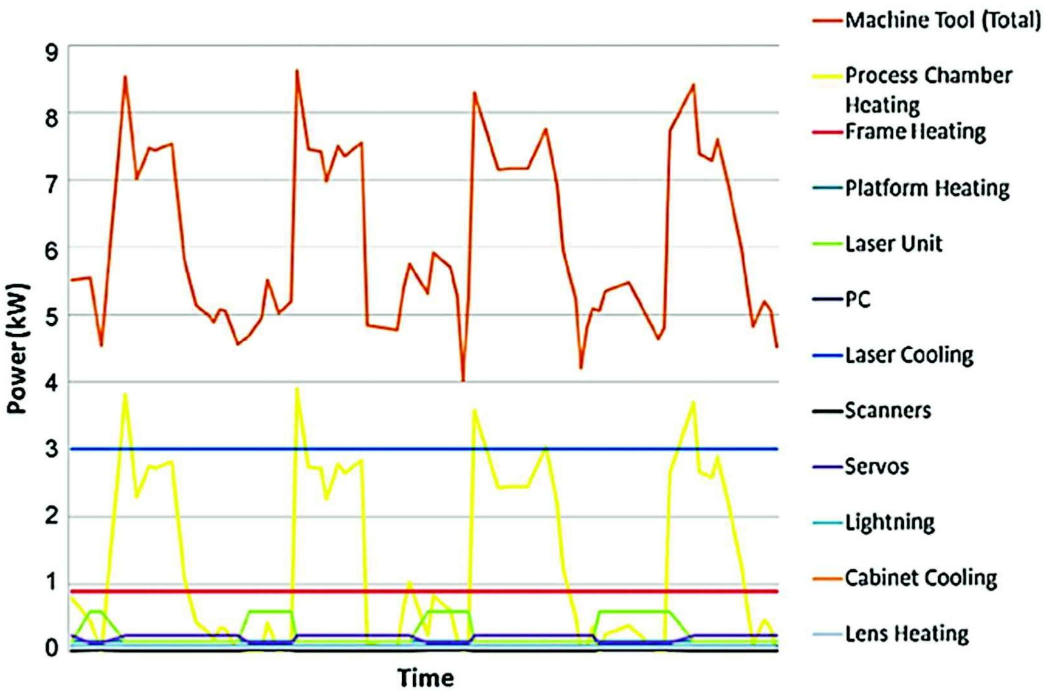


Fig. 4.4: Power levels during the productive modes of an EOSINT P700 Selective Laser Sintering machine tool [72]

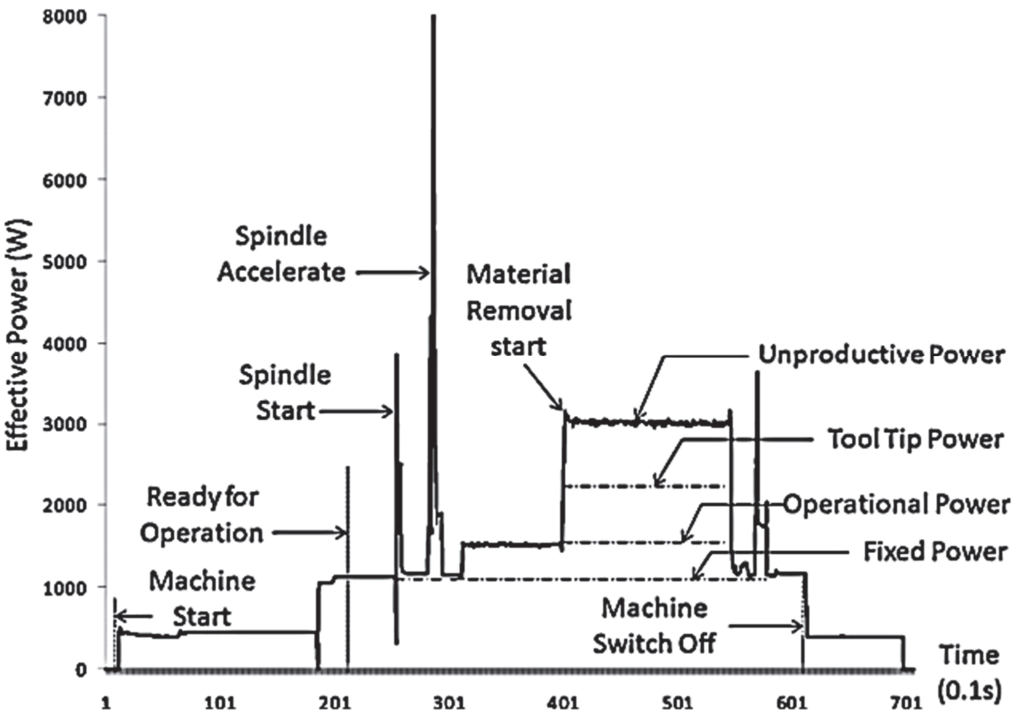


Fig. 4.5: Power profile of a turning process [73]

THE CASE STUDY

To better understand what process is the best in term of costs between the traditional machining and the additive manufacturing ones, in this paragraph a case of study is explained. The study subject is a support for pivoting legs of office chairs made of PA2200 (polymeric material). The dimensions of the output piece shown in figure 4.6 and 4.7 are 50 mm x 40 mm x 60 mm.

Fig. 4.6: traditional design of a support for pivoting legs

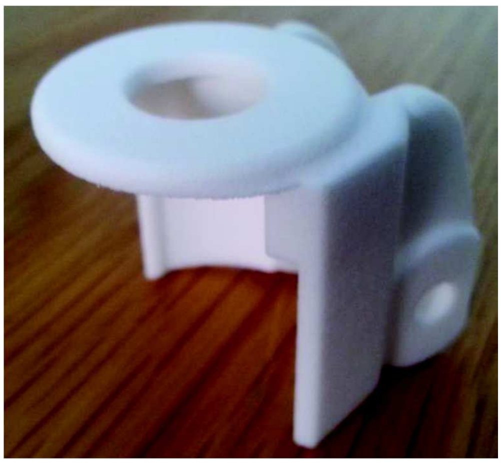


Fig. 4.7: optimized design of a support for pivoting legs

In table 4.2, the material characteristic suggests which its mechanical behavior is.

Table 4.2: PA2200 characteristics

PA2200			
PROPERTIES		**APPLICATIONS**	
-Polyvalent material -High strength and stiffness -Good chemical resistance -Good high mechanical and thermic loads resistance -Excellent constant behavior in the long term -High selectivity and detail resolution	-Various finishing options (for example, metallization, coating fire, vibratory grinding, tub coloring, bonding, powder coating, flocking) -Environmental sustainable according to EN ISO 10993-1 and USP / VI / 121 ° C Approved for food contact according to EU Plastics Directive 2002/72 / EC (except: alcoholic food high)	-High quality plastic functional parts -Medical applications (e. g prostheses) -Replacement plastic molding to typical injection -Furniture components connections -Suitable use in most commercial laser sintering systems	
GENERAL CHARACTERISTICS			
AVERAGE PARTICLE SIZE	LASER DIFFRACTION	60	µm
BULK DENSITY	ASTM D4164	0.44	g/cm^3
DENSITY OF LASERSINTERED PART 20°C	ASTM D792	0.95	g/cm^3
MOISTURE ABSORPION 23°C	ASTM D570	0.41	%
MECHANICAL CHARACTERISTIC			
TENSILE MODULUS	ASTM D638	1700	MPa
TENSILE STRENGHT	ASTM D638	45	MPa
ELONGATION AT BREAK	ASTM D638	15	%
FLEXURAL MODULUS	ASTM D790	1300	MPa
IZOD – IMPACT STRENGHT	ASTM 256	440	J/m
IZOD – NOTCHED IMPACT STRENGHT	ASTM 256	220	J/m
TERMIC PROPERTIES			
MELTING POINT	DSC	180	°C
DTUL, 0.45 MPa	ASTM D648	177	°C
DTUL, 1.82 MPa	ASTM D648	86	°C
ELECTRICAL CHARACTERISTICS			
VOLUME RESISTIVELY 22°C, 50% RH, 500 V	ASTM D257-93	$3.1*10^{14}$	Ohm*cm^3
SURFACE RESISTIVELY 22°C, 50% RH, 500 V	ASTM D257-93	$3.1*10^{14}$	Ohm*cm^3
DIELETRIC CONSTANT 22°C, 50% RH, 5V 1000 Hz	D150-95	2.9	
DIELETRIC STRENGHT 22°C, 50% RH, in air, 5V V/sec	D149-95a	$1.6*10^4$	v/mm

SURFACE FINISHING			
UPPER FACING (AFTER PROCESS)	Ra	8.5	µm
UPPER FACING (AFTER FINISH)	Ra	0.13	µm

In table 4.3, the resume of the main steps for the two type of processing.

Table 4.3: Machining and Additive Manufacturing machine steps

MACHINING	ADDITIVE MANUFACTURING
Product specifications definition	Product specifications definition
CAD model creation	CAD model creation
Machine powering	Platform placement to zero level
Machine not in use	Data processing and starting activity
CAD model processing	Work area heating
Machine tooling	Layer by layer production
Workpiece	Piece finishing by the operator
Shavings output	Post process tooling
Piece removing	Piece removing
Machine Standby	Tooling removal
Machine switching off	Machine switching off

Following, the detailed expositions of the two production processes and their comparison.

MACHINING PROCESS

To realize the output previously introduced with machining process, the *VERTICAL CENTER MAZAK NEXUS 410* has been used. Its technical data sheet is below reported.

Fig. 4.8: Mazak Nexus 410

Table 4.4: Technical work characteristics

CAPACITY	right/left board	900 mm
	longitudinal board	430 mm
MANDREL	mandrel cone	40
	maximum speed	12.000 rpm
	motor power	11 KW
STOCK	tools number	30
PROGRESS AXIS	work capacity (X axis)	560 mm
	work capacity (Y axis)	410 mm
	work capacity (Z axis)	510 mm
OTHER PARAMETERS		
PROGRESS SPEED		300 mm/min
PITCH		1 mm
LUBRICANT		mineral oil

The instrument to measure power parameters value was the wireless electricity monitor EFERGY e2 (fig. 4.9).

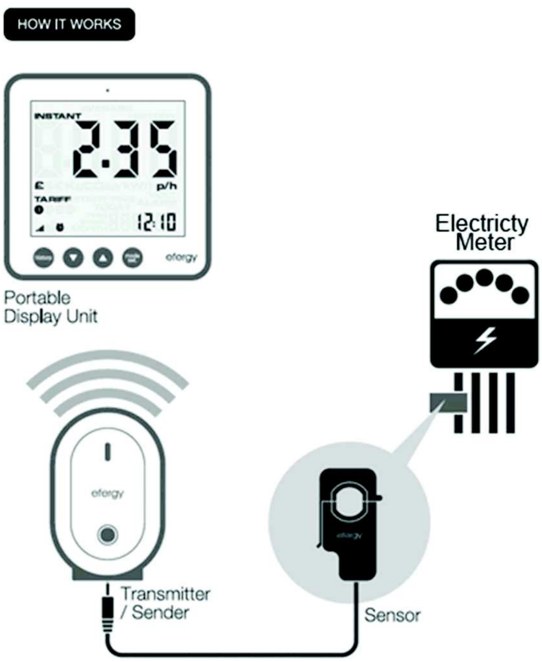


Fig. 4.9: EFERGY e2

Below, the working diagram in which nine are the main steps reported.

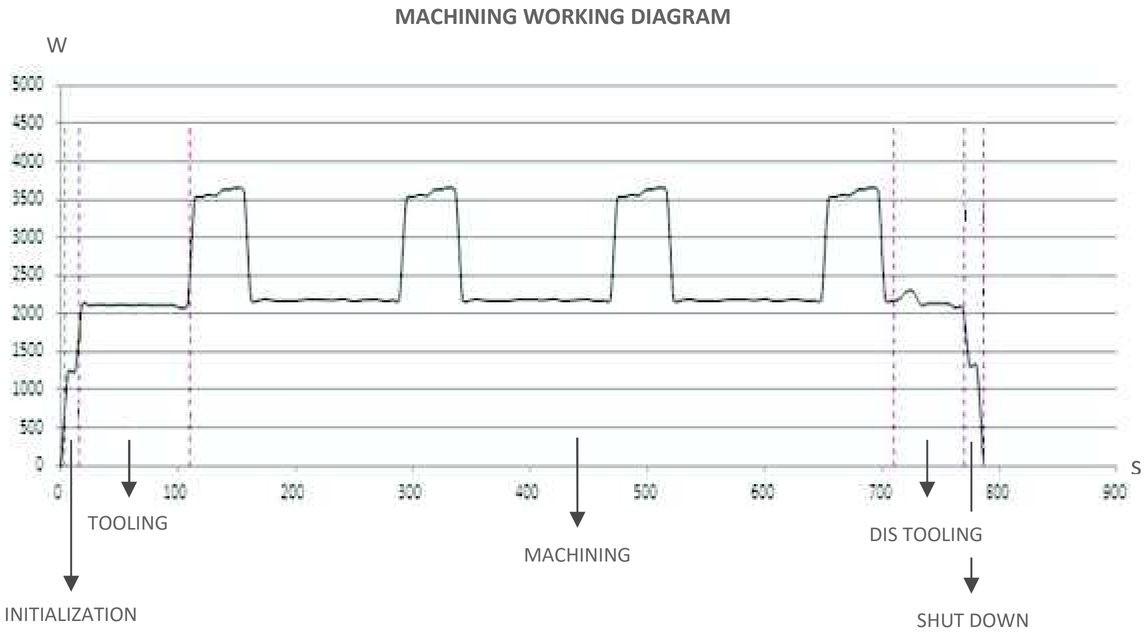


Fig. 4.10: Machining working power

Now, observe the incidence of each step on total working time is very interesting.

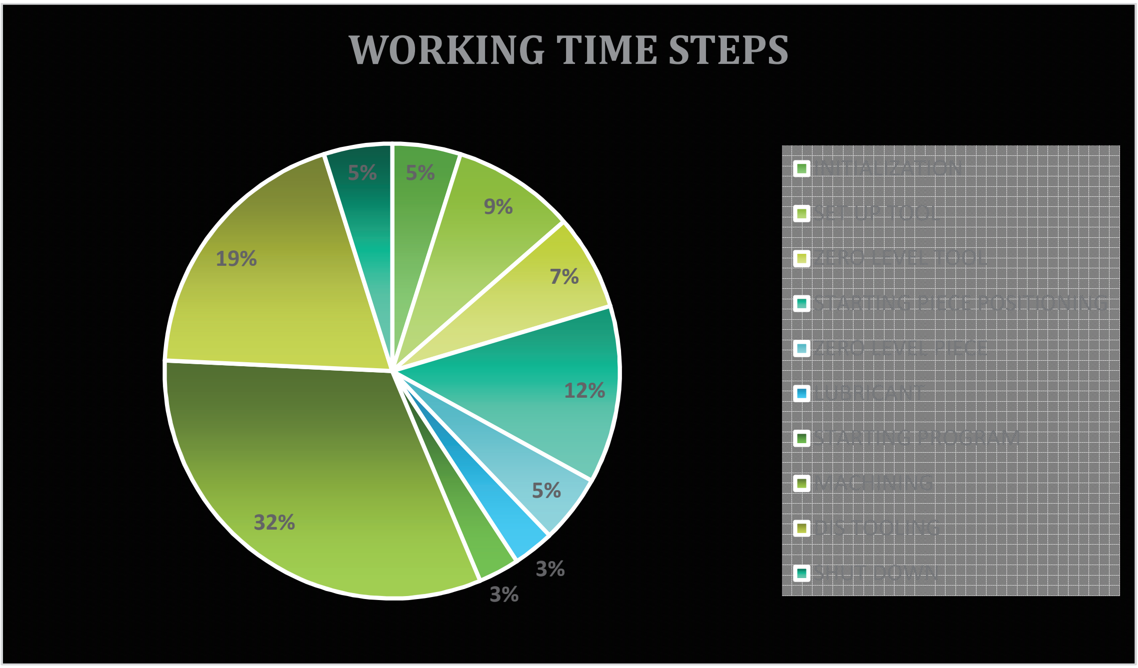


Fig. 4.11: Working steps incidence on total time

The last figure will be useful to suggest what are the steps which need to be better analyzed and compared with Additive Machining ones.

ADDITIVE MANUFACTURING

To realize the output previously introduced with additive manufacturing process, the *FORMIGA P110* has been used (*SLS*). Its technical data sheet is below reported.

Fig. 4.12: Formiga P110

After the safety work activities making, the operator starts the initialization steps in which the project is transmitted to the machine that prepares the powder base to start the production process. Subsequently, a check on the initial parameters of the two work chambers, as shown in fig 4.13.

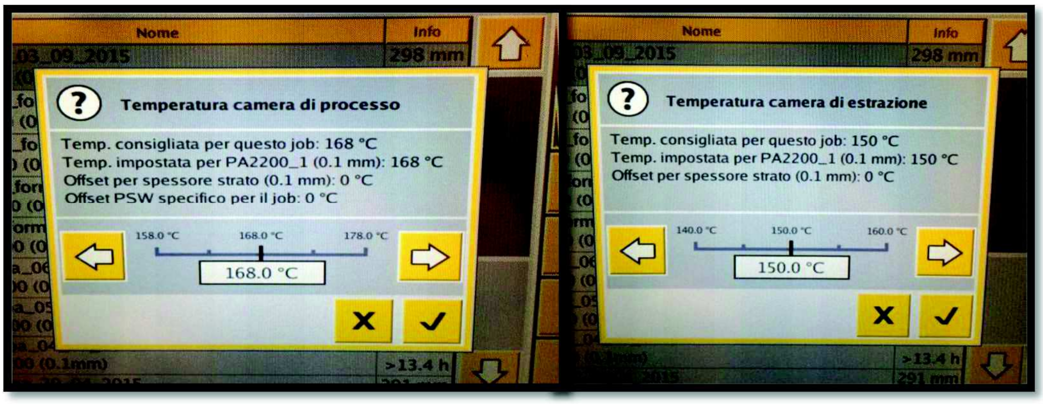


Fig. 4.13: Work temperature setting

The heating step consists of the sequence of brushing through arm and ignition of the thermo-resistors, moving occasionally the powder so that this does not harden with heat.

At the end of this step, there is the maintenance of the building chamber. After about an hour the manufacturing process starts. Before starting the construction of the pieces, the machine lowers the printing plate (layer 0 to 60). It is important to compact well the support surface, especially for the extraction step. The production process starts from the 61° up to 393°, which constitutes the final and bottom layer of the structure. A forward movement of the arm, the laser sintering and the return motion of the arm itself followed this.

Below, the working diagram in which nine are the main steps reported.

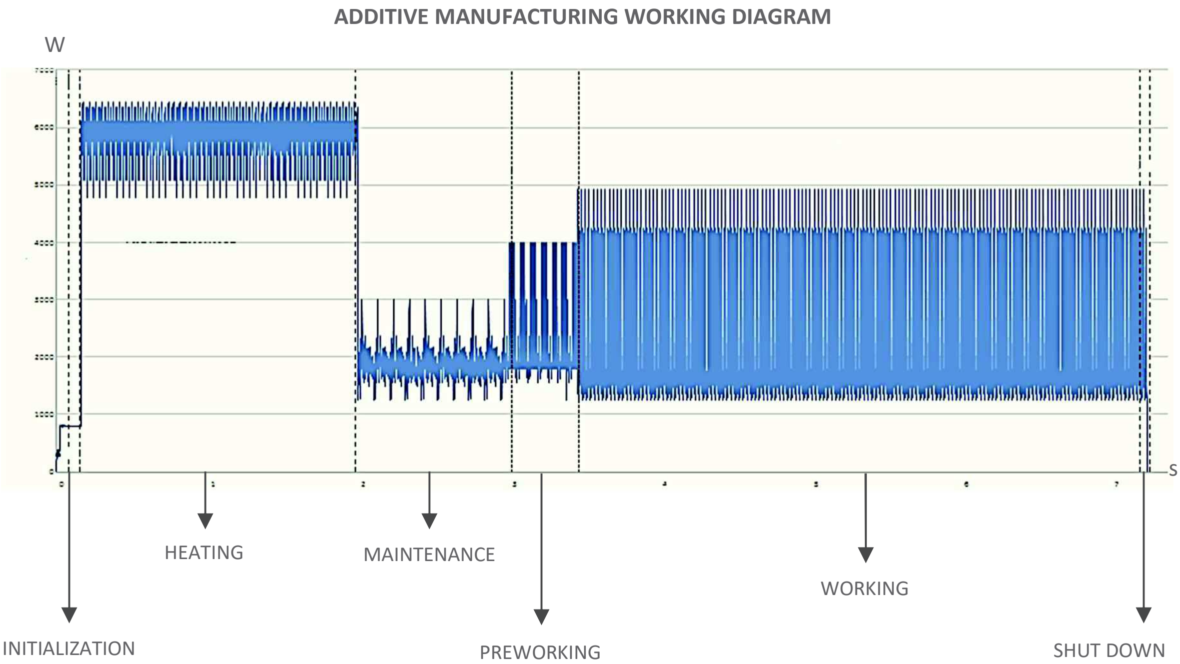


Fig. 4.14: Additive manufacturing working power

Time distribution is divided as shown in table 4.5:

Table 4.5: Additive manufacturing process steps

STEP	POWER (W)	TIME (m)
INITIALIZATION	negligible	3,33
HEATING	6kW	110
MAINTENANCE	3kW	66
PREWORKING	4kW	18
WORKING	5kW	213
SHUT DOWN	negligible	6

Based on the previous table, the following diagram shows which are the steps with more impact on the totality of the process.

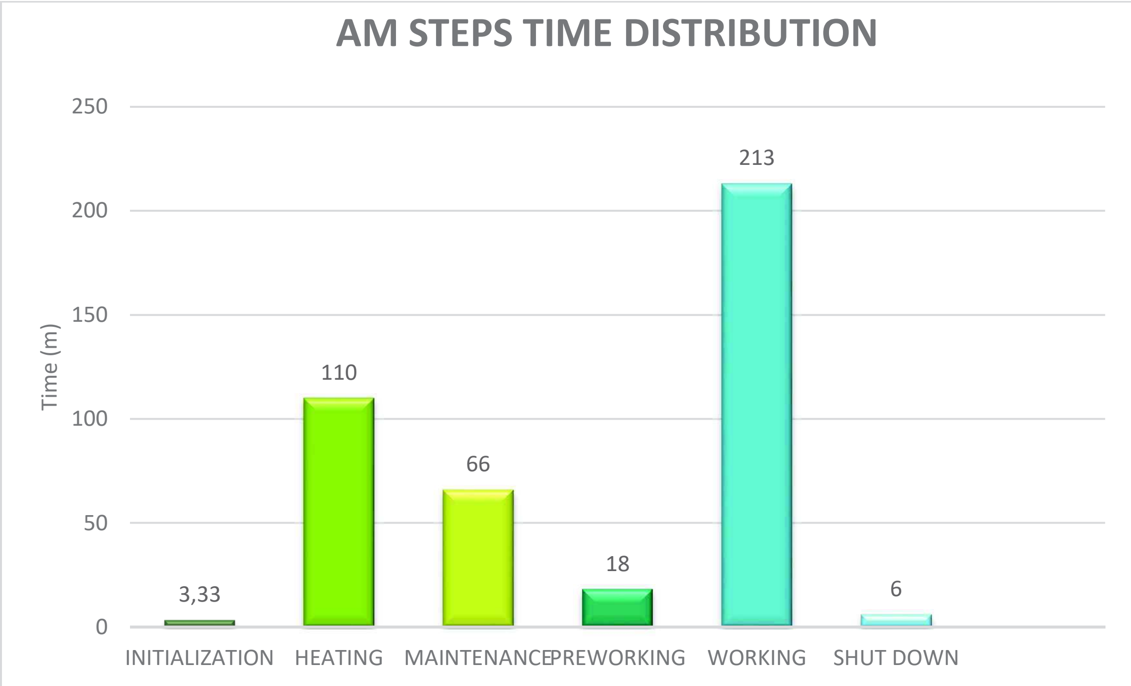


Fig. 4.15: AM steps time distribution

At this point of the analysis, it is fundamental to compare the energy consumption of the two analyzed processes in relation with a specific number of output. The energy amount has been estimated with the two following formula for machining and AM processes.

Table 4.6: Energy consumption for the two processes

$E_{machining} =$ $E_{initialization} + E_{set\ up\ tool} + E_{zero\ level\ tool} + E_{starting\ piece\ positioning} + E_{zero\ level\ piece} + E_{lubricant} + E_{starting\ program} + E_{machining} + E_{dis\ tooling} + E_{shut\ down}$
$E_{AM} =$ $E_{initialization} + E_{heating} + E_{maintenance} + E_{preworking} + E_{working} + E_{shut\ down}$

Comparing the two abovementioned processes on the production of a unique unit of output piece, the result is that the traditional machining process provides better results in terms of energy consumption, with a significant difference compared to the more innovative additive manufacturing process, as shown in fig. 4.16.

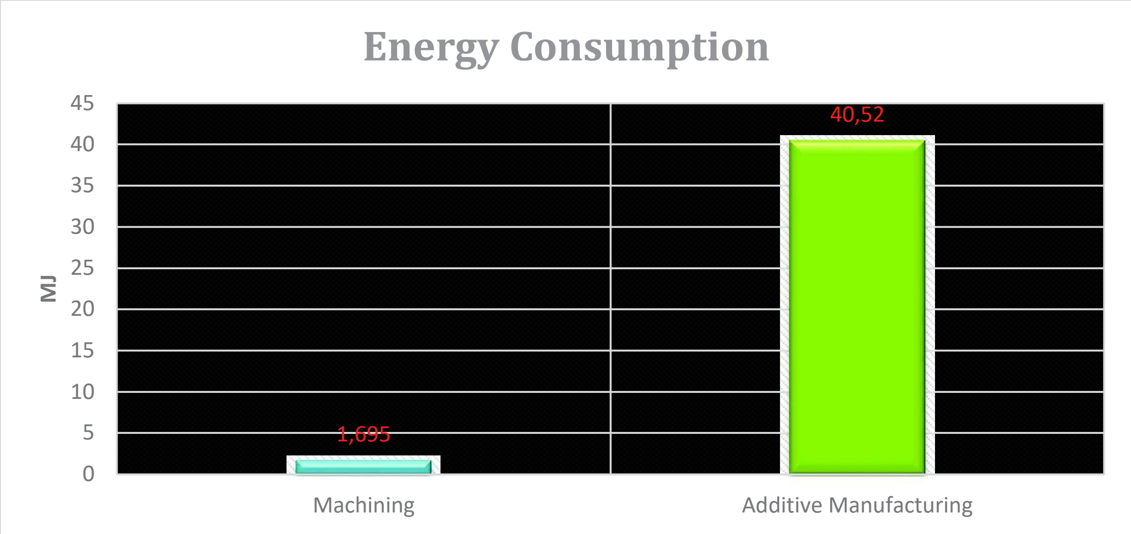


Fig. 4.16: Energy consumption for Machining and AM processes

However, a real industrial production is characterized from a production of more pieces. Therefore, it is more appropriate to extend the analysis to more pieces for both the process. The results are the following.

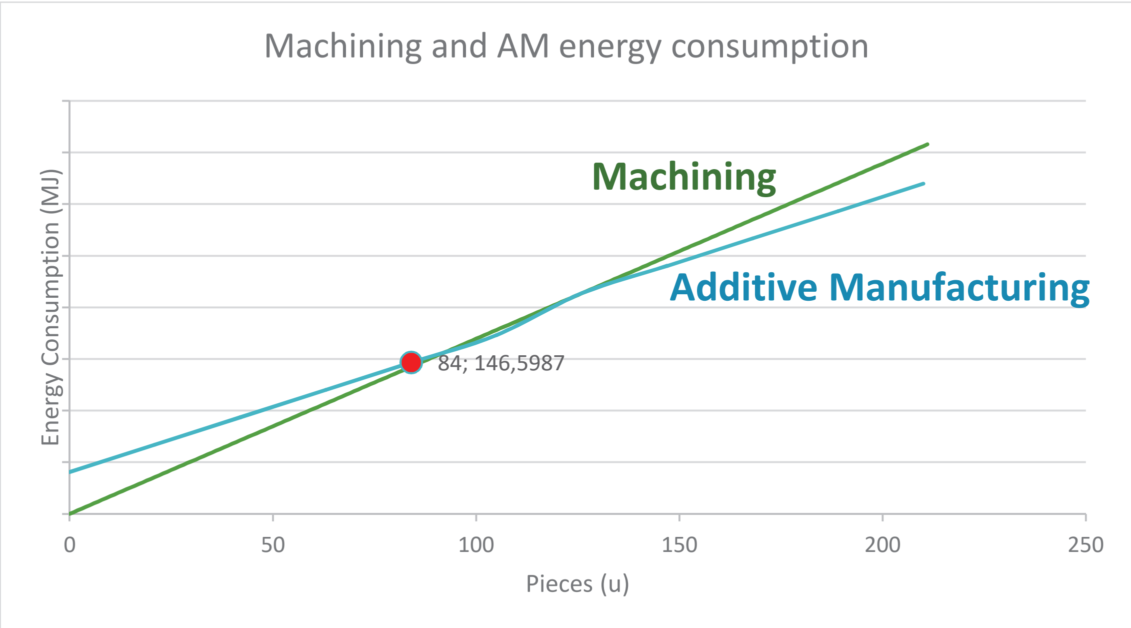


Fig. 4.17: Machining and AM energy consumption – break even point

The point highlighted in red is the number of pieces beyond which it is advisable to use Additive Manufacturing process.

This evaluation in not complete in order to determine which is the more sustainable process in term of environmental impact. There are, in fact, many others factors influencing the CO_2 emissions increment, into the all production process and not only in manufacturing activity. Therefore, the research has to be enlarged to all activities starting from input material supply to waste disposal.

To do that it is important to understand which the activities are contributing to CO_2 emissions along the production chain. In particular, in the following table there are the hypothesis for the calculation of the rates contributing to the carbon dioxide increase.

Table 4.7: CO_2 aliquots hypothesis

	MACHINING	**ADDITIVE MANUFACTURING**
TECNIQUE	Milling	SLS
PIECES [units]	84	84
INPUT RAW MATERIAL [cm^3][1]	10.080	1.017
OUTPUT RAW MATERIAL [cm^3] or WASTE	9.064	n. p.
LUBRICANT [ml/pz][2]	50,4	n. p.
ENERGY [J][3]	1.285,95	1.285,95
TOOL [units][4]	0,42	0

The next step is to calculate the carbon dioxide amount emitted from the two processes. Following, a table in which each previous aliquot is converted into CO_2 according to the appropriate transformation indices.

Table 4.8: Machining and AM CO2 emissions compare

	MACHINING	**AM**
INPUT RAW MATERIAL [Kg]	11,49	1,16

87

[1] For machining process, raw material quantity is calculated considering the volume of the initial cube from which the machine will discard the excess material in order to realize the legs support. For AM, raw material quantity is exactly equal to the final output volume.

[2] Anghinelli, O., Ambrogio, G., Di Lorenzo, R., & Ingarao, G. (2011). Enviromental Costs of Single Point Incremental Forming. *Steel Research Int*, 525-530 [39].

[3] As shown in fig. 4.17 of this paragraph, it is the energy consumption estimated in correspondence of the production of 84 pieces.

[4] A machining tool can produce 200 pieces (based on the machine technical data sheet). The AM layer can be used to produce an infinite number of pieces.

EMISSION FACTOR [KgCO_2/Kg][5]	7,90	7,90
CO_2 EMISSIONS for IRM [KgCO_2]	90,77	9,164
OUTPUT RAW MATERIAL [Kg] or WASTE	10,33	n. p.
EMISSION FACTOR [KgCO_2/Kg][5]	7,90	-
CO_2 EMISSIONS for ORM [KgCO_2]	81,607	n. p.
LUBRICANT [ml/pce]	50,4	n. p.
EMISSION FACTOR [KgCO_2/Kg][5]	1,07	-
CO_2 EMISSIONS for lubricant [KgCO_2]	53,92	n. p.
ENERGY [J]	1.285,95	1.285,95
***CES* [mgCO_2/J]**[6]	0,114	0,114
CO_2 EMISSIONS for energy [KgCO_2]	$1{,}5 \cdot 10^{-4}$	$1{,}5 \cdot 10^{-4}$
TOOL [kg]	0,04	0
EMISSION FACTOR [KgCO_2/Kg][5]	1,77	-
CO_2 EMISSIONS for tool [KgCO_2]	0,065	0
TOT CO_2 [KgCO_2]	**226,305**	**9,164**

The above analysis shows how the AM process is less polluting than the traditional machining process in correspondence with certain amount of output. It is also true that often many factors come into play, factors that an experimental study, certainly, can not bring to light compared to a company in which reality could be, sometimes, a little bit different. However, the goal of this study is also to provide guidelines on how carrying out the comparative analysis between processes and on what factors are important to evaluate the process environmental impact. Furthermore, technology is constantly

[5] Measure of the average amount of a specific pollutant or material discharged into the atmosphere by a specific process, fuel, equipment, or source, expressed as number of kilograms of particulate per ton of the material or fuel. EPA (United States Environmental Protection Agency) provides the EF values.

[6] *CES method* proposed by *Jeswiet and Kara* [35], better exposed in chapter 3 of this work.

88

growing. While this treaty is written, some inventor are identifying a 3D molding system even more innovative as well as a new milling machine characterized by a very low energy consumption is invented.

Therefore, there are many options to consider. In the final chapter of this thesis, there are some suggestions on possible future developments.

4.2.2. Incremental Sheet Forming and Stamping processes

A similar analysis was made for two other important production processes: the traditional stamping process compared with the innovative SPIF one.

In the third chapter of this work, a great space was devoted to the incremental forming process discussion, as well as to its experimental application which allowed assessing its environmental effects.

Stamping is a process in which thin walled metal parts are shaped by punches and dies. The punches and dies are mounted on mechanical or hydraulic presses and they perform two functions during the stamping process: shearing and bending. Mechanical presses utilize a flywheel to store the energy required for the stamping operation. The flywheel runs continuously and is engaged by a clutch only when a press stroke is needed. The drawback of mechanical presses is the driving force varies with the length of the stroke. Hydraulic presses use pressurized oil acting against one or more pistons to drive the punch and die on the press. It is capable of providing full force of the hydraulically driven piston over the entire length of the stroke. However, hydraulic presses are slow compared to mechanical presses. Most stamping operations are carried out on high-speed mechanical presses even though they are more expensive than hydraulic presses [74].

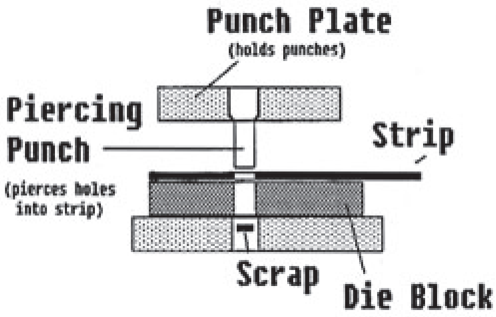


Fig. 4.18: Stamping Process

This paragraph scope is to estimate the incidence of environmental cost on industrial cost referring to the compare between the two above-mentioned processes.

THE CASE STUDY

Initial conditions are the same exposed in relation with SPIF process in chapter 3. The material starting blank is AA5754 sheet, 1 mm thick. To can compare the two processes, the better conditions for both have been chosen:

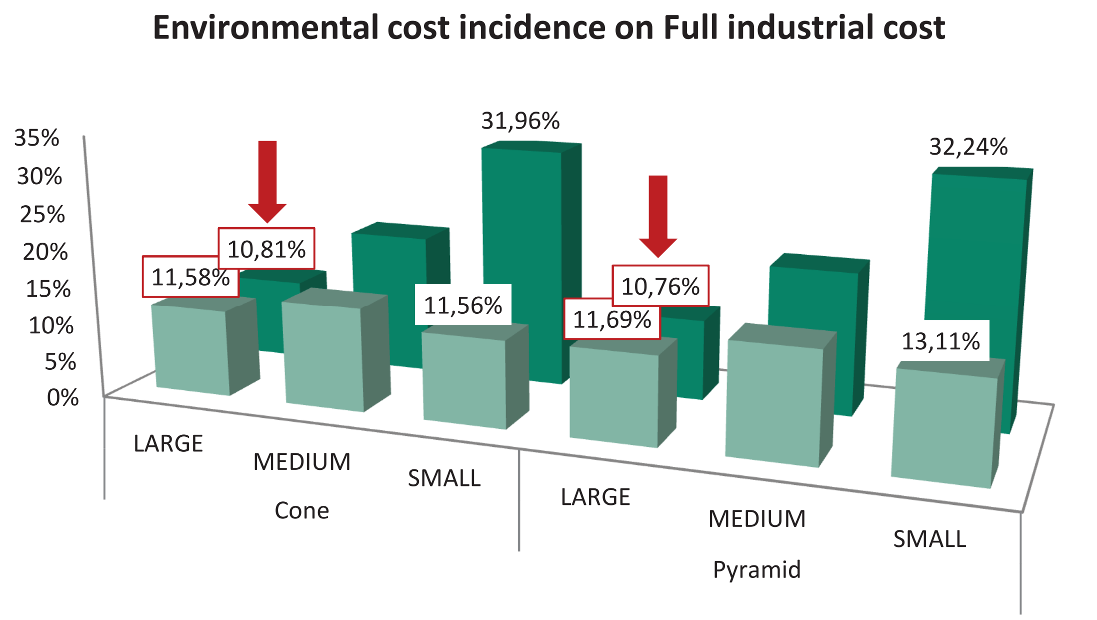
- SPIF: feed rate 30 m/min, tool depth step 0,25 mm;
- Stamping: speed 300 m/min, height 20 mm; alpha 50°.

Therefore, the experimental plane:

Table 4.9: Experimental plane SPIF vs Stamping

		CONE			*PYRAMID*		
		Large	Medium	Small	Large	Medium	Small
STAMPING	**FULL INDUSTRIAL COST [€/pce]**	26,76	4,25	1,2	33,76	5,15	1,31
	FULL ENVIRONMENTAL COST [€/pce]	3,1	0,59	0,14	3,94	0,75	0,17
SPIF	**FULL INDUSTRIAL COST [€/pce]**	16,96	5,15	2,28	19,45	5,43	2,32
	FULL ENVIRONMENTAL COST [€/pce]	1,83	0,97	0,73	2,1	1,03	0,75

Below a graph to evidence the incidence on environmental aliquot on industrial cost.



	Cone			Pyramid		
	LARGE	MEDIUM	SMALL	LARGE	MEDIUM	SMALL
Stamping	11,58%	13,82%	11,56%	11,69%	14,50%	13,11%
Incremental forming	10,81%	18,77%	31,96%	10,76%	18,99%	32,24%

Fig. 4.19: Environmental cost incidence on Full industrial cost for Stamping and SPIF

As it happened for the SKF case study (in chapter 3) on the industrial bearings production, the analysis on the two mentioned-above processes leads to a similar result:

the impact of environmental costs on total production costs is with less influence for large output case. Here, the detachment percentage from the other two dimensions is less accentuated compared to the machining process in relation with the bearings production, but it still presents a significant drift.

Moreover, by comparing Stamping and SPIF processes, it can be established that for large pieces the environmental impact difference between the two techniques is relatively low. Therefore, producing with the conventional stamping process or with the innovative incremental forming one appears almost indifferent. This situation changes in negative for SPIF process, moving to smaller output. For small pieces, in fact, the environmental impact for incremental forming process is about three times the environmental impact for stamping process. This will orient definitely to continue to produce by molding.

However, also here the processes combination options can be varied and endless. The technology is advancing day by day and the secret is to stay up to date and in step with the times in order to capture the right ideas making possible a qualitative, less polluting and economical production.

Chapter 5

The reuse of aluminium production scarfs: a new challenge

Nowadays, the industrial companies are facing a new vision of creating value: offered new product/service not means only to generate something of useful but also environmental, social and economic sustainable. This vision increases the complexity of the production systems design because it is not limited only to the product, but it also affects the technologies adopted in industrial fabrics. Therefore, there is a third important factor in addition to the two main guidelines in defining corporate strategies, which are reduction of costs and improvement in quality: the environmental sustainability.

The present chapter is focused on developing an innovative recycling method of aluminium processing waste through cold compaction processes. At first, a thorough analysis of the state of the art has been carried out, regarding the recycle of production scarfs resulting from machining operations through cold compaction process and the subsequent extrusion operations performed to test the quality of the material coming from the preceding processes. It was subsequently examined a case study relating with a company specialized in the production of containers and rolls of aluminium, film and oven paper for food use. Finally, three routes are been analyzed: aluminum recycle starting from primary raw material, recycle through recasting of production scarfs, recycle through cold compaction. Gabi Software has been used to do this.

5.1. Aluminum recycling, the state of art

In this chapter, the attention is focused on a special material with almost unique features: the aluminum. The main characteristic, which attracts the scientist and technical experts, is its recyclability: the consumption to produce aluminum from aluminum scarfs is only the 5% of the energy needed to produce the primary raw material [75]. This happens because the metal extraction process from the mineral is much expensive rather than the energy consumption to reuse aluminum scarfs thanks to its very low fusion temperature. More specifically, a study conducted by the US Council for Automotive Industry Research shows that the production of primary aluminum requires about 45 kWh and emits about 12 kg of CO_2 per kg, considering the generated electricity, losses of transmission, and transportation. In contrast, the recycled aluminum requires only ~ 2.8 kWh of energy (~ 5%) and emits only ~ 0.6 kg (~ 5%) of CO_2 for every kg of metal.

Moreover, there are two others characteristic which stimulate the attention to this material: its resistance to corrosion under the main environmental conditions, maintaining a high value even after use, exposure to adverse conditions, or storage, and its versatility in the production of marketable products.

The recycled aluminum, or secondary aluminum, can be produced from new or old scraps. The first are the production scarfs. The second are the given by market products like tins or aluminum containers. In fig. 5.1, the aluminum recycle process.

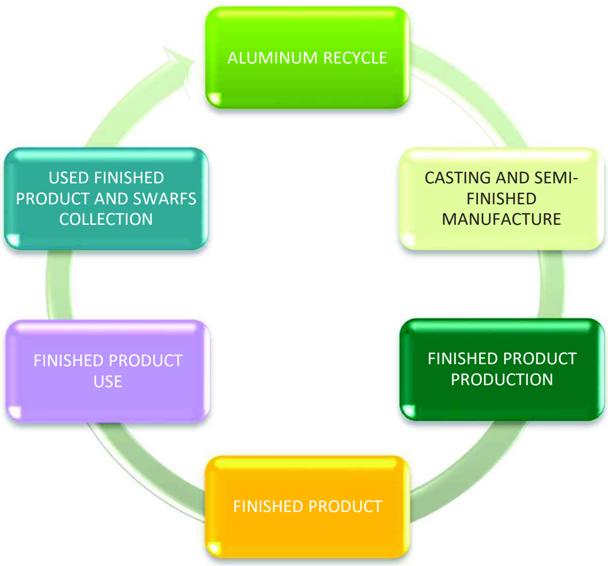


Fig. 5.1: Aluminum recycle process

According with Gronostajski et al. [76] and Sharma e Nakagawa [77] different aluminum recycle methods exist and, more in particular, they wrote about the method of cold compaction of scarfs. The traditional fusion, in fact, in addition to the loss of part of the recycled material due to the oxidation process, implies a higher consumption of energy, time and workforce. The innovative material recovery method consists in the cold compaction of the waste recovered from previous machining processes, which are then hot extruded to create the billet of departure for the successive new production processes. In fig. 5.2 a resuming.

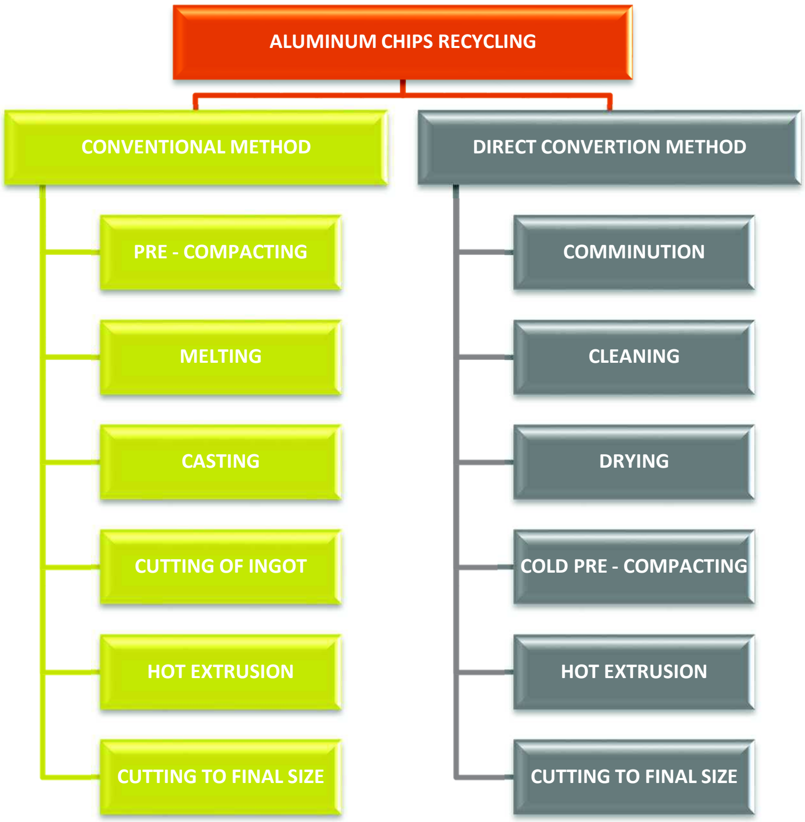


Fig. 5.2: The two aluminum recycle techniques

The conventional method for the recycling of chips is mainly based on re-melting processes, generating a large amount of highly polluting fumes. Moreover, this aspect greatly influences the metal losses: the metal lost because of the fusion is about 10%, for the impurities is another 10%. The losses quantities are irreversible and could reach 35% if the re-melting phase takes place in a gas or oil-fired furnaces. A loss of about 8% occurs in the passage from one step to the other during the process. At the end, during the recycle phase (billet creation), the loss could arrive until the 18%. In conclusion, the recoverable material with conventional method is about 54%. Furthermore, in order to recover a greater amount of material by increasing its density, the costs raise considerably. The direct conversion, instead, allows recovering the 95% of the material with a loss of 2% for impurities and a 3% bound to the discards of machining processes (generally extrusion). The material recovery percentages for the two recovery techniques are represented in the following figure.

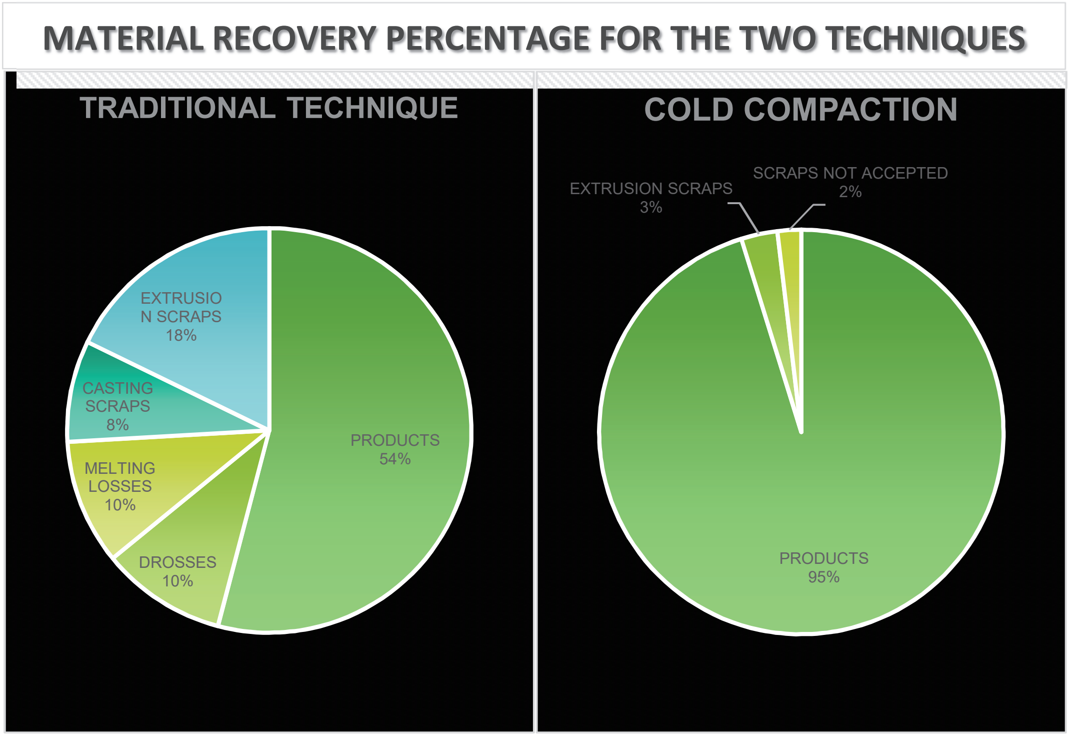


Fig. 5.3: Material recovery percentage for the two techniques

Furthermore, the conventional methods energy consumption is about 16-19 GJ/t with 11-15 person-hours per ton; direct methods consume 5-6 GJ/t with 5-6 person-hours per ton. In summary, the direct methods allow cost savings and a lower environmental impact.

5.2. The direct conversion methods: the compaction and the extrusion

The *compaction process* allows increasing the density of a material (which generally is in the dust form) so as to be workable for different industrial processes (such as extrusion) (Misiolek et al. [78]). A typical compaction is the axial on both sides one, characterized by the movement of two punches in the opposite direction, one upper and one lower. This system is used in order to obtain a more density of pieces of maximum 80 mm in height. A variant is the use of floating matrices: while the lower punch is left fixed, the lateral part of the mold is localized on some springs (precisely floating matrix). Then, the upper punch displacement (downwards) compresses the metal particles causing friction for the handling of the matrix; in this way, it is possible to obtain a more homogeneous density. Pressing the metal powder, the density should theoretically increase. However, in reality the desired density is not achieved because with the applied pressure increasing, the following conditions happen:

a. the plastic deformation is flanked by the consequent hardening of the metal and this is an opposition of the metal to the same plastic deformation;
b. it has an increased contact between the particles (as the compaction goes on) and consequently, decreases the local shear stress that is necessary to the obtaining of further deformation.

The compaction of the metal powder process can be synthesized in the following steps.

1. The metal powders are densified by the particles redistribution in the space.
2. The elastic deformation becomes ever increasing. However, because of it is elastic deformation, the metal particles are not cohesive so if they were removed from the mold, they would return in a non-cohesive phase.
3. The real densification begins with the particles plastic deformation, which allows the material hardening. This causes a slowdown in the densification speed and so the requirement of higher pressures to thicken the materials. At the end of this phase, the powders will be almost completely cohesive between them.
4. As the plastic deformation is extended to the whole mass of the particles, the strain hardening increases, causing a greater material resistance to further thickenings. In this way, the material acquires cohesion in all its volume.
5. During the process, lubricants are often added (for example the graphite fat [79]) in order to reduce friction. This has the effect to reduce the powder theoretical density, which could be reached.

There are two kind of compaction process: a) cold compaction; b) hot compaction (Gronostajski et al. [76]; Hu et al. [80]; Samuel, [81]). The first is made at room temperature. The hot compaction, instead, requires high temperatures to prevent the hardening process. It requires lower pressures and allows to have a greater dimensional product control, and reduces the impact to the input materials physical characteristics, and also, allows to obtain higher density than the cold compaction and so a higher strength of materials compacted. Cold compaction performance is better in terms of costs related to the times, the production and the work than the hot compaction; however, the latter is more precise.

The ***extrusion process*** is a plastic deformation industrial process used to produce tubes, rods, profiles, plates, etc. starting from a specific material (for example, metals such as aluminum, steel, lead, copper, etc.). It consists of compressing the specific material (e.g. aluminum) to pass through a matrix with the goal to produce the piece from which will start a finished product industrial production. There are several classifications of the extrusion process (Kalpakjian and Schmid, [82]): direct extrusion, reverse extrusion or hydrostatic extrusion. Also the process temperature provides a distinction detail. However, the factors that affect its quality are die design, extrusion ratio, billet temperature, applied lubrication, extrusion temperature and speed [82]. Moreover, Gronostajski and Matuszak [76] state that the direct extrusion method causes the least environmental impact and lower costs.

5.3. Primary aluminum or recycled one: the Alupack LTD case study

In this paragraph, the case study presented will allow exposing the innovative recycle process experimented for the aluminum scarfs.

The company chosen for the experimental process is Alupack LTD, a model of governance made in Italy, with a branch in Poland, specialized in the production of about fifty types of aluminum trays. The company operates in an area of 20,000 square meters, in full compliance with safety and environment legislations, in fact, the structures, certified ISO 14001, are equipped with solar panels and the company is involved in further business development programs, aimed at reducing CO2 emissions. Since 2010, Alupack, considering the export data covering 25% of total sales so it has moved some production from Italy to Poland acquiring a strong position in the market of Eastern Europe. It is a company in constant search for high quality, which believes in the importance of investing in research & development, design creativity and new technologies.

The emerged problem in this company lies in the procurement phase due to the oligopoly of the main raw material of Alupack, aluminum. To satisfy the market demands, the company needs to work 1.935.000 Kg_{Al}/year or 161.250 Kg_{Al}/month aluminum. The aluminum oligopoly allows procuring of only a part of this amount that is 100.000 Kg_{Al}/month, causing a considerable gap, which do not permit to satisfy the request.

To overpass this important problem, the company could recycle its scarfs to realize the remaining part of finished products. In this way, it could recover about 25.000 Kg_{Al}/month.

Of course, it needs to outsource the lamination phase of the recycled material through the cold compaction processes, chosen by the company for its more sustainable characteristics rather than the hot ones.

Following, a scheme in which the recovery phase features through a cold process for Alupack LTD.

Table 5.1: Cold compaction process in Alupack

ALUPACK LTD

COMPACTOR	POTENTIAL	400 V
	COMPACTION CHAMBER DIMENSION	500 X 295 X 105 MM
	AVERAGE AMPERAGE	12 A
	POWER	4.000 W
	10,2 KG MASS COMPACTION TIME	180''
ALUMINUM COMPACTED DENSITY	$\rho = \frac{m}{V} = \frac{10{,}2\ Kg}{500 * 295 * 105\ mm^3} = 0{,}66\frac{Kg}{dm^3}$	

The results of the Alupack compaction process generated an aluminum density much less than the theoretical density of aluminum that is 2,7 Kg/dm^3. This result is also visible to the naked eye in the figure 5.4.

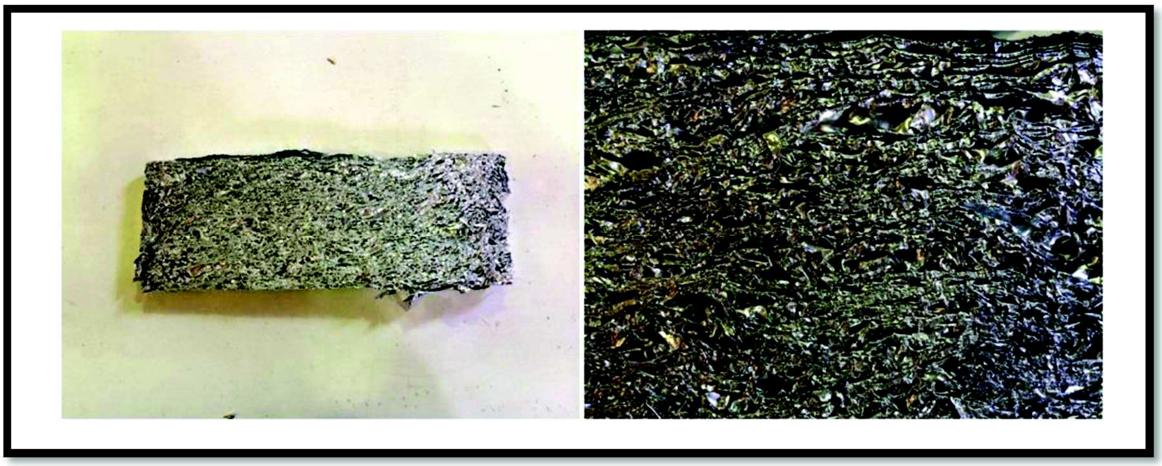


Fig. 5.4: Cold compaction result in Alupack LTD

From the obtained material, more compaction stages were made with a maximum load of 200 KN for a billet of 0,032 Kg, at the technical laboratory of the Mechanical, Energy and Management Engineering Department (DIMEG) of University of Calabria (fig. 5.5).

Fig. 5.5: Cold compaction at DIMEG

The result is the billet shown in fig. 5.6, with a density equal to 2,6 Kg/dm^3, thus much more similar to the theoretical density, and with dimensions equal to Ø 20 x 30 mm.

Fig. 5.6: Cold compaction result at DIMEG

The material is initially subjected to an annealing process and subsequently heated in an electric oven with temperature of 500°C. It is maintained at this temperature for a sufficient time to obtain a suitable homogenization.

Now, the feasibility of the approach proposed will be demonstrated by the execution of a porthole extrusion process of compacted billets, Ø20 x 30 mm size, carried out in the DIMEG laboratory, using an Electro-hydraulic Machine MTS/INSTRON 1276 with a die temperature equal to 450°C . Finally, to objectively evaluate the quality of the extruded profiles, the tensile tests were carried out on the test piece, to measure the weld resistance.

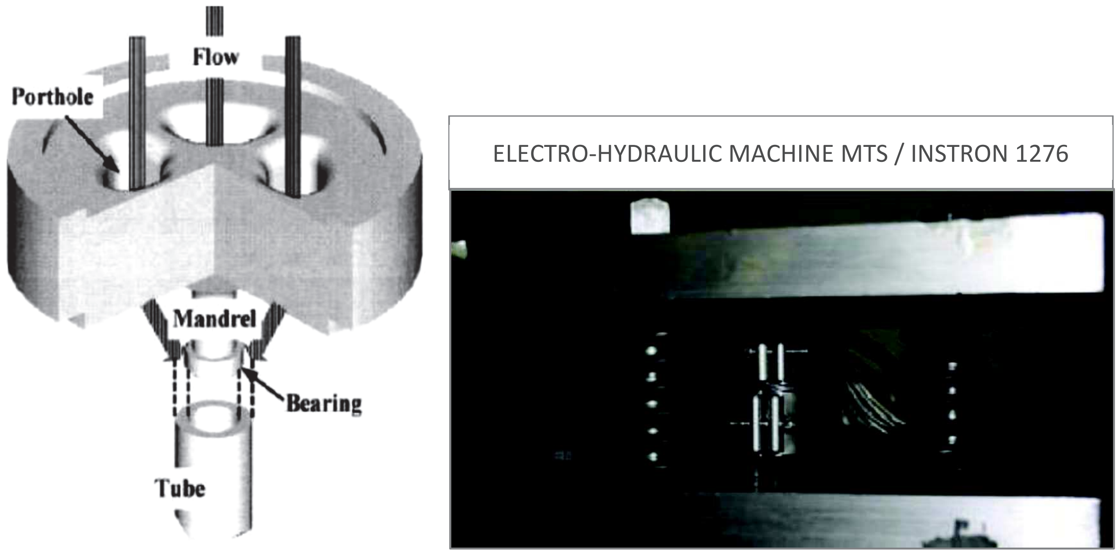


Fig. 5.7: Porthole process

Then, extruded profiles (fig. 5.8) were cooled to ambient temperature.

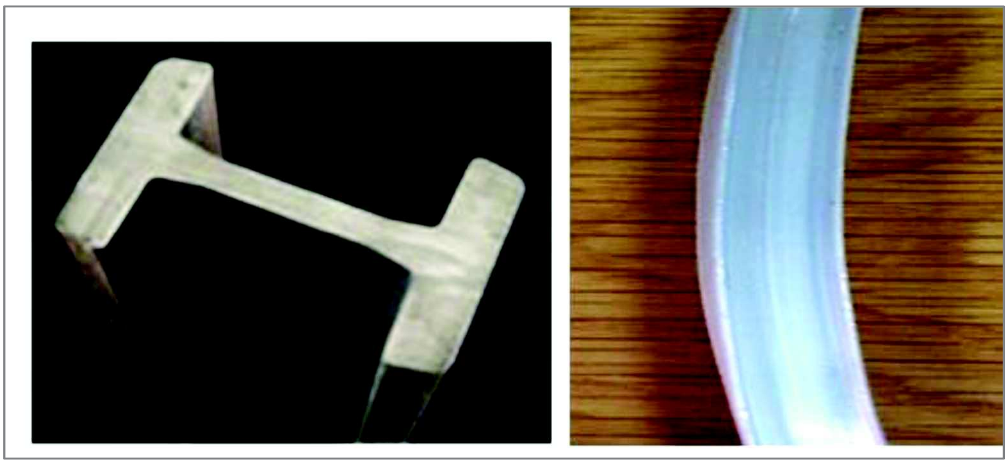


Fig. 5.8: Extruded profile

The samples for tensile test were obtained by cutting the extruded profiles along their transverse direction, getting the sections "I". Their external wings were fixed to the testing machine MTS/Instron (machine capacity load equal to 5 kN) (fig. 5.9).

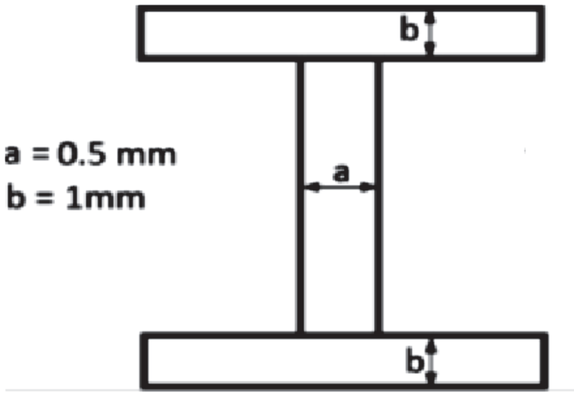


Fig. 5.9: Tensile test

By tensile test, the average strain curve obtained is represented in the following chart:

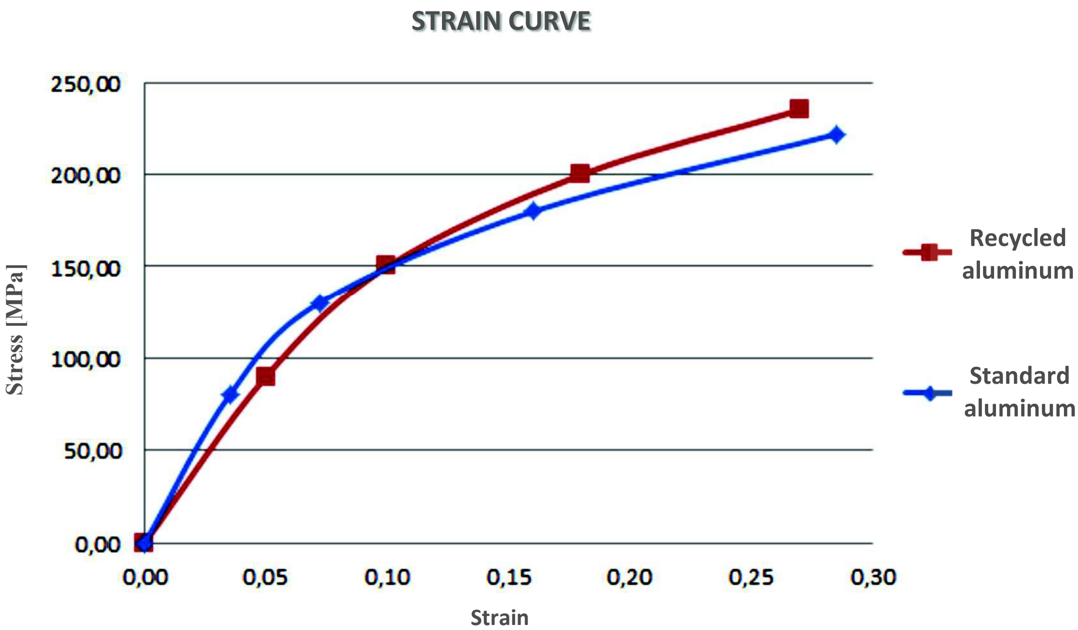


Fig. 5.10: Strain curve obtained from tensile test results

The results tests for recycled aluminum via the direct method (cold compaction) have shown that the breakdown voltage of the material slightly increases. The formability that is the ability of a given material to deform plastically without damage/breakage, slightly decreases compared to aluminum standards. All other mechanical properties remain unchanged.

Therefore, it can be state that technically the properties of aluminum obtained by cold compaction are perfectly suited to the characteristics sought by the company in order to achieve their products. Below, an economic analysis to understand if monetarily can be established the same thing.

Table 5.2: Alupack Economic Analysis

<table>
<tr><td colspan="4">ALUPACK ECONOMIC ANALYSIS</td></tr>
<tr><td>DIRECT ALUMINUM PROCUREMENT</td><td colspan="3">2,9 €/Kg</td></tr>
<tr><td>ALUMINUM SUPPLY WITH COMMUTING</td><td colspan="3">1,2 €/Kg + 1 Kg</td></tr>
<tr><td colspan="4">2,9 €/Kg = 1,2 €/Kg + x → x = 1,7 €/Kg</td></tr>
<tr><td colspan="4">So, for Alupack, commuting a recycled aluminum kilogram means to gain 1,7 €/Kg</td></tr>
<tr><td colspan="4"></td></tr>
<tr><td colspan="4">If the recycled aluminum is employed to produce straws or coasters by extrusion process</td></tr>
<tr><td>Diameter billet = Ø 20 mm</td><td colspan="3">Punch speed = 10 mm/s</td></tr>
<tr><td rowspan="3">STRAWS</td><td colspan="3">Price = 0,15 €/pce
Ø 6 mm
Length = 210 mm
Thickness = 0,5 mm
ρ = 2,78 kg/dm^3</td></tr>
<tr><td colspan="3">Billet length = 0,6 mm</td></tr>
<tr><td>V = 1,81 cm^3</td><td>m = 0,005 Kg</td><td>t_{PRO} = 0,6’’</td></tr>
<tr><td>Diameter billet = Ø 35 mm</td><td colspan="3">Punch speed = 10 mm/s</td></tr>
<tr><td rowspan="3">COASTERS</td><td colspan="3">Price = 0,16 €/pce
Width = 100 mm
Length = 100 mm
Thickness = 1 mm
ρ = 2,78 kg/dm^3</td></tr>
<tr><td colspan="3">Billet length = 11 mm</td></tr>
<tr><td>V = 10 cm^3</td><td>m = 0,0278 Kg</td><td>t_{PRO} = 1,1’’</td></tr>
</table>

COMPACTION AND EXTRUSION FACILITY COSTS	1.200.00 €
Based on the equivalent annual depreciation policy: n = 5 and i = 8%	
25 working days per month - 8hour shift per day	
Worker average salary: 23.000 €/year	

In a month, Alupack has the availability of 25.000 Kg. To produce straws only 6.000 Kg of process waste are used. So this investment hypothesis has been abandoned because it is used only 24% of the available waste in the considered time.

In a month, Alupack can produce 654.545 units of coasters. The material employed is 18.196 Kg so the 73% of waste material. To use the remaining parts, the company could optimize the production time trying to increase the production, or the work shifts or resorting to overtime.

For Alupack, this option is an excellent revenue opportunities, as summarized in the following table:

Table 5.3: Revenues from the production of coasters

Monthly revenues from the sale	104.727 €/month
Monthly amortization	25.046 €/month
Labor monthly cost	2.300 €/month
Monthly Earnings	**77.381 €/month**

This value should be compared with the compacted aluminum commuting value, calculated above and equal 1,7 €/Kg (to be multiplied by the aluminum required quantity to produce the coasters):

Monthly value compacted Kg = 1,7 €/Kg ∗ 18.196 Kg/month = **30.934 €/month**

It can be state that the first alternative to produce coasters could be for the company an important opportunity. Moreover, with its experience, introducing a new product in the market in which she still works could be the perfect way to extend its business.

Conclusions

This work has the purpose to give the enterprises useful and real suggestions and instruments addressing to measure their level of environmental sustainability.

The 6R approach, exposed in the first chapter, helps in this goal providing a complete overview on what activities industrial company have to monitor. This work examines some of these activities suggesting the right view to begin to obtain a more sustainable production behavior. Among the six approach activities, three are relevant in relation with the topic of this work: redesign and remanufacture, closely linked and dealt in the fourth chapter, and recycle, dealt in the fifth one.

To better understand the logic under the work, in the first chapter there is a wide exposition of the "sustainability" concept, whit all its implications and worldwide regulations. The LCA method is discussed and, at the end of this chapter, the 6R approach is presented, introducing the later analysis. This approach is framed into two guidelines that are "cost" and "environmental impact assessment", based on which every good enterprise would evaluate its behavior and act consequently.

All the considerations and case studies carried out based on this approach are addressed by monitoring costs and sustainability according to two different and complementary points of view: microeconomic and macroeconomic ones.

The macroeconomic considerations are carried out in detail in the second chapter of this work, in which the SKF case study has been considered. SKF is a leader enterprise in industrial bearings sector. It has several facilities located in Italy, with different characteristics and sizes. Considering only production sites, the Environmental Management Assessment method (by Cristine Jasch) has been exposed and applied. As demonstrates in the chapter, the only application of the method as presented by the author is not enough to provide accurate and timely information on the corporate sustainability. For this reason, a set of performance indexes have been specially studied and designed in order to complete the analysis conducted by the previous method. Applying these ratios to the case study presented, it is evident that only by including to the *Jasch* method a serious of appropriate indexes, it possible to suggest to the companies what the right direction in terms of sustainability is.

The microeconomic considerations are carried out in detail in the third chapter of this work. A microeconomic model for the environmental cost evaluation is widely exposed. A Mechanical, Energy and Management Engineering Department research group have formulated this method. For the first time, it incorporates in a single formula all the environmental considerations that a company must take into account. This model is applied on two cases study, an experimental production case and a real business one. In the first case, two are the output product realized: a truncated pyramid and a truncated cone, starting from a AA5754 sheet, 1 mm thick with a CNC milling machine used to perform the ISF process. The results demonstrate that environmental costs incidence on full industrial cost is equal to 20%. A sensitive analysis has been carried out, changing the feed rate and the depth step, with the results of a bigger incidence of environmental cost on industrial one for small profile dimensions. For the second case study, a real business context is chosen. In particular, the case is referred to the industrial bearing production by SKF enterprise. Three are the bearings dimensions considered: 10 mm, 100 mm, 1.000 mm. For all of that, the environmental cost and the full industrial cost have been calculate. The results demonstrate also here that the environmental costs are higher for little dimensions.

In the fourth chapter, the redesign and remanufacturing activities are analyzed. In particular, two direct comparisons between innovative and traditional production processes are considered: Additive Manufacturing (AM) and Machining Process, Incremental Sheet Forming (SPIF) and Stamping one. In the first case, the realized output is a support for pivoting legs of office chairs made of PA2200 (polymeric material). The dimensions of the output piece shown are 50 mm x 40 mm x 60 mm. To realize the output previously introduced with machining process, the *Vertical Center Mazak Nexus 410* has been used. To realize the output previously introduced with additive manufacturing process, the *Formiga P110* has been used (*SLS*). The energy consumption has been estimated thanks to the wireless electricity monitor EFERGY e2 with the result of 1,695 MJ for Machining and 40,52 MJ for AM. A breakeven graph was delineated in order to understand for which quantity of output pieces, AM gets better energy consumption. Finally, in correspondence of this number of pieces, the total CO_2 emissions quantity has been estimated for both the technique. The result is that AM allows to emit smaller CO_2 amounts rather than Machining process. The second comparison between SPIF and Stamping has been made on the truncated pyramid and truncated cone. Here, the incidence of environmental costs on industrial costs for each three dimensions of the two profiles has been estimated. In addition, here, as in chapter three with the bearings production, the incidence of environmental cost on industrial one is smaller for large output profiles. Therefore, it is in large output profiles that the CO_2 quantity emitted is smaller than the other two dimensions.

The last fifth chapter deals with the recycle process. In particular, the issue of recycling of aluminum starting from a local company case study has addressed. The company is Alupack LTD, specialized in the production of about fifty types of aluminum trays. The problem on the amount of the available aluminum supply not sufficient to satisfy its requirements led the company to think to an alternative furniture system. From here, the idea of processing waste recycle. The evaluation is performed on two different types of scarfs compaction, cold and hot, without using the traditional fusion process, which is more expensive and more abrasive for the material. The obtained billet from aluminum scarfs have been subjected to tensile test in order to evaluate its quality. The result obtained are good: the recycled aluminum density is about equal to original one and the tensile test gave optimum results. The difference is in the costs: the primary aluminum costs 95% more of the secondary aluminum with about the same characteristic.

From conducted analysis, the importance to act on sustainability conditions of a production company is much evident. Important not only morally but also economically. An interesting study would be to evaluate if in correspondence of high investments in activities aimed at making the company more sustainable, the typical performance measures used to evaluate corporate performance (ROI, ROS, ROE, etc) increases too.

Furthermore, another important area to consider is constituted by hybrid processes: parts could advantageously be designed with modular and hybrid points of view in which parts are seen as 3-D puzzles with modules realized separately and further assembled. So the best production process for each part can be used in order to get the best cost savings and better quality for that product.

Certainly, the possibilities of sustainable development field are endless. At the base of this, technological innovation is the driving force behind new opportunity growth that allows to match economic and environmental factors needs. Following the sustainability direction is sure and definitely the best way to deal with a truly looming problem for the whole of humanity, but also an excellent development strategy in order to reduce costs while maintaining high quality of its products.

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