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A uniform environmental metric based on exergy for early design evaluation

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Abstract

Environmental accountancy and environmental impacts analysis are characterized by fragmented approaches encompassing a number of different perspectives and analytical techniques. A uniform framework has not yet been established or proposed. Although Life Cycle Assessment method (LCA) is the most commonly used tool by which environmentally conscious design is carried out, LCA techniques have been criticized as scientifically questionable tools. Its identified limitations include a lack of adequate inventory data, disparate underlying assumptions, and environmental assessment made in terms that are not directly comparable. Those limitations make LCA technique ineffective during the early design stage. This paper addresses this shortcoming by outlining antecedent researches in design theory and thermodynamic fields. It highlights fundamental similarities between design theories and thermodynamic approach and proposes a promising integrated framework dedicated to the early design process. It is argued herein that the concept of exergy may be a promising basis for the development of a uniform, broad-based measure of environmental impact, and that such a measure can significantly advance a scientific approach to environmentally conscious design. Some theoretical background is presented, although the reasoning is intended to be accessible to a broad audience.

Keywords

General Design theory, dimensional analysis theory, environmental metrics, exergy

Nomenclature

$\cap$: Intersection,
$\cup$: Union,
$\in$: Belong to,
$\notin$: Not belong to,
$A \subseteq B$: A weaker than B or B stronger than A,
$A \subset B$: A strictly weaker than B or B strictly stronger than A,
$\bar{S}$: Complementary set of the set S,
Open set of O [1]: An element of *O*,
Closed set [1]: The complement of an open set,
$\leq$: Inferior or equal,
$\Rightarrow$*:* Implies,
iff: If and only if,
T_0*:* standard temperature of the reference environment (298.15 K),

P_0: standard pressure of the reference environment (1 atm = 101 325 Pa),
Ex_Q : transferred exergy associated with the heat transfer (J),
Q: transferred heat (J),
T: temperature at the place where the heat transfer takes place (K),
Ex_{Tot} : exergy associated with the flow of matter (J),
Ex_{Kn}: Kinetic exergy (J),
Ex_{PT}: Potential exergy of the flow (J),
Ex_{Ph}: Physic exergy (J),
Ex_{Ch}: Chemical exergy (J),
m: mass (kg),
h: specific enthalpy of the flow (J/kg),
h_0: specific enthalpy of the flow at temperature T_0 and pressure P_0 (J/kg),
s: Specific entropy of the flow (J/(kg.K),
s_0: Specific entropy of the flow at temperature T_0 and pressure P_0 (J/(kg.K),
C_x is the heat capacity of a fluid at constant pressure (C_P) or constant temperature (C_T) (J/kgK),
$Ex^0_{Ch_i}$: Standard chemical exergy of the perfect gas (kJ/mol),
R: perfect gas constant (R = 8,314 J/K.mol),
P_0: Pressure of the environment (Pa),
P_{00}: Partial pressure of the perfect gas at the reference state (Pa),
Ex_{ChP}^O : Standard chemical exergy of a compound (J/mol),
G_0: Gibbs free energy of formation of the compound from the elements (J/mol),
ni: the number of moles,
Ex_{Chi}: Standard chemical exergy of the *i*th reactant required to form *n*p moles of the product compound (J/mol),
ni and *n*p: Stoichiometric balancing numbers of the appropriate chemical reaction (Eq.6),
ni: Mass fraction of the *i*th pure substance in the complex substance (Eq.8),
Ex_{Chi}: Standard chemical exergy of the *i*th pure substance (kJ/mol) (Eq.8),
δEx : Exergy loss due to irreversibility inside the system (J) (Eq.10),
Ex_d, Ex_a: Exergy of the input and output matters (J) (Eq.10),
Ex: Increase of exergy in the heat source in contact with the system (J) (Eq.10),
W: Work performed by the system (J) (Eq.10),
Ex_i^m : Exergy of the composition-dependent component in joules (J) (Eq.11),
n_i : Total number of moles of the species (Eq.11) ,
y_i : Activity in the thermodynamic system under consideration (Eq.11),
y_i^0 : Reference activity in the appropriate environment (sea, earth crust or atmosphere) (Eq.11),
p_i : Partial pressure of the gas (bar) (Eq.12),
C_i : Concentration of the liquid specie I (mol/l) (Eq.13),
Co : $C_o = 1$ (mol/l) (Eq.13),
Ex material: Flow of raw materials' exergy (Eq.6 or 8) (J),
Ex supply: Flow of exergy supply (J),
Ex $product_i$, *Ex* $bi\text{-}product_i$: Desired products and bi-products flows (Eq.6 or 8) (J),
Ex $environment_{Mixing}$: Exergy rejections in the environment, computed via the exergy of mixing formula (Eq.11) (J),
Ex $environment_{Standard}$: Exergy rejections in the environment, computed via the standard chemical exergy formula (Eq.6 or 8) (J),
Ex $recycled_{Standard}$: Exergy of waste not directly rejected in the environment (J),
Cv: Connecting variable of an exergy organ,
Π_{PECE} : Primary exergy conversion efficiency (Eq.20),
Π_{MRCE} : Material and resource consumption efficiency (Eq.21),
Π_{EIE} : Environmental impact efficiency (Eq.22),

DEFINITIONS

S: representation of an object called a *concept of entity,*
T: S*et of all abstract concepts*,

Class: Division of the set of *concept of entity* using *a classification*,
Abstract concept: A type of *class*,
Filter (F) [1]*:* The set of design specifications is a filter. A filter of S is a collection F of subsets of S that has the following properties:

(a) $\emptyset \notin F$, (b) if $A \in F$, and $A \subset B \subset S$, then $B \in F$, and (c) if $A,B \in F$ then $A \cap B \in F$,

B: Fundamental system of entourages of a uniformity *U* iff $B \subseteq F$ (filter) and for any $V \in U$ there is $W \in B$ such that $W \subseteq V$.

Metamodel: Integrative model developed in order to combine multiple design objects models and to represent relationships among the concepts of these different models. The models are developed according to the three domains (physical, economical and informational) introduced in the PhD thesis of Coatanéa [2].

T_0: For each pair $a \neq b$ in *S*, there is $U \in T$ such that $a \in U$ and $b \notin U$ or vive versa.

T_1: For each pair $a \neq b$ in *S*, there is $U, V \in T$ such that $a \in U$ and $b \notin U$ and $b \in V$ and $a \notin V$.

T_2 *(Hausdorff space): similar to* T_1 *but* $U \cap V = \emptyset$.

T_3: T_3 is a generalization of T_2 where A is a set instead of a single entity but still using *b*.

T_4 *(Normal space)*: Satisfies T_1 and for every pair of disjoint closed sets $A, B \in \overline{S}$ there exists a pair of disjoint open sets $U, V \in T$ such that $A \subset U$ and $B \subset V$.

T_5: Satisfies T_1 and for every pair of closed sets $A, B \subset \overline{S}$ with $\overline{A} \cap B = A \cap \overline{B} = \emptyset$, there exists a pair of disjoint open sets $U, V \in T$ such that $A \subset U$ and $B \subset V$.

Metric space: There exists a metric on the space such that a set S is called a metric space if with every pair of points $x, y \in S$, there exists a non-negative real number d(x, y) that satisfies:

If d(x, y) = 0 then x= y and d(x, x)=0.

For any pair of points x, y, d(x, y) = d(y, x)

For any three points x, y and z, $d(x, z) \leq d(x, y) + d(y, z)$

1 INTRODUCTION

In the development of a new product, the early stage of the design process poses major challenge to the engineering team and to the researchers of the product development community. It is because numerous types of requirements, involving multidisciplinary and multilevel analysis and synthesis, have to be fulfilled simultaneously. These requirements are often qualitative, imprecise and situation-dependent. Nevertheless, the team has to deal with this type of imperfect knowledge. Consequently, the task of a development team, during the early design process can be divided into four main groups (e.g. grasping and understanding customer needs, refining these needs, synthesizing concepts of solutions, evaluating and selecting them). Evaluating, comparing and selecting solutions are critical stages because various types of metrics are used to measure performances of concepts. These metrics are often not compatible and need to be aggregated for simplification and comparability. This fact represents a real problem for the design activity and more specifically for environmental impact analysis and environmental accountancy because the repeatability relies less on the methods themselves than on the homogeneity of the product development teams, which use them.

This lack is clearly an important motivation for developing a more repeatable method based on generic principles. The goal of this article is to present an approach for analyzing the environmental impact and the environmental accountancy aspects of the early design process. Nevertheless, it is important for the readers to keep in mind that the design framework described in this article is based on very general principles and it is argued herein that the scope of the resulting methodology is very broad and can include the entire early design process [2].

The rest of this paper is organized as follows:

Section 2 gives a short theoretical overview of the necessary conditions required in order to best compare and evaluate concepts of solutions at the end of an early design process. This section summarizes one fundamental finding of Coatanéa [2], which is considering the axiom of hierarchical separation/recognition of the Enhanced General Design Theory [3] [4] as a fundamental element of the design process. This leads to organize the design process in a specific manner. This organization generates at first a certain type of ontology and mapping summarized in a metamodel structure [2]. Secondly, this organization leads to use dimensional analysis [5] [6] [7] as a central tool for comparison of concepts. In practice, this means that concepts are best compared by using dimensionless numbers.

Section 3 gives contrasting perspectives about the LCA and Functional/systems analysis. This comparative analysis is needed in order to meet simultaneously the fundamental requirements of section 2, to deal with the partial and imperfect knowledge available during the early design phases and to provide flexibility in the definition of the boundaries of the environmental analysis. This section ends with a description of a combined approach, which fulfills the list of requirements.

Section 4 answers to the most critical question for product development teams working with an environmental perspective: Which one of the technological alternatives is preferable from an environmental perspective?

At first, the section makes a short state of the art of the existing environmental metrics. Secondly, the concept of exergy is defined and its practical computation is extensively described. A proposal for extending its scope to the measure of environmental impacts is proposed. Third, the concept of Extended Exergy Accounting (EEA) is introduced, in order to analyse complex systems or processes. This section ends with a presentation of generic efficiency and cost indicators adapted from the EEA approach. These indicators result from a transformation process using dimensional analysis used in a bottom-up manner [8]. Consequently, the environmental approach described in this paper meets the fundamental requirements defined in section 2. The environmental comparison and accountancy method described herein is a new module of a more general integrated design framework described in the thesis of Coatanéa [2].

Section 5 presents the example of a comparison between different production technologies by using exergy for environmental accountancy and environmental impacts analysis. The example consists of comparing a complex process, which combines sand casting and milling with another alternative that is the milling process alone.

2 THEORETICAL OVERVIEW OF THE CONDITIONS TO BEST ACHIEVE COMPARISON OF SOLUTIONS

From a general perspective, the development activity requires a simultaneous fulfillment of numerous types of requirements involving multidisciplinary and multilevel analysis and synthesis. As said earlier these requirements are often qualitative and imprecise. Nevertheless, the development team has to deal with this type of imperfect knowledge.

The repeatability of the methods used to measure performances of concepts is a real issue and an important motivation for developing a more reliable framework based on generic principles.

In this chapter we give a summary of previous research works [2] combining AI-based qualitative methods derived from mathematics (e.g. topology) with dimensional analysis and General Design Theory (GDT).

The impact of the theoretical foundation described in this chapter is important. It has been shown [2] that an early design framework, flowing from design requirements to physical implementation of the concepts of solutions, should follow necessary intermediate steps in order to provide the most suitable properties for comparison of concepts of solutions. The necessary steps have been partially formalized by Pahl and Beitz [9] or Hubka, Andreasen and Eder [10].

This chapter defines more precisely the structure of a design framework by presenting the theoretical conditions for obtaining the best possible comparison structure at the end of the conceptual design process.

2.1 Theoretical foundations

The desire to create an integrated framework [2] has its roots in the intuitive idea that dimensional analysis approach, which is a well-accepted approach to analyze similarities in science, can be used as a fundamental basis for comparison and evaluation purposes within the design activity. The dimensional analysis relies on the concept of similarity. Similarity refers to some equivalence between two things or phenomena that are actually different. For example, under some particular conditions there is a direct relationship between the pressure involved in a full-size hydroelectric power plant and that of a small-scale model of it. The question is, what are those conditions?

Dimensional analysis addresses this question. Mathematically, similarity refers to a transformation of variables that leads to a reduction in the number of independent variables that specify the problem. Here the question is, what kind of mathematical transformation works?

The authors of this article argue that coherent answers to these questions can be found by applying a research method combining General Design Theory (GDT) [3] [4], dimensional analysis [5] [6] [7] and Abstract Design Theory (ADT) [11] [12]. All mentioned studies rely on the concepts developed by Bourbaki, the most prominent father in the field of mathematics called topology [1].

This chapter demonstrates that there is a fundamental reason for using dimensional analysis theory during the comparison and evaluation stage of the design process. Dimensional analysis can be a powerful comparison and evaluation method in design. Dimensional analysis requires to be preceded by initial conditions. These conditions cast the design approach, which has to be followed by the designers.

2.1.1 From GDT to dimensional analysis:

GDT is a notable exception in the domain of design theory in the sense that it is a mathematical theory of design [9]. The major hypothesis of the GDT theory consists of considering that design has a topological structure.

Topology is associated with geometrical considerations, but the scope of a topological approach is much broader and it could be seen as an extension of the concept of continuity [13] [14]. The concept of continuity exhibits four major properties according to Reich and Bourbaki [13] [1]. These properties are: distance, continuity, convergence and transformation.

Distance: The distance is a metric, which can provide answer to questions like: How close are those two functions? Or how close are these two concepts of solutions? Or How far are the concepts of solutions from the expected functions?

Continuity: The continuity guarantees that a small change in the functional description will result in a small change in the product concepts and vice versa. This property ensures that mapping is possible between functions and attributes, which are describing the product concepts.

Convergence: The convergence guarantees that a sequence of small incremental changes on the product concepts attributes will cause only small incremental changes to the functionality and vice versa.

Transformation: This property guarantees that a transformation conserves the continuity and convergence. This allows for example clustering the descriptive attributes of a product concept in order to create new viewpoints of design.

The last property is the premise for formally connecting GDT principles with dimensional analysis theory (DAT) [5] [6] [7].

In the context of this article where the main focus is centered on the comparison and evaluation of design concepts, the axiom 4 of the GDT plays a fundamental role. This axiom states that:

$\textit{Metric space} \Rightarrow T_5 \Rightarrow T_4 \Rightarrow T_3 \Rightarrow T_2 \Rightarrow T_1 \Rightarrow T_0$

and that none of these implications are reversible.

Therefore, the type of separation defines an order on topological spaces.

However, it has been argued by Braha et al. [15] that the GDT theory and its extended version [4] do not detail the nature of the design process. They argue that the GDT theory is only a special case of their framework. Nevertheless, in their framework Braha and Reich [15] agreed that metric space deserves special attention but they do not describe a formal way to obtain it. They just argue that metric spaces “will be introduced as they arise naturally in applications”.

This, in our viewpoint, is an implicit validation of the axiom 4 of the GDT theory.

At this stage, one fundamental question emerges:

What are the necessary conditions to obtain a metric space?

Answer to this question can be found in the literature related to topology [1] and in the theoretical literature related to design [11] [12]. The necessary conditions to answer this question have already been summarized [2]. It is required at first to have a *metamodel* structure. The Figure 1 describes the *metamodel* structure of our integrated framework.

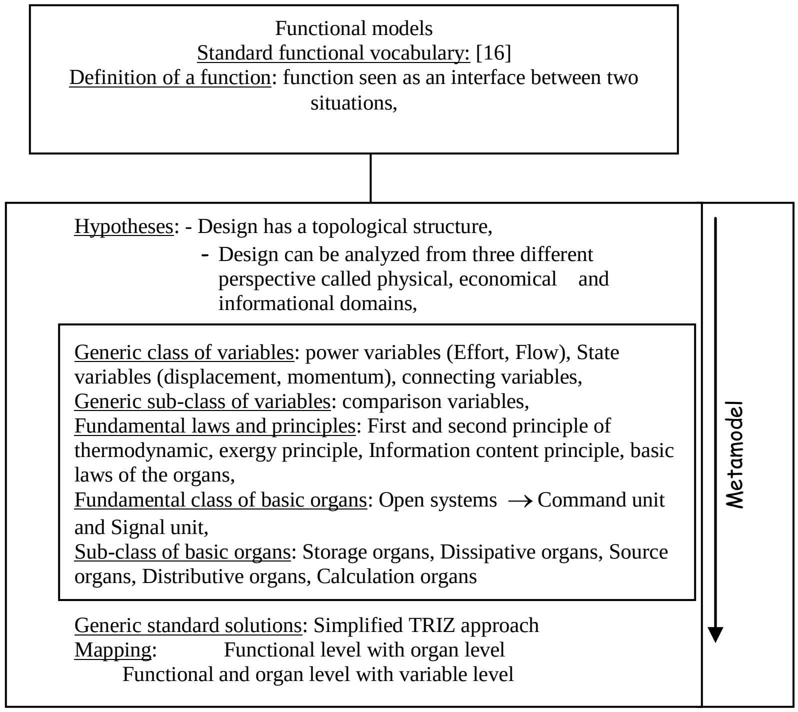

Figure 1: Position of the metamodel framework within the design process [2]

Table 1: The enhanced countable fundamental system of entourage [2]

The seven Base SI quantities and units		
Physical quantity (symbol)	Base unit	Unit Symbol
Length (L)	meter	m
Time (T)	second	s
Mass (M)	kilogram	kg
Electric current (A)	Ampère	A
Thermodynamic temperature (K)	Kelvin	K
Luminous intensity (Cd)	Candela	cd
Amount of substance (Mol)	mole	mol
The two non physical quantities and units		
Quantity (symbol)	Base unit	Unit Symbol
Informational (Sh)	Shannon	Sh
Economical (C)	cost	€ or $ or others

In order to transform the final classification spaces induced by the *metamodel* structure into a metric space, the following conditions need to be met.

- Having a *fundamental system of entourages*,
- Having *a sufficiently detailed* fundamental system of entourage in order to ensure separation ,
- Having a *countable* fundamental system of entourage,

Dimensional analysis method, whose aim is to transform a design space into a metric space [6] [7], fulfills exactly this list of requirements. We argue that this is a clear demonstration that it is possible to flow progressively from design requirements to evaluation and comparison of concepts by using dimensional analysis. Nevertheless, it should be noticed that the conditions presented in this short summary are not sufficient to ensure that the second condition is performed. We assume that the metamodel structure developed above is sufficient in most of the cases. Nevertheless, the structure can be enhanced when required to ensure the second condition.

2.1.2 Summary of the framework procedure

The mathematical analysis made in the previous chapter has demonstrated two fundamental elements:

- In order to be used the dimensional analysis machinery requires some initial conditions:
  - Describing the design process, (i.e. this progressive refinement starting by functional descriptions and ending with a physical implementation of a product described by using a set of attributes) has a succession of classifications (i.e. the set of progressive classification which constitutes the metamodel structure also called the fundamental system of entourage),
  - The classification system needs to be detailed enough to ensure separation,
  - An enhanced system of basic quantities and units needs to be defined for the design activity. Two extra quantities have been added to the international system of units in order to take into account information (e.g. complexity, exchange of information, etc…) and economic aspects.
- Application of the dimensional analysis theory during the comparison and evaluation stage of the design process leads to the most suitable structure to ensure separation and recognition of concepts of solutions.

Based on this theoretical analysis, the characteristics of a module dedicated to environmental analysis and accountancy can be established. This is the purpose of the following chapters.

3 CONTRASTING ANALYSIS OF LIFE CYCLE ANALYSIS AND FUNCTIONAL/SYSTEM ANALYSIS

Both Life Cycle Assessment and System analysis embody the notion that environmental problems should be examined from a holistic perspective rather than a reductionist approach. Although there are significant differences between these two approaches, they are both sensitive to how the boundaries of the study are defined. Whereas LCA approach relies on a product or process lifetime, system analysis is more flexible. The system analysis approach is able to deal with various scales of problems: from single product or process to an entire industry or geographic region.

LCA is used as a descriptive model, while systems analysis is used as a prescriptive model. For this reason, the data requirement of LCA may be more extensive than in systems analysis. LCA is therefore more applicable to problems, with an emphasis on examining specific materials, flows and processes whereas systems analysis is more applicable to problems, which emphasis on examining interrelationships.

3.1 Life cycle assessment

LCA is the most commonly used approach by which environmental analysis is carried out during a design process. The entire framework is based on the assumption that the appropriate scope of the analysis is the life cycle of the material, product or service [17]. LCA usually follows a four-step methodology, consisting of:

- Scoping: This is the process of identifying the goals that motivate the assessment and determination of the boundaries of a study.
- Inventory analysis: The inventory analysis is a method for accounting the resource requirements of a particular product, process or industry from virgin material extraction to final disposition.
- Impact assessment: The goal of the impact assessment is to relate the inventory data to specific environmental concerns.
- Improvement assessment: This interpretation phase identifies those aspects of the materials' life cycle that might be most improved, and/or evaluates the potential for new design for environment strategies that offer the main environmental profits.

Nevertheless, LCA approach has been criticized as an unreliable scientific method because at each of the four-step methodology a significant scientific limitation can be highlighted [18].

Indeed, the limitations include difficulties in identifying the boundaries of the system, a lack of adequate inventory data because data required is not always available from published sources. Moreover, data can be unverifiable and may well be erroneous. In addition, widely disparate conclusions can be drawn depending on what information is

excluded from the study, or which underlying assumptions are applied. Finally, the impact assessment is made in terms that are not directly comparable. This is a very difficult problem, which may be impossible to solve even at the conceptual level.
Nevertheless, LCA framework guides the investigating process by forcing consideration of factors that may have previously been ignored. Additionally, the life cycle hypothesis underlined in LCA framework offers a holistic view of design problems, which probably leads to better-optimized solutions.

3.2 Functional/Systems analysis

System analysis, used in thermodynamic analysis share many similarities with functional analysis used in design. Indeed, both analytical approaches require a model that characterizes the type of relationships and constraints governing the system and their components. These models are usually the result of analysis made in order to establish links among components. The boundaries of a study can be defined narrowly (e.g. around the system itself) or more broadly (e.g. to include the system and its environment). Both system analysis and functional analysis are design tools, which help decision making by focusing on all the elements of a system towards a single objective function or an overall function.
Therefore, in order to measure the final objective a uniform metric must be expressed. This aggregated metric should simultaneously embody multiple other metrics. They represent sub-objectives integrated to the overall objective. This is a great challenge to the development of a quantitative measurement during the evaluation phase of a functional or system analysis because such holistic measure is difficult to develop. The authors argue that this article tackles this issue.

3.3 Summary comparison of LCA and Functional/Systems analysis

The results of the previous discussion are summarized in Table 2. The authors argue that during the early development stage, a suitable approach for environmentally conscious design should combine LCA and functional/systems analysis characteristics by selecting the four steps of the LCA approach. In addition, the approach should model the type of relationships and constraints governing the system and its components. The selected approach is summarized in the following figure.

Table 2: LCA versus Functional/system analysis

Characteristics	Life cycle assessment	Functional/systems analysis
Boundaries	Cradle to cradle/grave	modular
Data requirements	Broad	Focused
Emphasis	Materials recycling	Limited list of fundamental metrics

The framework described in Figure 2 has been selected by the authors as the methodological approach used to deal with design problems from an environmental perspective. The approach is coherent with the generic structure of the metamodel described in the chapter 2. The authors argue that the methodology is a coherent answer to some of the LCA and functional/system analysis drawbacks.
In the following chapter, the problem of the environmental metrics is discussed and an extension of an existing metric is proposed.

4 ENVIRONMENTAL METRICS

At first, before going further with new approaches, it is necessary to tackle environmental issues at the conceptual design level. It is essential to discuss the different aspects of the environmental impact.
According to Seager [19] all sustainable metrics may be characterized in a classification, that includes six broad categories:

- *Financial metrics* estimate environmental impacts or ecosystem services in terms of currency so that they may be compared with monetary transactions or industrial accounts. In practice, monetization may lead to the erroneous assumption that environmental exploitation can be reversible in a manner analogous to pecuniary transactions, even if, in many cases ecological systems are damaged beyond recovery.

- *Thermodynamic metrics* indicate the resource requirements of industrial activities or services, usually thermodynamic metrics do not indicate the specific environmental impacts associated with resource consumption.
- *Environmental* (including health and safety) *metrics* estimate the potential for creating chemical changes or hazardous conditions in the environment. They may be simple measures of what is released to the environment, without considering chemical considerations such as pollutant degradation, catalysis, or recombination to form new pollutants; or they may include factors, such as toxicity, reactivity, or rarity. Most are directed at specific biological or ecological end points, such as death, cancer, or mutation, while others may indicate a loss of environmental quality without suggesting any particular ecological manifestation, such as ozone formation [20].
- *Ecological metrics* attempt to estimate the effects of human intervention on natural systems in ways that are related to living things and ecosystem functions. The rates of species extinction and loss of biodiversity are examples, and may be incorporated in the concept of ecosystem health. Ecological metrics relate to biological processes, but environmental relate to chemical or other hazardous conditions. For example, a pollution free environment may not lead to recovery of depleted bear population if there is a total absence of quality sites because of the human pressure.
- *Socio-political metrics* evaluate whether industrial activities are consistent with political or ethical goals.
- *Aggregated metrics* may combine features or metrics belonging to a variety of other categories, or they may group a number of metrics that belong to a single category.

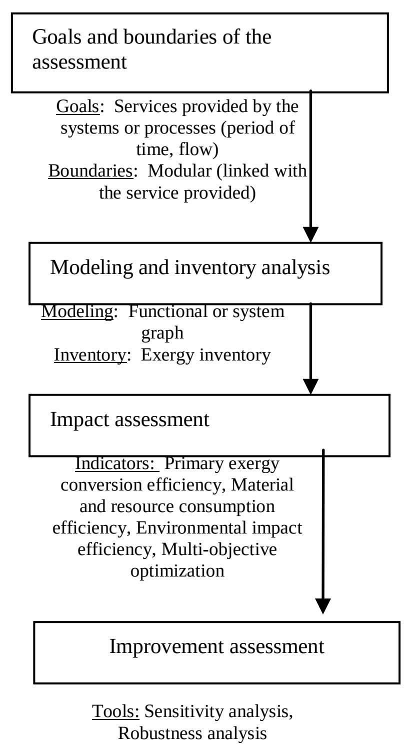

Figure 2: Methodological approach selected

The proposal developed in the following chapter is meant to provide an aggregated metric combining simultaneously several different metrics.

4.1 Exergy as a uniform environmental metric

The lack of an uniform metric basis for comparison or expression of different types of impacts or requirements has been clearly pointed out in chapter 2 as a shortcoming of the Life Cycle Assessment (LCA) and systems analysis approaches [21] [22]. The previous chapter has given a summarized classification of the metrics used in the sustainability framework, which integrate both LCA and systems analysis approaches.

Ayres et al. [22] have proposed a unified basis for LCA based upon the thermodynamic concept of *exergy*, which gives a more complete vision of the resource and waste accounting. This is clearly an improvement in the energy measurement. Exergy introduced by Rant [23] is defined as the maximum amount of work that can be produced by a system or a flow of matter or energy as it comes to equilibrium with a reference environment. Exergy can theoretically provide a common scientific framework for both LCA and systems analysis, merging the two perspectives into complementary tools

Exergy combines the first and second laws of thermodynamics in a way analogous to Gibbs free energy. Nevertheless, the advantage of exergy compared to Gibbs free energy or entropy is a system of environmental reference states, first proposed by Ahrendts [24], which identify the chemical characteristics of three different reference environments for computation of standard exergies: the atmosphere, the ocean, and the earth's crust.

In many cases the most oxidized form of an element provides the appropriate reference state in each environment, nevertheless consideration must also be given to the molar concentration of a compound in the specified environmental sink.

Exergy is expressed in Joules (J) unit or ML^2T^{-2} using the international system of fundamental quantities with *(M) Mass*, *(L) Length* and *(T) Time* respectively.

It is widely accepted that exergy is a suitable approach for measuring material and energetic resource consumption. It can be consequently classified as a thermodynamic metric, as currently, no methodology exists whereby exergy may be reliably related to environmental impact. This is primarily because waste exergy, which is released to the environment in the form of chemical pollutants and waste heat, comes in different forms that may have different quantitative and qualitative environmental effects. Therefore, a simple waste exergy (or exergy emissions) approach (i.e. the approach proposed by Ayres et al. [22]) can provide only a first approximation of the environmental impact.

A better approach for evaluating the environmental impact may be to focus on the portion of the chemical exergy, which is resulting from material transfers or changes in composition. This approach called *exergy of mixing* has been proposed by Seager et al. [25] for evaluating the environmental impact.

4.2 Exergy calculation

Wall stated that exergy is a measure of the quality of natural resources [26]. Jørgensen and Nielsen [27] emphasize that exergy can be used as an ecological indicator. Ayres et al. [28], also describe exergy as a measure of the *distinguishability* of a substance or system from its surroundings, which is a measure of its 'distance' from equilibrium.

The following paragraphs give the necessary formulas to compute exergy when the resource consumption is analyzed. T_0 and P_0 are the references used for computing the physical and chemical exergy. The chemical exergy is calculated in the paper by using the method proposed by Szargut et al. [29].

4.2.1 Exergy as a measure of material and energetic resource consumption

Exergy has four basic forms, *kinetic, potential, chemical and physical* (e.g. pressure-volume and heat exchange type of work). From an environmental perspective, both the chemical and the physical exergies are the two exergies of interest.

Higher quality of energy:

Form of energy such as gravitational, electric and kinetic energy can be completely recovered as mechanical work. Therefore, according to the definition of Szargut, exergy and energy are equal for these types of energies. Consequently, work (e.g. mechanical work) and electrical energy are high quality energies.

Degraded form of energy:

On the opposite, the variation of exergy associated with a heat transfer between a system and a reference environment is:

$$Ex_Q = (1 - \frac{T_0}{T})Q \qquad \textbf{Eq. 1}$$

Where:

The Eq.1 shows that heat is a degraded type of energy because $Ex_Q \leq Q$.

Exergy linked to a flow of matter:

The literature often neglects the nuclear, magnetic and electrical exergy [25]. Then we obtain:

$$Ex_{Tot} = Ex_{Kn} + Ex_{PT} + Ex_{Ph} + Ex_{Ch} \qquad \textbf{Eq. 2}$$

As stated above the physical and chemical exergies are those of interest from the environmental point of view. The physical exergy is due to the difference of temperature between the flow and the environment.

$$Ex_{Ph} = m[(h - h_O) - T_O(s - s_O)]$$ **Eq. 3**

In practice, the entropy is calculated using the heat capacity as presented in the following formula:

$$\Delta S = \int \frac{C_X}{T} dT$$ **Eq. 4**

The chemical exergy is the useful work, which can be produced when a chemical equilibrium between the flow and the environment is reached. The definition of the environment requires defining at first the reference environment and its reference chemical species [29].
The *standard chemical exergy* of a reference gas, which constitutes the reference atmosphere, is:

$$Ex^0_{Ch_i} = RT_O \ln \frac{P_O}{P_{OO}}$$ **Eq. 5**

However, in many cases, the most oxidized form of an element provides the appropriate reference state in each environment, and consideration must be given to the molar concentration of a compound in the specified environmental source. Szargut et al. [28] describe the principles for computation of the *standard chemical exergy* (Ex_{ChP}^O) of any compound.

$$Ex_{ChP}^O = G^O + \sum_i \left(\frac{n_i}{n_P} Ex_{Chi}^O\right)$$ **Eq. 6**

The formation of ammonia gas from nitrogen and hydrogen provides a simple illustrative example given by Seager et al. [25]. The chemical reaction is represented below:

$$0{,}5N_{2(g)} + 1{,}5H_{2(g)} \rightarrow NH_{3(g)}$$ **Eq. 7**

With $Ex_{N2}^O = 0.72$ kJ/mol and $Ex_{H2}^O = 236.1$ kJ/mol [29]
Then:
Ex_{NH3}^O = 16.48+0.5.(0,72)+1,5.(236,1)=338kJ/mol
The Gibbs' free energy of formation of ammonia gas is given as -16.48 kJ/mol. However, the standard chemical exergy is found to be 338 kJ/mol by substituting thermodynamic data into Eq. 6.
The Gibbs' free energy is representative of the ideal thermodynamic work required to synthesize pure ammonia from pure elements. On the contrary, the standard chemical exergy is representative of the maximum work that could be obtained under ideal conditions from pure ammonia gas.
For complex substances (i.e. those substances or materials formed by several different pure compounds, e.g. stainless steel such as X2 CrNiMo 17-12-2) standard chemical exergy can be computed by means of the following formula [25]:

$$Ex_{ChP}^O = \sum_i (n_i . Ex_{Chi}^O)$$ **Eq. 8**

Even if energy and exergy are expressed in similar units, there exist significant differences between the concepts. Szargut [29] has presented these differences. The most important of these differences is listed in the following table.

Table 3: Energy versus Exergy [29]

Energy	Exergy
Is subject to the law of conservation (first principle of thermodynamic)	Is exempt from the law of conservation (first and second principle of thermodynamic)

Consequently, because of the irreversibility expressed by the second principle of thermodynamic, a balance of exergy should be closed by the introduction of a term representing the exergy loss in the system.
The exergy loss takes the following form:

$$\delta Ex = T_0 \Sigma \Delta S$$ **Eq. 9**

Where T_0 = Temperature of the environment (K).

Exergy balance equation:

The exergy balance takes the following form according to Szargut [29]:

$$\delta Ex = \sum Ex_d - \sum Ex_a + Ex - W \qquad \textbf{Eq. 10}$$

4.2.2 Exergy as a measurement of the environmental impact

As noted above, a waste exergy approach can provide only a first approximation of environmental impact. To remedy this theoretical deficiency, the concept of exergy of mixing [29] can provide a universal, broad-based environmental metric because exergy of mixing focuses on the portion of the chemical exergy, which is solely due to material transfers or changes in composition. It is argued by the authors of this article that it is a measure of the potential chemical change due to the introduction of any pollutant into the environment.

There are two mechanisms by which, chemical exergy is converted into work or entropy -heat transfer and mass transfer-. The first is manifested in the chemical bond and released during chemical reaction, and the second in dilution or dissipation of reaction products throughout the environment.

The exergy of mixing also called composition-dependent component of chemical exergy [29] is computed for the *i*th chemical species of any reaction as:

$$Ex_i^m = n_i R T_0 \ln\left\{\frac{y_i}{y_i^0}\right\} \qquad \textbf{Eq. 11}$$

y_i the activity in the thermodynamic system under consideration. For a mixture gas y_i can be evaluated by:

$$y_i = \frac{p_i}{p_0} \quad \textbf{Eq. 12}$$

For a liquid in solution y_i can be evaluated by: $y_i = \frac{C_i}{C_0}$ **Eq. 13**

For a solid chemical species $y_i = 1$ if the solid is alone in his phase.

y_i^0 the reference activity in the appropriate environment (sea, earth crust or atmosphere) and can be found for most of the species in the textbook of Szargut et al. [29],

For instance, if we use the case of the combustion of the methane CH_4 as an illustrative example, the chemical equation of the combustion is:

$$CH_{4(g)} + 2O_{2(g)} \rightarrow CO_{2(g)} + 2H_2O \qquad \textbf{Eq. 14}$$

The exergy of mixing of the exhaust gases coming from the methane (CH_4) is computed below using Eq.11:

$$Ex^m_{exhaust-gases} = Ex^m_{CO_2} + Ex^m_{H_2O} \qquad \textbf{Eq. 15}$$

$= 8{,}314 . 298{,}15\left(\ln\left(\frac{1}{3{,}31.10^{-4}}\right) + 2\ln\left(\frac{1}{2{,}17.10^{-2}}\right)\right) = 38{,}8 kJ/mol$ with $y^0_{CO_2} = 3{,}31.10^{-4}$ and $y^0_{H_2O} = 2{,}17.10^{-2}$ [23].

Based on this example, if we create new chemical substances and release these substances in the environment, their exergy of mixing is becoming infinite because the initial reference activity of the substances in the reference environment is null. This is simply proved below by Eq.16.

$$Ex_i^m \rightarrow +\infty \textbf{ because } \lim_{y_i^o \rightarrow 0} \ln\left(\frac{1}{y_i^o}\right) = +\infty \quad \textbf{Eq. 16}$$

This conclusion is against the common sense. Consequently, this demonstrates that the definition of the reference environment should be considered from a dynamic viewpoint. Indeed, reference conditions change over time and the reference activities of components should be computed *after* complete dissipation of the pollutant of interest.

It is important to notice from the example above that exergy is a cumulative value. This property is used in the following chapter to deal with complex systems.

4.3 Presentation of the extended exergy accounting (EEA)

Several attempts have been made to combine exergy and LCA to quantify the environmental impact of industrial processes, such as cumulative exergy consumption (CExC) analysis [29], life cycle exergy analysis (LCEA) [26], exergetic life cycle analysis (ELCA) [30]. Chapter 2 has analyzed extensively LCA and Functional/Systems analysis and different type of shortcomings in each framework have been highlighted. Consequently, an integrated framework giving a generic vision of LCA approach combined with the more focused and flexible approach of the Functional/system analysis is probably a better approach. The authors argue that the concept of extended exergy cost (EEA) introduced by Sciubba [31] meet the three fundamental requirements of the generic integrated approach developed in this article:

- by being able to combine both characteristics of LCA and functional/system analysis,
- by being part of the integrated design framework developed for providing better evaluation and comparison through the use of dimensional analysis,
- by being adapted to an exergetic approach for the evaluation of the resource consumption, and environmental impact,

Nevertheless, the original EEA approach is also integrating *financial metrics*. In this article, the scope has been limited to the *thermodynamic* and *environmental metrics* in order to measure *material and energetic resource consumption* and *environmental impact*. This has been done because the authors argue that, the generic integrated framework developed by Coatanéa [1] offer already a coherent answer to the financial metrics' issue.

4.3.1 EEA method combined with dimensional analysis

The EEA approach is considering functional representations or physical processes implementations as black boxes (see following figure). This viewpoint is similar to the approach developed by various authors investigating design science issues [9]. This standpoint is coherent with the framework developed by Coatanéa [2] and used in this research.

The authors state here one major hypothesis. The physical exergy is neglected (see Eq. 2 and 3) and only the chemical exergy is taken into account (Eq.6,8,11) in our approach because it is assumed that the flow of heat or substances, at the overall process scale, are released in the environment at temperature T_0 and pressure P_0. Masini et al. [32] have evaluated this hypothesis for environmental accountancy. The consequence of this hypothesis is that the thermodynamic evaluation of the efficiency of processes is not possible but this does not belong to the scope of this article, which concentrates on the environmental effects of systems or processes.

The EEA approach [31] describes the model as an elementary organ *O* or a complex process as shown in Figures 3 and 4. A certain well-defined material output is produced; the inputs to the process are represented in the most general case by:

- a flow of raw materials' exergy (*Ex material*),
- a flow of exergy supply (*Ex supply*),

The outputs consist of:

- The desired products and bi-products flow ($Ex\ product_i$, $Ex\ bi\text{-}product_i$),
- Exergy rejections to the environment ($Ex\ environment_{Mixing}$) computed via the exergy of mixing formula (Eq.11),
- Exergy rejections to the environment ($Ex\ environment_{Standard}$) computed via the standard chemical exergy formula (Eq.6 or 8),
- Exergy of waste not directly rejected in the environment ($Ex\ recycled_{Standard}$),
- The exergy loss *(δEx)* due to irreversibility,

The organ is characterized by *Cv*, which is called the connecting variable of the process or organ [2]. All the exergy inputs and outputs are expressed in Joules (J).

The basic model presented above is characterized by different dimensionless numbers, also called *Π* numbers [5] [6] [7] [2] related to exergy.

The *Π* numbers are the result of the transformation process described in the chapter 3. They lead to a transformation of the initial design space into a metric space best suited for comparison and separation.

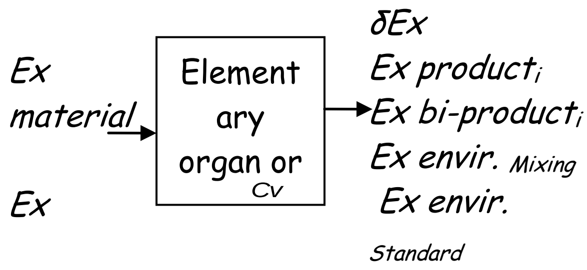

Figure 3: Exergy diagram of a basic organ or process

Two manners exist to create *Π* numbers. The first, called by the author of this article, the *top-down* approach has been described by Matz, Barenblatt and Sonin [5] [6] [7] and is using the Vashy-Buckingham theorem to transform the design space. The second method called the *bottom-up* approach consists of creating *Π* numbers based on the idea that each basic organ of a complex system is ruled by a law. This law can be defined in our case as:

$$(\sum_{i=1}^{n} Ex_{ouput\ i}) = (\sum_{j=1}^{m} C_{V_j} . Ex_{input\ j}) \qquad \textbf{Eq. 17}$$

On each side of Eq.15 exergy is expressed in joule (J). It is possible to build a resulting dimensionless number [8] (Eq.18).

$$\Pi = \frac{\sum_{i=1}^{n} Ex_{ouput\ i}}{\sum_{j=1}^{m} C_{V_j} Ex_{Input\ j}} \qquad \textbf{Eq. 18}$$

C_V is dimensionless in our case. The approach can be generalized to complex systems or processes according to the Figure 4. The entire system or process can be modelled according to Eq.19. This bottom-up approach has been described by Tomiyama [8] and he calls it "ultimate function element".

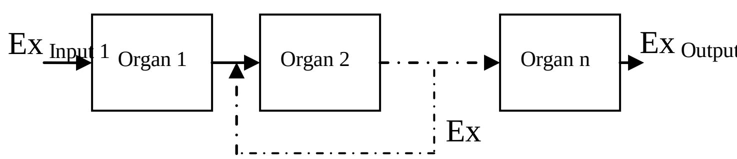

Figure 4: Complex structure model

$$\Pi_{Overall} = \frac{Ex_{ouput\ N}}{Ex_{Input\ 1}} = \frac{Ex_{Ouput\ 1}}{Ex_{Input\ 1}} \cdot \frac{Ex_{Output\ 2}}{(Ex_{Out\ 1} - Ex_{Rec\ M})} \ldots\ldots \frac{Ex_{Output\ N}}{Ex_{Output\ N-1}} \qquad \textbf{Eq. 19}$$

The advantage of the bottom-up approach is to provide dimensionless numbers, which have a real meaning. In addition, the approach provides an efficient manner to model complex processes or systems. Nevertheless, this approach can make difficult to combine attributes related to different types of performances such as technical, environmental or cost performances.
The top-down approach provides an integrated model combining numerous kinds of attributes and performances but the *Π* numbers generated can be difficult or impossible to interpret. In addition, the top-down method generates non-unique solutions.

The method presented in this article includes both approaches and provides guidance in the exploration of the design space by combining the benefits of both perspectives [2].
Consequently, it is possible to create different types of dimensionless numbers (e.g. *Π* numbers) as described below. In this article, the *Π* numbers are classified in two groups, the material and resource consumption numbers and the environmental impact number.
<u>Material and resource consumption numbers</u>:

The *primary exergy conversion efficiency* of the organ or process is computed as the exergetic ratio of the sum of the useful output to the sum of the inputs that concurred to produce it:

$$\Pi_{PECE} = \frac{Ex_{product-i} + Ex_{bi-product-i}}{Ex_{material} + Ex_{supply}} \qquad \textbf{Eq. 20}$$

The *material and resource consumption efficiency* of the organ or process is computed as the exergetic ratio of the output, except the exergy loss, to the sum of the inputs minus the recycled bi-products.

$$\Pi_{MRCE} = \frac{Ex_{prod-i} + Ex_{env-Stand}}{Ex_{Material} + Ex_{Supply} - Ex_{Recy-Stand} - Ex_{bi-prod-i}} \qquad \textbf{Eq. 21}$$

Environmental impact number:

The *environmental impact efficiency* of the organ or process is computed as the exergetic ratio of the sum of the inputs, to the exergy of mixing.

$$\Pi_{EIE} = \frac{Ex_{Env-mixing}}{Ex_{Material} + Ex_{Supply} - Ex_{Recy-Stand} - Ex_{bi-prod-i}} \qquad \textbf{Eq. 22}$$

Π_{PECE} , Π_{MRCE} are thermodynamic metrics, when Π_{EIE} is an environmental impact metric.
The initial requirements are now met. The resource/material consumption and the environmental impact are measured through the *Π* numbers above. A limited number of base quantities presented in Table 1 have been used to produce this result.
Following the introduction of the concepts, the following chapter demonstrates the ability of the framework to provide improvement during early design process. The authors apply the approach to the selection of a manufacturing process. Readers should notice that the approach provides flexibility in the analysis by performing either one of the following analyses:
- While maintaining unchanged the chain structure and the type of the individual organs *Oi*, modify some of the design parameters for one organ *Os*, to assess its influence on the overall environmental efficiency: this is a *sensitivity study*.
- Modify the environmental efficiency of one or more of the organs *Oi* of the chain, and recompute the overall environmental efficiency. This constitutes a *comparison of different technological scenarios*.
- Compare different technological chains that produce the same output, to assess their relative merits. This is a *comparison between different production technologies*.

This procedure can be applied at different levels of aggregation in a structure [9] [2].

5 CASE STUDY

5.1.1 Goals and boundaries of the assessment

This chapter is using the developed approach presented above in order to make a comparative study of two manufacturing processes (e.g. sand casting and milling versus milling). An engineering company has launched a project for designing a new type of pressure regulator. They are exploring the life cycle of this pressure regulator systematically [2]. At first, the use phase of the life cycle has been analyzed. They have ranked and compared different concepts of solutions by using an integrated design approach [2]. They study the manufacturing phase in order to evaluate possible manufacturing solutions. The goal is to assess the two manufacturing processes from two different viewpoints, the consumption of resources and the environmental impact respectively.
In order to ensure comparability of both studies, the boundaries of each process are carefully examined. An algorithm ensuring comparability [2] has been used. The casting and milling process is formed of the following phases - melting, pouring, checkout, shot blasting, plasma cutting and milling -. The other process is composed of a single phase: milling process.

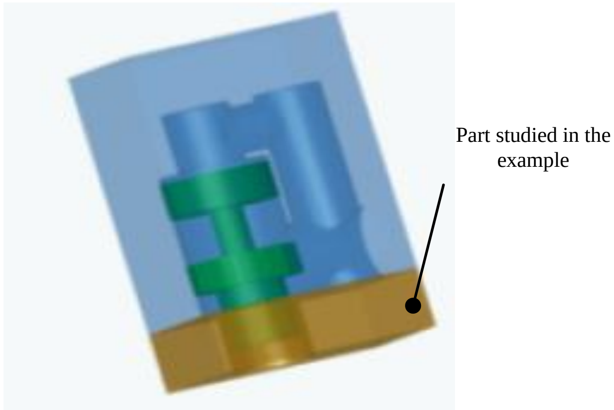

Figure 5: One concept of solution for a pressure regulator

5.1.2 Modeling and inventory analysis

The functional unit used for the study is the production of one part presented in Figure 5. The volume of the part is 729 cm^3. The internal recycling process of the foundry solution is taken into account. The metal selected exhibits in both cases similar mechanical properties and composition. They are both stainless steel. The foundry process is using a steel type GX 2 CrNiMo 18-12 and the milling process is using an X2 CrNiMo 17-12-2. The mass of one finished part is 6 kg in both cases. The foundry process requires 12kg of material, for the part, the sprue, the feeding and feeling system, per casting and the milling process requires 9kg of material per machining, for the clamping and machining trajectories of the tools .

Hypotheses:
In order to fit with the length of this article, three major hypotheses have been used:
- The exergy consumed and discarded into the environment during the pattern and sand mold manufacturing is not taken into account in the model of this study,
- The exergy consumed and discarded into the environment during the dust's collecting process is not considered.
- The milling process is considered not to discard matter directly into the environment.

These hypotheses are made for simplifying the mode for this specific example. Nevertheless, in order to evaluate these choices, an additional phase can evaluate the impact of these simplifications on the result by completing a sensitivity analysis.

Characteristics of the equipments:
Process 1: Casting and milling
The type of furnace used for preparing the steel has the following characteristics:
- Electrical induction furnace with a frequency f=3000 Hz. A power of 75 kW and a melting speed of 100kg/h [33].

The characteristics of the sand mold are:
- Type of sand and mass[34]: Silice (SiO_2), 6 kg,
- Type of binder and mass [34]: Kaolinite ($Al_2Si_2O_5(OH)_4$), 0,2 kg,
- Type of coating and mass [34]: ($2SiO_2$,Al_2O_3,$2H_2O$), 0,16 kg,

The characteristics of the checkout process are:
- Electrical energy of the machine [35] : 5 kW,
- Check-out cycle time: 60s,

The consumption of water is neglected because its contribution is insignificant.
The characteristics of the shot blasting process are:
- Electrical energy of the machine [35] : 10 kW,
- Shot blasting cycle time: 120s,

The characteristics of the plasma cutting process are:
- Electrical energy of the machine [36] : 3,2 kW,
- Cutting cycle time: 30s,
- Neutral gaz consumption (Ar) [36]: 129 l/min at 414 kPa

After the sand casting process, a milling phase takes place. The waste steel produced by the milling process is accounted in the plasma cutting process for simplicity. The characteristics of the process are defined for a minimize wear's cutting speed (Vc):

- Milling time: 2 min,
- Power of the machine 13 kW,
- Flow of cooling fluid emulsion: 7l/min,
- Mass/Volume of Crude Oil N°5 [37]: 0.9,
- Proportion of Crude oil in the emulsion: 0.5,

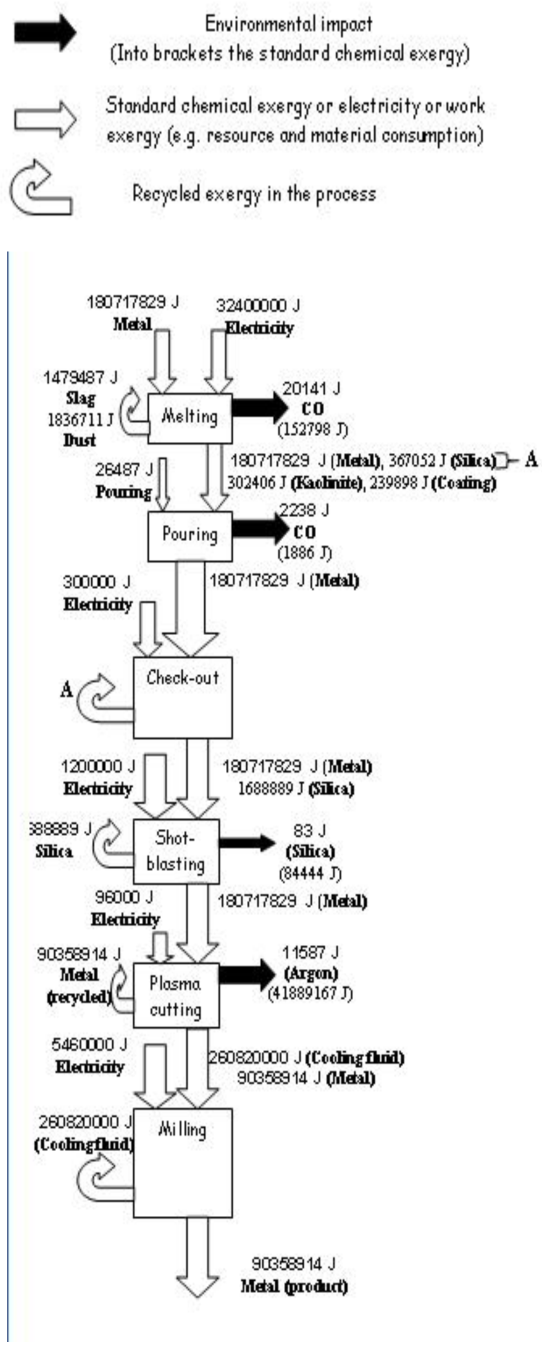

Figure 6: Exergy accounting of the sand casting and milling process

Process 2: Machining (milling)
The milling process is considered using similar cutting conditions than the ones used in the previous studied process. The characteristics of the machining process are:

- Milling time: 8 min,
- Power of the machine 13 kW,
- Flow of cooling fluid emulsion: 7l/min,
- Mass/Volume of Crude Oil N°5 [37]: 0.9,
- Proportion of Crude oil in the emulsion: 0.5.

Some gases and slag are resulting from the melting and pouring phases. The melting phase is producing around 90% of the gases [38]. The main gas resulting from the process is the carbon monoxide (CO) some other gases are also emitted (e.g. NO_X for example). The proportion of the other gases has been considered as negligible for simplification purpose of this exercise. The production of CO is approximately of 0,16 kg/hr [39]. The chemical reaction producing CO inside the furnace and mold is:

$$SiO_2 + 2C \rightarrow Si + 2CO \qquad \textbf{Eq. 23}$$

In many cases, the slag is not recycled [38] so we have considered also the exergy of mixing of slag in this example. The slag is mainly composed of the following compounds (CaO, SiO_2, MgO, Al_2O_3, S).

The slag is composed of 55% of CaO, 15% of SiO_2, 5% of MgO, 25% of Al_2O_3, 0,6% of S [33]. The amount of slag produced is 35kg/ton [33]. In addition, the melting and pouring processes are producing dust (10kg/ton) [33]. The dust is composed of the following elements (S, Fe, Mn, Cr, Ni). The proportion of the elements or oxide in the dust are considered to be 0,6% of S, 18% of Cr, 12% of Ni, 2% of Mo, 57% of Fe [33].

The shot blasting process is also producing dust. This dust is composed of silica (SiO_2). The amount of silica used by the sand blasting machine is 800kg/h [35]. The amount of silica lost into the environment is evaluated to be 5% of the total amount. The amount of dust in the checkout process is null because of the type of process selected (e.g. closed equipment).

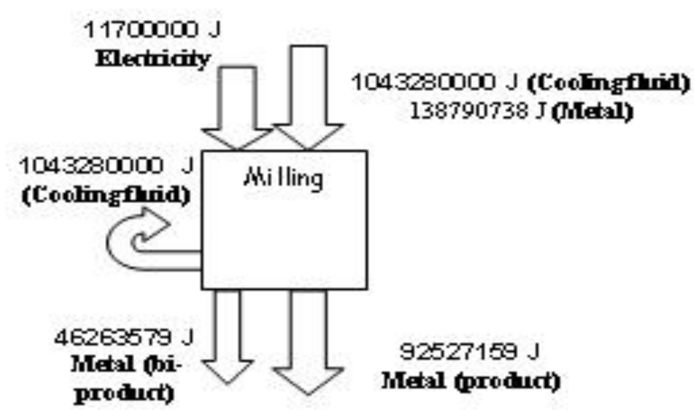

Figure 7: Exergy accounting of the milling process

Table 4 defines the activity coefficients necessary for computing the *exergy of mixing* (e.g. the environmental impact) of Figures 6 and 7. The numerical information has been found in Szargut et al. [29].

Table 5 presents the standard chemical exergy of the elements and compounds present in the dust, slag and gases. Figures 6 and 7 present the exergy accounting computed for both processes.

Table 4: Activities of elements in the environment

Chemical elements and Compounds	Chemical activity in the thermo. system (y)	Chemical activity in env. (y^O)	conventional molar fraction in env. (x)	Comment [23]
CO (gas)	1	120 ppb		
CaO (solid)	1	2,50E-04	2,50E-04	y^0 evaluated using x
SiO_2 (solid)	1	4,72E-01	0,472	y^0 evaluated using x
MgO (solid)	1	2,30E-03	2,30E-03	y^0 evaluated using x
Al_2O_3(solid)	1	2,00E-03	2,00E-03	y^0 evaluated using x
S (Solid)	1	0,11		
Fe (solid)	1	1,30E-03	1,30E-03	y^0 evaluated using x
Mn (solid)	1	2,00E-04	2,00E-04	y^0 evaluated using x
Cr (solid)	1	4,00E-07	4,00E-07	y^0 evaluated using x
Ni (liquid)	1	0,2		
Ar (gas)	1	0,00933	0,00933	

Table 5: Standard chemical exergy of elements and compounds present in the gases, slag and dust

Chemical elements and Compounds	Standard chemical exergy (kJ/mol) [23]
CO	275,1
CaO	110,2
SiO_2	1,9
MgO	66,8
Al_2O_3	200,4
S	609,6
Fe	376,4
Mn	482,3
Cr	544,3
Ni	232,7
C	410,26
Mo	730,3
Ar	11,69

Table 6: Molar mass of the elements of the example

Chemical elements and Compounds	Molar mass of the elements (g/mol)
Ca	20
O	8
Si	14
Mg	12
Al	13
S	16
Ni	28
Cr	24
Mo	42
C	6
H	1
Fe	26
Ar	18

5.1.3 Impact assessment

The Table 7 computes the dimensionless indicators introduced in Eq. 20, 21 and 22.
The Figures 8 and 9 are summarizing the results of Table 7. In order to optimize the result, the two resource consumptions criteria of Table 7 need to be maximized. The environmental impact criterion needs to be minimized. The environmental impact of the milling process is supposed to be null in our case. This is due to the hypotheses of the example.
It should be kept in mind that the main importance is not the relative value of each criterion but more the relative difference between the criteria.

Table 7: Impact assessment

		Resource cons.		Environmental Impact
	Dimensionless criteria	π_{PECE}	π_{MRCE}	π_{EIE}
Production technologies	Weights	***13,54***	***86,45***	***0,01***
	Optimization goal	Max.	Max.	Min.
Sand casting and milling		19	105	0.03
Milling		12	89	0

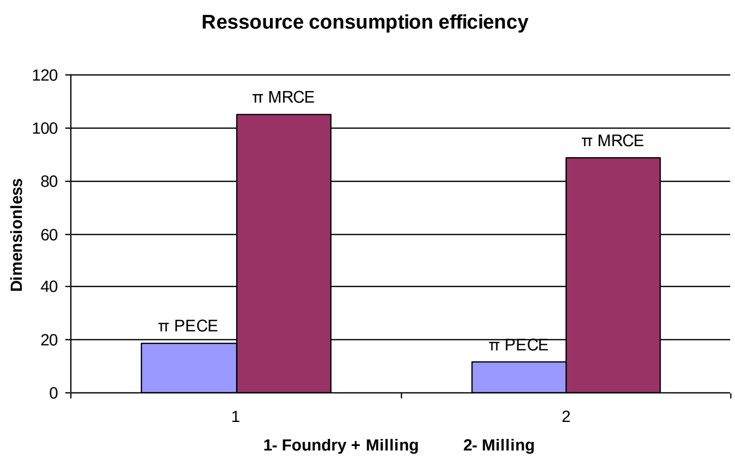

Figure 8: Resource consumption efficiency of the two processes

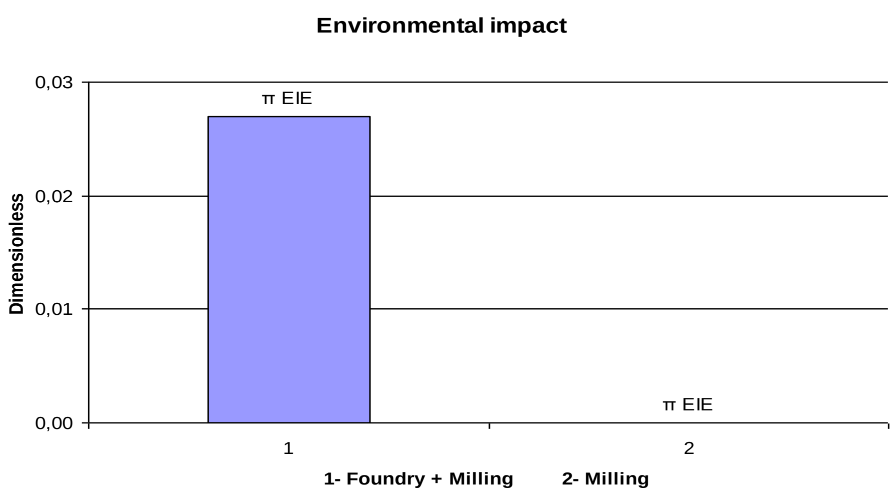

Figure 9: Environmental impact

The weight factors of Table 7 have been computed according to their contribution to the sum of all the dimensionless criteria. Another approach, such as the pair wise comparison [40], can also be used to compute such results. This choice is possible because all the dimensionless criteria are presented in a similar scale due to the method selected in this article. Obviously, a sensitivity analysis can modify these weights if some experts consider for example that the environmental impact should have a higher priority.
None of the two manufacturing methods are dominating from a Pareto perspective. The choice of a solution can be made by using a multi-criteria evaluation method like Electre 1 or Prométhée [41].

In the example, the choice is quite trivial. It is clear that the process combining foundry and milling is better because of the higher global impact of the resource consumptions criteria (Figures 8 and 9).
Nevertheless, the choice of a final manufacturing solution environmentally friendly requires a sensitivity analysis of the parameters selected in the study.

6 CONCLUSION

This article has demonstrated the existence of a formal scientific link between an integrated design framework comparing concepts of solutions via dimensionless numbers and environmental analysis conducted by using the concept of exergy. The main contribution of this article is to provide a simplified environmental accounting and comparison approach based on a limited number of base quantities. In addition, this framework is dedicated to the conceptual design phase. This characteristic is fundamental because the reliability of traditional LCA approach during the conceptual design process is very poor.
The framework developed in this article is using existing information already published in textbooks. In addition, the method is not time consuming. This is a very important aspect because this is probably the most critical aspect for practitioners of environmental analysis methods. The last part of the proposed method (e.g. the improvement assessment) is not fully developed in this example because of the limited format of the article.
Future work will concentrate on combining different types of requirements such as customer, cost and environmental requirements in order to evaluate fully the scope of the integrated framework.

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