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Hybrid Exergetic Analysis-LCA approach and the Industry 4.0 paradigm: Assessing Manufacturing Sustainability in an Italian SME

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Abstract

Assessing sustainability of manufacturing is a fundamental prerequisite to the improvement of efficiency or effectiveness of manufacturing processes. The LCA is used to estimate the resource consumption along the life-cycle, while the exergy analysis introduces hints about the quality of resource consumption. The hybrid analysis descending from combining these two approaches has been proved to be a powerful tool to recognize the process optimization opportunities, as well as improvements and/or innovation paths of manufacturing processes. The incoming Industry 4.0 paradigm, providing new on-time information on the process status, is going to strongly improve this approach. The article analyzes the existing hybrid approaches and their potential features by the grace of an industrial case of an Italian SME where the Industry 4.0 is taking place. The company redesigned its sensing systems and partially the manufacturing organization as a function of the manufacturing predictability.

Keywords: Sustainable Manufacturing; Exergy analysis; Lca; Hybrid Sustainability Assessment;

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Nomenclature

i	sub-system
m_{in}	input mass
m_{out}	output mass
$H_{m,in}$	input enthalpy of material
$H_{m,out}$	output enthalpy of material
W_{in}	input work
W_{out}	output work
Q_{in}	input heat
Q_{out}	output heat
$Ex_{m,in}$	input mass exergy
$Ex_{m,out}$	output mass exergy
$Ex_{W,in}$	input exergy work
$Ex_{W,in}$	output exergy work
$\left(1-\frac{T_0}{T_{in}}\right)Q_{in}$	input exergy heat
$\left(1-\frac{T_0}{T_{in}}\right)Q_{out}$	output exergy heat
Ex_{loss}	exergy loss
e_i^{ph}	physical exergy of material
ρ_z	density of zamak
V_z	volume of zamak
V_{re}	reuse volume of zamak
V_l	loss volume of zamak in the melting phase
V_g	loss volume of zamak in the injection phase
$Q_{f,i}$	energy for melting
$Q_{l,i}$	energy for the transformation
$Q_{c,i}$	energy for casting
T_f	melting temperature
T_s	temperature of the ingots at the entry of the furnace
T_0	environmental temperature
T_z	injection temperature of zamak
T_g	loss temperature of zamak in the injection phase
c_1	stroke of the piston in the first phase of injection
c_2	stroke of the piston in the second phase of injection
c_m	stroke of the piston in the second phase of injection
t_1	time of injection in the first phase
t_2	time of injection in the second phase
t_m	time of injection in the third phase
v_1	velocity of injection in the first phase
v_2	velocity of injection in the second phase
v_m	velocity of injection in the third phase
p_1	pressure of injection in the first phase
p_2	pressure of injection in the second phase
p_m	pressure of injection in the third phase
$F_{inj,1}$	injection force in the first phase
$F_{inj,2}$	injection force in the second phase
$F_{inj,m}$	injection force in the third phase
T_{mo}	mold temperature
h_z	specific enthalpy of zamak
s_z	specific entropy of zamak
S_{inj}	injection surface
$c_{p,z,i}$	specific heat of zamak
$c_{l,z,i}$	latent heat of zamak

1. Hybrid Sustainability Assessment

In 1987, the World Commission on Environment and Development (WCED) defined "***sustainable development***" as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs". Mihelcic defines sustainability "the design of human and industrial systems to ensure that humankind's use of natural resources and cycles do not lead to diminished quality of life due either to losses in future economic opportunities or to adverse impacts on social conditions, human health, and the environment" [1].

Resource utilization is one of the key factors of engineering sustainability: the sustainable engineering may also be defined as a prudent utilization of resources for the economic, environmental, and societal benefits. In order to quantify and evaluate the resource utilization during a product lifecycle, a simple and fundamental metric is required.

Several methods adopted so far to improve the sustainability of manufacturing processes were focused on energy consumptions, waste reduction, efficiency improvement in the use of resources and adoption of recyclable material.

Assessing sustainability of manufacturing processes through LCA (Life Cycle Assessment) tool is a common approach today. LCA is an analytical tool used to quantify and interpret the flows to-and-from the environment through the whole life cycle of a product, process or service; but it suffers some limitations. The first is that it appreciates only quantities of elements flowing in the processes (say, energy, materials, etc.); the second is the dependence on standard databases referring to general or averaged figures, independently of the specific process analysed.

The thermodynamic analysis method [2] instead makes it possible, first of all, to identify and recognize the optimization opportunities. Then it makes it possible to recognize improvements and/or innovation paths for the sustainability of processes and products.

Indeed, the use of state variables, concerning products and processes, makes it possible to precisely and objectively quantify (both in physical and economical terms) the gap between the processes efficiencies and their maximum achievable values, as a function of the physics of processes and the surrounding circumstances.

Energy analysis measures the energy required directly and indirectly to produce specified good or service. Energy analysis to evaluate efficiency has been recognized for years but the loss of quality of energy is not taken into account.

The exergy analysis instead examines efficiency change in a more practical way This method provides the evaluation of the quality of energy usage, the identification and quantification of the energy inefficiency of the process through the measurement of the Exergy Loss.

Exergy is defined as "*maximum theoretical useful work obtainable as the system is brought into complete thermodynamic equilibrium with the thermodynamic environment while the system interacts with this environment only"* [2].

Exergy analysis is an analytical method to deeply assess the sustainability of manufacturing processes (economical and environmental features) [3].

There are many methods that use this type of analysis:

1. First paradigm is the Cumulative Exergy Consumption, CExC ('electricity consumption of exergy'), which considers exergy contained in all the input process.

   It expresses the sum of the exergy content of natural resources consumed in all the steps of a production process. This approach allows the analyst the possibility to find out all the exergy losses generated in all the steps of the production process of a final product, reaching the stage where natural resources are extracted from the environment. The impact categories considered, are all natural resources, renewable and non-renewable [4].
2. Second paradigm is the Thermo Ecological Cost, TEC which considers only the input of non-renewable resources, subdividing them further into fuel ('fuel resources') and minerals ('mineral resources'). This paradigm is based on the fact that only what is not renewable is exhaustible and for this reason you have to estimate consumption. It considers the cumulative exergy consumption of not renewable resources along the entire production process of a commodity. The balance equations may be formulated according to the principles of life cycle assessment LCA [2].
3. Third paradigm is the Exergetic Life Cycle Assessment, ELCA ('assessment exergetic life cycle'), which combines analysis of life cycle with exergy. Basically, the ELCA is equal to CExC with the addition of considering, explicitly, life stages of a generic system: production or construction, operation,

decommissioning. The ELCA follows the criterion of life cycle irreversibility, accounting for all the exergy losses occurring during the entire life cycle. Knowing which component causes the losses, the problem of natural resources depletion can better be addressed reducing those losses. When the ELCA is used separately, it is often used to reduce the use of natural resources or the costs associated with their use, while it usually could be used together with LCA to calculate other environmental impacts [5].

4. The fourth paradigm is Cumulative Exergy Extraction from the Natural Environment, CEENE, ('cumulative exergy extracted from the environment'), which considers, in addition to the impact categories of CExC, the occupation of the land. It aims to quantify the exergy that the natural ecosystem is deprived of over the life cycle of a commodity, and to perform a comprehensive resource based life cycle impact assessment [6].
5. Fifth and last paradigm is Extended Exergy Accounting, EEA ('extended exergetic analysis'), which can be seen as an extension of the CExC paradigm since, in addition to materials and energy, it also includes contributions of labor, capital, and costs of repairing the environmental damage. To take into account all these factors, the 'equivalent exergy' is used; it makes it possible to convert all these terms in exergy and to have the opportunity to add them, to each other, using the same units [7].

In this paper the Hybrid Exergetic – LCA Analysis approach is introduced, a hybrid analysis descending from combining LCA and exergetic analysis. The main drawback of LCA is the fact that databases, to which they are referred, cannot be considered as a standard for a particular process, since they cannot take into account the context they are in. Accordingly, it is clear that LCA might serve as one possibility for assessing process sustainability, i.e., a benchmark to contextualize specific assessments of sustainability related to efficiencies or to other technical problems appreciated on site with appropriate approaches. The Hybrid Exergetic Analysis-LCA approach overcome this problem as it is intended to define a monitoring strategy to increase the sustainability manufacturing of the process. The phases of the approach are:

1. Identification of the system where the analysis has to be applied: choice of the product and the manufacturing process object of the analysis. In this step it is necessary to implement the LCA which makes it possible to identify the set of critical products and processes. LCA analysis should assess the amount of resource consumed and relative emissions to produce the functional unit (chosen as the single product). In International Standard Organization 1997, 14040 [8], the functional unit is defined as the measure of the performances of the functional outputs of a considered system. In the same standard, the importance of the functional unit for the comparability of the LCA results is highlighted. The functional unit makes it possible, in this way, to normalise efficiency of processes, and thus to have a fast glance to the overall efficiency of the production process life-cycle. Boundaries of the system to be analysed typically include the following elements: raw material production; semi-finished products preparation; additive production; internal and external logistic; product component production; waste management; water and energy consumption; emission in air. The time-dependency of the impacts should be carefully considered for our scope. It refers to the time irregularity of emissions [9], impacts that requires years to become evident [10], impact comparisons have resulted that changes over the considered time horizon [11] Usually this time-dependency is ignored, and the impacts are averaged [12]. To the scope of the present approach, the time dimension pertains the systemic perspective of the processes [13].
2. Application of the exergetic analysis, as detailed in the subsequent points. Split the system into different subsystems and draw a detailed representation of the operation of every subsystem under consideration.
3. Performing a mass and energy balance of each subsystem according to the following equations:

$$\mathrm{m_{in}} = \mathrm{m_{out}} \tag{1}$$

$$\mathrm{H_{m,in}} + \mathrm{W_{in}} + \mathrm{Q_{in}} = \mathrm{H_{m,out}} + \mathrm{W_{out}} + \mathrm{Q_{out}} \tag{2}$$

4. Performing an exergy balance of each subsystem to compute the exergy loss $\mathrm{Ex_{loss}}$:

$$\mathrm{Ex}_{\mathrm{m,in}} + \mathrm{Ex}_{\mathrm{W,in}} + \left(1 - \frac{T_0}{T_{in}}\right) Q_{in} = \mathrm{Ex}_{\mathrm{m,out}} + \mathrm{Ex}_{\mathrm{W,out}} + \left(1 - \frac{T_0}{T_{out}}\right) Q_{out} + \mathrm{Ex}_{\mathrm{loss}} \quad (3)$$

5. Definition of the thermodynamic parameters critical to measure for each subsystem.
6. Performing the Exergy efficiency index calculation η:

$$\eta = 1 - \frac{\mathrm{Ex}_{\mathrm{loss}}}{\mathrm{Ex}_{\mathrm{m,in}} + \mathrm{Ex}_{\mathrm{W,in}} + \mathrm{Ex}_{\mathrm{Q,in}}} \quad (4)$$

2. Hybrid Exergetic – LCA Analysis and I4.0

The pervasive diffusion of technologies related to the routing and the management of information are inspiring the fourth industrial revolution, which is often defined as Industry 4.0 (I4.0) [14]. The scope is to ensure a better flexibility and scalability of manufacturing systems through information technologies and industrial automation [15], [16].
The widespread commercial platforms [17]–[20], for instance, provide tools for the creation of the I4.0 personalized solutions. They are oriented to data mining and communication between resources (with resources we refer both to the informative systems that to the production machines).
The potentialities of measurement extraction from process is the corner stone of the I4.0 revolution which allow the method proposed to be really effective for sustainability improvement of manufacturing processes.
The availability of knowledge about the processes, based on sound measurement systems (quite often with on-line setting) allow to clearly track the system features and system evolution. The main idea here, inherited from [21] is that measurement is the fundamental of the knowledge model of a real system. Since the measuring systems are considered as the only way designers can represent the reality (i.e. perceive and react on it), the resulting model of a real system is explicitly connected with how the human being is interfaced with the reality. Measurements should replace the role of the abstract concepts, which pertain also to sustainability measurement. The I4.0 sensoring system is the physical support to avoid user interpretations (i.e. ambiguity) on the system sustainability, provided everything is represented as measurements and mathematical relations between them.
It is quite obvious how, the time dimension before recalled, becomes critical to have a significant representation of the sustainability performances of a process, provided the time scale of different processes may be inhomogeneous. And in fact, the main problem we also face here is to set the acquisition frequency of data, which turn to be really significant to the scope of the analysis, provided the LCA analysis is typically an average analysis over a long scale time horizon (months) while the exergetic analysis addresses typically—despite its integral nature—short scale phenomena (seconds), provided it concerns the transformation processes.

3. Case study

The thesis here sustained is that the outcome of the previous hybrid analysis is an excellent guideline to set up a smartness model for the transition toward the Industry 4.0 paradigm.
A real industrial case from Master Italy s.r.l., a SME Italian company producing small accessories for civil window frames, is here considered to test the Hybrid Exergetic Analysis-LCA approach. The objective of this case study is the development of a retrofitting solution for a die casting process through hybrid exergetic analysis-LCA approach.
The LCA analysis was drafted with the aim of calculating the Global Warming Potential (GWP) over 100year of each product. The objective of the LCA analysis is to evaluate the amount of resources needed and the emissions produced to produce the various components.
The most important products of the company are hinges, steel corner, handles and tilt and turn used to aluminium windows. Thanks to the LCA assessment, the selected product is the handle (Fig. 1) since the GWP_{100} impact is the highest: 2,972 $kgCO_2$eq/pcs.
The different handle components undergo several mechanical processes: die casting aluminium, die casting zamak, varnishing, and assembly. Analysing each production process, the greatest contribution is given by the die casting zamak process (0,8034 $kgCO_2$eq/pcs due to the energy consumption) and the die casting aluminium process (1,1395 $kgCO_2$eq/pcs due to the methane gas consumption).

Fig. 1. Handle

The die casting process involves the use of a furnace, metal, die casting machine, and die. The metal, typically a non-ferrous alloy such as aluminium or zamak is melted in the furnace and then injected into the dies in the die casting machine, where it rapidly cools and solidifies into the final part, called the casting. Cold chamber machines are used for aluminium since the melting point is high (680-700 °C); hot chamber machines would damage the pumping system. The melting point of zamak is 380-386 °C, so hot chamber machines are used for this kind of alloy.

Applying the exergy analysis, the die casting system is divided in four different subsystems:

1. Melting: the alloy enters at the solid state (ingots) and exits at the molten state (shot).
2. Injection: the molten metal, which is maintained at a set temperature in the furnace, is next transferred into a chamber where it can be injected into the die.
3. Cooling: the molten metal that is injected into the die will begin to cool and solidify once it enters the die cavity.
4. Extraction: after the predetermined cooling time has passed, the die halves can be opened, and an ejection mechanism can push the casting out of the die cavity.

Each subsystem can be interpreted as an individual thermodynamic system characterized by its corresponding input and output flows of mass and energy.

For die casting zamak, the exergy of material, work, and heat are reckoned in each subsystem (i) with the following equations:

$$\mathrm{Ex}_{\mathrm{m},i} = \mathrm{e}_i^{\mathrm{ph}} = \rho_\mathrm{z} \cdot \mathrm{V}_\mathrm{z} \cdot \left[(\mathrm{h}_{\mathrm{z},i} - \mathrm{h}_0) - \mathrm{T}_0 \cdot (\mathrm{s}_{\mathrm{z},i} - \mathrm{s}_0)\right] \tag{5}$$

$$\mathrm{Ex}_{\mathrm{W},i} = \mathrm{F}_{\mathrm{inj},i} \cdot \mathrm{c}_i = (\mathrm{p}_i \cdot \mathrm{S}_{\mathrm{inj}}) \cdot \mathrm{c}_i \text{ where the stroke of the piston determines } \mathrm{c}_i = \mathrm{v}_i \cdot \mathrm{t}_i \tag{6}$$

$$\mathrm{Q} = \mathrm{Q}_{\mathrm{f},i} + \mathrm{Q}_{\mathrm{l},i} + \mathrm{Q}_{\mathrm{c},i} = \mathrm{c}_{\mathrm{s,z},i} \cdot \rho_\mathrm{z} \cdot \mathrm{V}_\mathrm{m} \cdot (\mathrm{T}_{\mathrm{f},i} - \mathrm{T}_{\mathrm{s},i}) + \mathrm{c}_{\mathrm{l,z},i} \cdot \rho_\mathrm{m} \cdot \mathrm{V}_\mathrm{m} + \mathrm{c}_{\mathrm{s,z},i} \cdot \rho_\mathrm{m} \cdot \mathrm{V}_\mathrm{m} \cdot (\mathrm{T}_{\mathrm{z},i} - \mathrm{T}_{\mathrm{f},i}) \tag{7}$$

For each subsystem, the reckoned exergy loss ($\mathrm{Ex}_{\mathrm{loss}}$) and the exergetic efficiency (η), for a given recording observation time, are reported in Table 1.

Table 1. Exergy loss and Exergy efficiency (average data over a sample of 30 observations)

Subsystem number	Die casting Zamak	Exergy input (J)	Exergy output (J)	Exergy Loss (J)	η (%)
1	Melting	3.070	1.750	1.320	57%
2	Injection	5.375	1000	4.375	19%
3	Cooling	9.149	500	8.649	5%
4	Extraction	1.826	100	1.726	5%

The application of the exergetic analysis shows that the cooling phase (Subsystem 3) is the critical subsystem because the exergy loss is highest than other subsystems. In fact, during the cooling phase the mold acts as a real heat exchanger in which the heat is subtracted from the liquid zamak so that it solidifies to assume the desired shape.

In general, it is noted that the exergetic efficiency of the process is low especially for the phases that do not contribute to increase the exergetic content of the final product, e.g. the cooling and extraction phases (Subsystem 3 and Subsystem 4).

The LCA analysis performed allowed to measure the critical system (product and process) in terms of resource consumption and pollutions. This information was then used to provide input to the exergy analysis and split the selected system into different subsystems to assess their criticality in terms of sustainability. LCA was performed used the SIMAPRO® software using the Ecoinvent database.

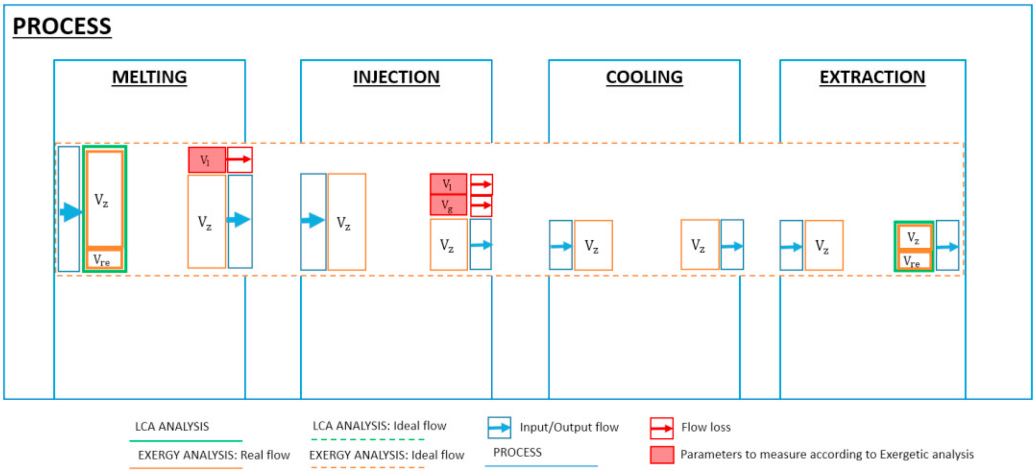

Fig. 2. Mass flow balance

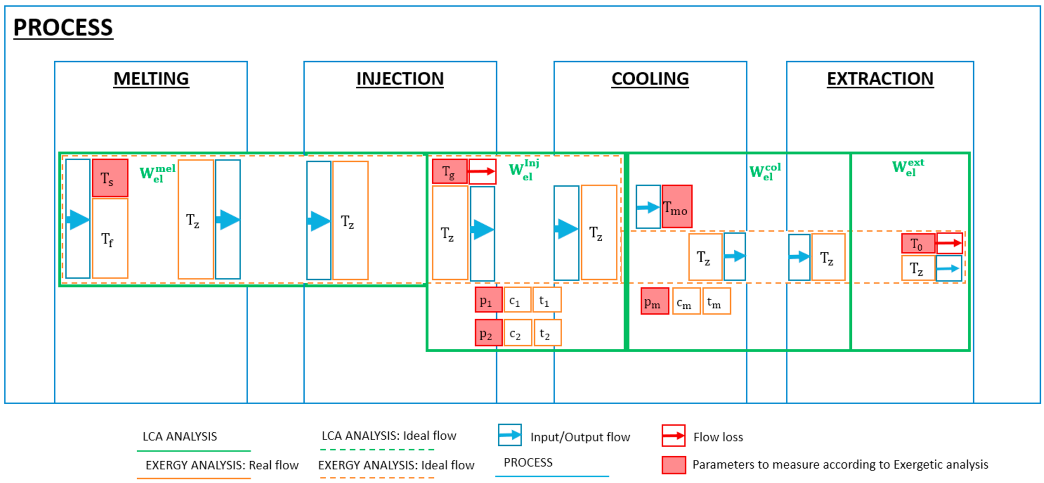

Fig. 3. Energy flow balance

Analysing the exergetic analysis equations it is also possible to define the critical thermodynamic parameters, identify the parameters not yet controlled and measure the same:

- Main parameters already controlled: $V_z, V_{re}, T_z, c_1, c_2, c_m, t_1, t_2, t_m$
- Main parameters not yet controlled: $V_l, V_g, T_s, T_0, T_g, T_{mo}, p_1, p_2, p_m$
- Derived parameters: $h_z, s_z, F_{inj,1}, F_{inj,2}, F_{inj,m}, v_1, v_2, v_m$
- Non-controllable parameters: $S_{inj}, \rho_z, c_{p,z}, c_{l,z}, h_0, s_0$

4. Conclusions

The aim of the paper is to present a novel approach to address production processes sustainability by means of an improved LCA analysis, Hybrid Exergetic Analysis-LCA approach, where regular analysis derived from LCA databases are supported by exergetic analysis. The aim of the present work is to show the potentialities of the Hybrid Exergetic Analysis-LCA approach to provide a clear view of the efficiencies of a manufacturing process. Through the integration of the Life Cycle Assessment and Exergy analysis is possible to structure the monitoring strategy. The monitoring strategy is a fundamental prerequisite for the implementation of Industry 4.0 technologies.

The Hybrid Exergetic Analysis-LCA approach provides the definition of the monitoring strategy for industry 4.0; it contains the definition of the measuring parameters, the application of the sensor, and the execution of the measurement.
The proposed approach is also an opportunity for the development of a retrofitting solution machine. In this way, the process could be able to automatically react to any machine failures, and it is in line with sustainable manufacturing in Industry 4.0 scenario.
The proposed approach combines also the current research approaches in the field of sustainable manufacturing with the requirements of Industry 4.0. The future developments of the present approach can be to evaluate the sustainability of the Industry 4.0, where the problem of time scale normalization for the different analysis—only partially faced in the present paper for the sake of brevity—will be object of a further analysis to come soon.

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