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Exergetic Control Charts
(Variability analysis in a real injection-moulding industrial application)

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Abstract

Decision concerning manufacturing process design and management, under sustainable constraints, are difficult to draw when taking into account variability of process conditions. Life-cycle analysis and exergetic analysis are even more jointly adopted to improve the accuracy of resource use efficiency – the so-called hybrid approach – even though these are based on the assumption of constant operating conditions.

The paper discussed a new idea to take into account variability in hybrid exergetic LCA due to contingent conditions, by proposing an exergetic control-chart (ExCC) scheme to formalise the variable conditions. The idea behind the ExCC approach is that manufacturing sustainability analysis may change its outcomes when taking into account this 'dynamic' point of view.

The control-charting scheme here proposed provides a mean to formalise explicitly the effects of variability in time, under the real operating conditions. The main advantage of the approach is to allow a more complete view of the process and to drive hints for improvements or innovations of processes. A real industrial case here presented of an Italian SME explains the potentialities of the idea as well as the limits of the current hybrid approaches available.

Keywords: Sustainable manufacturing; injection moulding ; exergy analysis; hybrid LCA, Control chart.

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1. State of the art on hybrid LCA approaches

Assessing sustainability of manufacturing processes through LCA tools is a common approach today, even though it suffers from some limitations mainly for two reasons. The first one is that it appreciates only quantities of elements flowing in the processes (say, energy, materials, etc.). The second reason is the dependence on standard databases, based on general or averaged assumptions and independent of the specific process analyzed.

Several authors faced the problem of improving the effectiveness of LCA output by combining a second-order exergy analysis. The resulting approach can be referred to as 'hybrid LCA approach' (see e.g. [1]).

The first attempt of life-cycle analysis using exergetic approach has been provided by [2], the analysis of Cumulative Exergy Consumption (CExC). Here the time component is introduced in calculating the CExC by adding up the total exergy requirement of a process, over a time period of observation. The approach concentrates only on defined life stages of the product.

In [3] the authors use exergy as a measure of resource depletion in LCA, by considering also chemical exergy contents of the natural resources of a product. The authors use exergy as a characterization metric within a proper selection of

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LCA boundaries. Mainly this approach is an attempt to better characterize the quality of resources used by LCA (say minerals and fuels extracted directly from the environment).

A similar approach is adopted in [4] to analyse the cement production. It is clear here how the level of detail is still lower, with respect to the analysis of variability of the operating condition in the production plants, which may determine change in the exergy losses.

In [5] the exergetic life cycle assessment (ELCA) is shown to be a more appropriate instrument to quantify the environmental problem of the depletion of natural resources. The case study discussed proof how critical is the evaluation of life cycle irreversibility in presence of renewable sources of energy.

In [6] the authors provide a well structured interpretation of exergy, and how this concept can dramatically improve LCA scopes. The same authors provide a practical calculation procedure to assess process sustainability as well. It is evident here that "standard" processes are considered, i.e. not dependent on the specific process condition decay over time or on local conditions.

In [7] authors introduces the concept of 'Exergetic Life Cycle Assessment' by combining exergy within the inventory analysis of the LCA framework. The proposed approach is intended to assess the exergetic efficiency of the natural resource use and to quantify their depletion. The author introduce the measure of irreversibility over the whole life cycle, as the sum of exergies lost in all the unit processes of a given system. The improvement opportunities can then be appreciated by minimizing the life cycle irreversibility. For multi-functional processes, three allocation methods are proposed [7]: i) based on the exergy of flows; ii) based on the exergy destruction in case of separate production of by-products; iii) based on the distribution of exergy destruction the flows. The interesting concept of "Zero-Exergy emission LCA" is also proposed to include the abatement of emissions exergy. In [5] the same authors provide the exergetic LCA for assessing the efficiency of natural resources consumption. The distinction between renewable and non-renewable exergy resources is then introduced without reference to the change in time.

Authors in [8] use the cumulative exergetic approach to analyze different waste treatment systems and to define an exergy-based measure of the sustainability of technologies. The life-cycle exergetic analysis is proposed as a measure depletion, by distinguishing renewable and nonrenewable resources. If only nonrenewable inputs to the life cycle are considered, the results (in terms of lost exergy) reflect the depletion of natural resources. No time dependency is taken into account for processes.

In [9] the authors integrate Cumulative Exergy Demand (CExD) factor within the LCA framework to improve accuracy of information carried by the ECOINVENT impact categories. CExD measures resource consumption and exergy removal from nature to produce products. The indicator assesses the quality of energy demand and includes the exergy of energy carriers, as well as of non-energetic materials. The exergy is calculated as an average reference value, since chemical, kinetic, hydro-potential, nuclear, solar-radiative and thermal exergies may change over location of resources.

The integration of Exergetic analysis within the LCA framework in discussed in several cases. In [10] the authors sustain the LCEA as a mean to effectively bridge the gap between traditional LCA practices and engineering process design is discussed. The LCEA framework taken as basis for the exergy balance is discussed for a production of TiO2 nanoparticles. The exergy contents of in- and out-flows are calculated using the CExC using the Simapro® tool for impact assessment. Again, no mention is provided about the degradation of process due to time or process location. The same approach is proposed in [11], for the case of a cane sugar production analysis where the cumulative exergy consumption is used for calculations.

In [12], on the other hand, the authors discuss the application of LCEA applied to a typical wind power plant, to bring new insight for sustainable design of the engineering conditions. Here the authors explicitly stress over the time dependency in the LCEA diagrams, but considering time as a measure of the life-cycle stage, i.e. not the dynamical part of the running of the power plant.

Finally, in [13] and later in [14] the authors elaborate upon the importance of a life cycle approach in sustainable engineering and exergetic analysis. Starting from the analysis of different methods, used to perform an exergetic analysis, the authors propose a very effective Life-Cycle Exergetic Analysis. Here the authors indirectly recognize the question of time dependency of exergy in defining the exergy power reckoned at different life stages of a generic 'system'

$$\dot{Ex} = d(Ex(t))/dt \quad (1)$$

The focus there is indeed the macroeconomics, to assess the performance of whole systems differently to the lower resolution scale of the present paper.

As concern the concept of control charts for exergy, no special references were found in the literature reviewed so far. Only a general mention with different meaning for sustainability analysis is provided in [8].

In summary, the question of considering the unsteady conditions of processes, that might thus changes over time due to interactions with other systems, is theoretically conceived in almost all the scientific literature (see [8]). When dealing with the exergetic analysis, this fact is not considered systematically if applied to discrete sequence of continuous transformation, which is typically the case in manufacturing processes.

The scope of the present paper is to discuss the question of taking into account the 'time' variability in ELCA. That means, to consider the variable nature of processes, due to their decay over time or variability in operating conditions. Furthermore, since the most of the analysis provided so far concerns continuous process, this paper proposes a control chart scheme for discrete processes, since rare examples are provided.

2. The dynamic aspect in exergetic analysis

The most of the LCA exergetic analyses performed so far take as reference the 'ideal' or 'average' processes conditions. This is mainly because such a kind of analysis serve much more on the design or redesign than to control processes. Since the natural environment is not in thermodynamic equilibrium, reference species are considered for all elements in the surroundings, representing the most stable compounds that are commonly occurring in the environment [9]. This fact leads to a 'static' view of the processes, thus not taking into account the degradation of it (the *'dynamical'* aspect) due to changing operating conditions. This dynamical viewpoint may imply a change in the extensive variables of substances involved in the chemical or physical reactions, namely: volume, mass, internal energy, heat flows. Even the reference environment is changeable as well, thus requiring an upgrade of the calculations variables: typically the reference temperature (T_0), while the reference pressure (p_0) rarely is considered variable for normal situations. When considering discrete processes, composed of a set of sub-processes, it may happen that exergy flows related to one product may thus change with respect to another one.

This is much more the rule than the exception in real manufacturing processes. This dynamic viewpoint may be irrelevant in a process design phase, where a-priori criteria are used. On the other hand, it becomes critical when running real manufacturing processes, where exergy components may change over time due to several reasons. Even for chemical reactions, based on intensive properties of matter, changes may occur over time in principle: raw materials may in fact change in composition from different locations [9], or even in time, due to changes in the supplier's conditions.

The reasoning here proposed is thus build on the idea that the operating conditions tend to degrade, or to be affected by varying external causes over time: this reflects in the related exergies calculations. This may imply the change in the exergy balances in ELC analysis:

$$\mathrm{Ex_{TOT}} = \mathrm{Ex_{Matter}} + \mathrm{Ex_{heat}} + \mathrm{Ex_{work}}[\mathrm{J}] \qquad (2)$$

where the term 'matter' may include either physical, chemical, kinetic and potential energy [1] .

Since the hybrid exergetic analysis is based on the exergy balance of each sub-process of a given process, it is clear that a dynamic approach must be applied for each sub-process recognized for a given system. The focus of the present paper is on the analysis of the production phase.

Capturing the dynamical nature of each sub-process means to measure the term Ex over time, so as to appreciate the variability of the exergy utilized per each component produced.

Real process operating conditions lead in fact to exergies figures subject to variability; as a consequence the exergy balance equation [6] can be rewritten accordingly:

$$\mathrm{Ex_{in}(t)} = \mathrm{Ex_{prod}(t)} + \Delta\mathrm{Ex_{process}}\,(\mathrm{t}) + \mathrm{Ex_{waste}}\,(\mathrm{t}) \qquad (3)$$

The term $\Delta\mathrm{Ex_{process}}$ accounts for the exergy lost in the process. Variability of exergy in product can be caused by material contents variation, while process variability is due to operating condition. As concerns wastes, the dependency over time is a consequence of the modification of the previous two terms (product and process).

In the present paper, we will focus on the sole process-related exergy components in eq. (3), to prove that this component may vary significantly over time, thus leading to potential misunderstanding in the final analysis. The strategy here adopted is to define adopt the "control chart" scheme to record and analyse exergy losses, considering the exergy loss a continuous random variable. It seems reasonable also the assumption that exergy-loss variable are not auto-correlated, descending from the nature of variability causes. As a consequence, it was possible to adopt the standard Xbar-R control chart [15]. Lower limit is fixed and set to LEx(t)=0, while the upper limit UEx(t) is calculated according to the classical approach as

$$UEx = \overline{Ex} + k\,\sigma_{Ex} \quad [\mathrm{J}] \qquad (4).$$

The average exergy component in (4) is evaluated as

$$\overline{Ex} = \textstyle\sum_{i=1,..,n} Ex_i(t) \qquad [\mathrm{J}] \qquad (5)$$

being n the number of observation over the single subprocess, and σ the relative standard deviation. The k factor in eq.(4) has been here adopted using the standard criteria for control chars (k=3).

As concerns the number of observations, it is clear that the physics of the process was considered. For a discrete manufacturing process, as is the case in this paper, exergy has to be evaluated based on the production unit: this can be the single product or a batch of products, depending on the specific manufacturing technology considered. The same rules of group sampling can be applied to the control chart accordingly [15].

The interpretation of the chart is consequently based on the same rules that apply to control charts, but with a slightly different meaning. The central limit should coincide with the average value typically assumed for the hybrid LCA approach.

The Upper control limit should be instead adopted more to interpret trends over time than to trace the single out-of-control points. A drift over the UEx, for instance, may imply the occurrence of a decay in the machine, or in the operating condition, which may in turn lead to a decay in the exergetic efficiency [13] in respect to the a-priori design conditions. In the same way, trend interpretation scheme are possible as well, provided the presence of limits in the control chart.

3. The industrial case example

A real industrial case example is considered here to test the approach, by analyzing a short time frame of process running. The company is a SME Italian producing small accessories for civil window frames. The component in object is a safety pin used in the angular fixing bracket used to tighten aluminum windows frames (see figure 1).

The manufacturing technology in object is an injection molding process of ZAMAK-5 zinc alloy (http://www.dynacast.it/zinco/zama-5). The injected alloy is melted at T=440(°C) in the hot chamber die. Process parameters are constantly traced, including the actual exergy use per each batch produced, made of 20 parts. The injection molding machine is fully integrated, to reach a greater temperature uniformity and a greater speed.

Fig. 1 The safety pin in the angular fixing bracket analysed.

The components of the injection molding machine process are: i) the injection group (a siphon and a plunger piston) that presses the molten alloy into the mold die; ii) the electric furnace within the same machine frame which is divided into two basins – in the first basin melting occurs, while in the second communicating basin maintain molten the alloy for priming the siphon. iii) the press group that closes-opens the mold and removes the sprues. Components (i) and (iii) are actuated by an hydraulic pump driven by electric motors.

The technological process is carried out through the following steps: 10) ingot loading and fusion; 20) injection; 30) moulding; 40) solidification; 50) extraction / ejection. The measurements performed for the present study where monitoring at intervals of 5min the active power consumptions for the pump and the furnace, as well as the overall active electrical power consumed. The reactive component was neglected for the scope of the analysis.

4. Outcome from Exergetic Control Chart

The analysis performed by applying the Exergetic Control Chart was done only for those process recognized as critical to sustainability by a previous LCA analysis. The system boundaries were selected to focus on the specific manufacturing phase, thus neglecting the rest of the product life cycle. The input border coincides with the input of the furnace while the output is the intermediate pallet, differing from the technological organization of manufacturing process.

As already stated, measured data reported on the control chart in figure 2 represents the quote ΔEx_{proc} in eq. (3) amongst the exergy losses. Exergy related to material were not considered because it was not possible to measure its variability and the same was for the wastes, which were negligible in this particular case.

Data here reported are voluntary altered due to confidentiality reasons, even though the overall meaning of analysis remain unaltered.

The interesting situation found on a week of observation is the occurrence of a critical drift of the process. It is clear, in fact, that around 61200 cycles something occurred that negatively altered the exergy balance. The causes suggested after a specific analysis where mainly attributed to the decrease in the production rate, that caused the exergy destroyed in the furnace to be lost over a smaller number of parts.

This specific outcome of the ExCC highlights the usefulness of the dynamic analysis point-of-view: it is in fact not possible to foresee such a kind of situation a-priori, in the process design phase. For the same reason, in this particular case, it is clear that a simple energy analysis can provide more or less the same information of the Exergetic Control Chart, being here the particular concern only on the electrical work of the pump and furnace. This is not completely true unless a similar statistical control scheme is also adopted for the energy measurements. On the other hand, when considering the complete set of the exergetic components (product and waste), it is quite evident that other variability sources can be captured, undetectable in the energetic analysis.

5. Discussion and future works

Contextualizing the exergetic view into LCA assessment is a new topic of interest, in striving for sustainable manufacturing. In most of the scientific approaches available so far, two main different reasoning scales has been adopted: the lower one closer to the single manufacturing phases, namely the exergetic analysis, and the higher one, more related to a systemic view of LCA. These two scales, in some sense, are faces of the same gold medal, which are related to each other. In the former scale, exergetic analysis for manufacturing processes is related to the quality of use of resources, thus providing a deeper contextual view of the specific processes but lacks of generality, because neglects the global balancing of resource use according to a conservation principle. The latter scale provides this systemic balance, but rarely is able to capture the single process specificity (average assumptions). Both of them are typically performed with the assumption of invariant operating conditions. This classical ‘static’ view of hybrid approaches, available in literature, presumes unchanged conditions during operations, which may be valuable only in the process design phase. Joining the two reasoning scales in the above might improve the overall assessment quality, provided the dynamical nature of processes is taken into account. The effort of adding a huge amount of information make sense, in fact, only if a reasonable increase of accuracy is reached.

In the present paper an Exergetic Control Chart approach is suggested, to introduce the dynamical point of view in the analysis among the components of exergy in the hybrid LCA approach. Since exergy is a measure of the degree of irreversibility of energy transformation, the earlier a degradation with respect to designed operating conditions is detected, the more sustainable is the manufacturing process as a whole.

Even though the case discussed focused on the sole process exergy, the analysis is susceptible of extension to other life cycle phases. The concept of exergy losses as stochastic variable, which therefore may vary significantly over time, leads to avoid potential misunderstanding in the overall sustainability analysis.

It will be interesting in a near future to explore also different control schemes in the exergy LCA approach (say multivariate control charts), to better understand the nature and usefulness of the 'dynamic' aspects of complex processes

Another interesting point is to appreciate the best design for the control scheme. For instance, by assessing the possibility of auto-correlation in the exergy-loss variable or choosing the criteria to define the appropriate control limits. Finally, further case analysis is required to proof that considering the variable conditions along the process life-cycle can provide useful benefits to the overall design and management phases to reach the process sustainability.

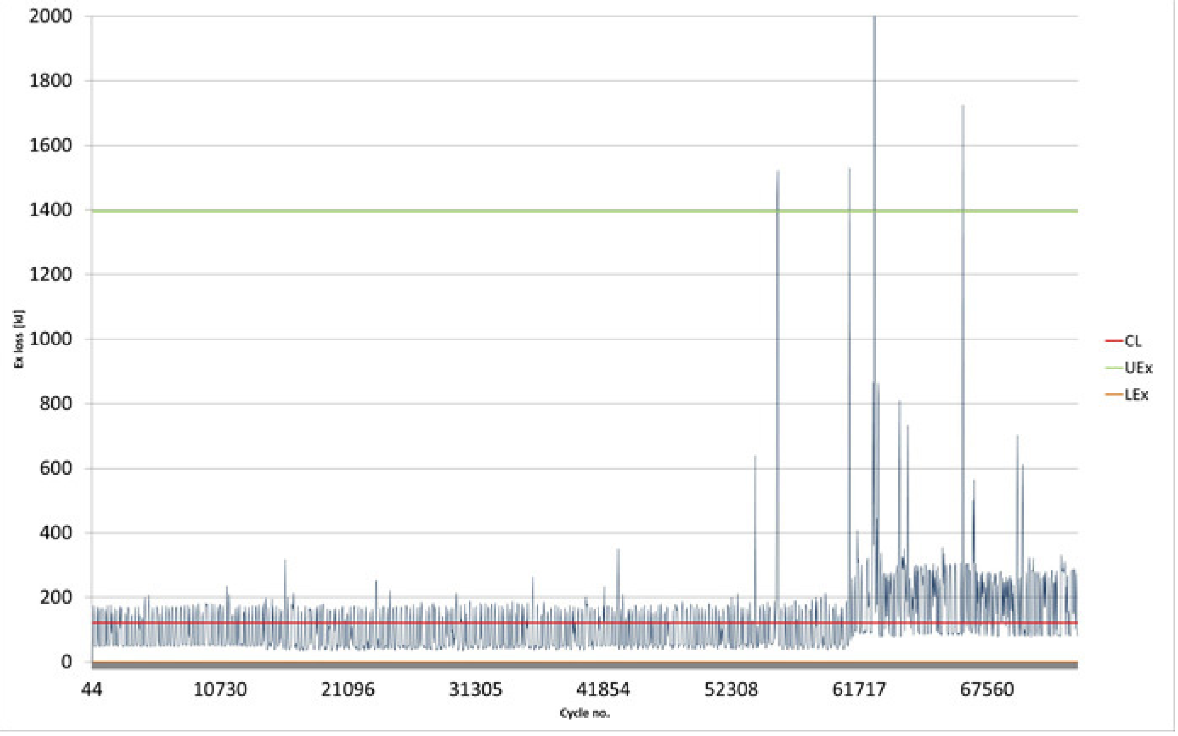

Fig. 2 The Exergetic control chart for the case example considered

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