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Exergetic model as a guideline for implementing the smart-factory paradigm in small medium enterprises: The Brovedani case

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Abstract

The development and implementation of the smart factory paradigm seems to be a must almost widespread all over the Western manufacturing companies so far. This article explores the application of exergetic analysis models as a feasible approach to customize such an announced paradigm shift: the implementation criteria as well as the true expected benefits are, in fact, far to be clearly understood or even perceived.
An Italian medium enterprise located in the south of Italy operating in the automotive sector is adopted as a test bench. The standard use of exergetic model was adopted to assess and improve the sustainability of the manufacturing processes performed by the company, namely: turning, milling, grinding, plating and dehydrogenation.
This thermodynamic view of the processes, on the other hand, represented a guideline to design a smart factory solution, and thus to structure the critical variables and the paths to digitalize processes for the intelligent control of the core production processes.

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Keywords: Exergy analysis, Smart manufacturign, Industry 4.0, Sustainable manufacturing.

1. Introduction

$Ex_{M,in}$	input mass exergy
$Ex_{M,out}$	output mass exergy
$Ex_{W,in}$	input exergy work
$Ex_{W,in}$	output exergy work
$Ex_{Q,in}$	input heat exergy
$Ex_{Q,out}$	output heat exergy
Ex_{loss}	exergy loss
$\dot{W}_0$	power in idle condition
$\dot{W}$	power consumption
t_{setup}	setup time
D_{avg}	average diameter
l	cutting length
α	cutting speed exponent
β	feed rate exponent
$t_{c.t.}$	change tool time
t_t	tool life
t_c	cutting time
t	cutting life
T	reference temperature
T_0	environmental temperature
A	experimental constant
k	specific cutting energy
$E_{cutting}$	footprint energy
v_c	cutting speed
f	feed rate
v_f	feed speed
L	milled length
p	depth of cut
A	engagement of cutter
V	volume of removed material
N	number of revolutions
η	exergetic efficiency

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m_p	mass of piece
$c_{p,p}$	specific heat of piece
m_b	mass of bath
$c_{p,b}$	specific heat of bath
$T_{in,p}$	input piece temperature
$T_{out,p}$	output piece temperature
$T_{in,b}$	input bath temperature
$T_{out,b}$	output bath temperature
h_b	enthalpy of bath
s_b	entropy of bath
h_p	enthalpy of piece
s_p	entropy of piece
W	work
Q	heat

The number of companies keen to improve their manufacturing activities' sustainability is increasing. Sustainable manufacturing consists of a production cycle that involves social, economic and environmental benefits for entire product life cycle.

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.

The thermodynamic analysis is a powerful tool to support the shift of manufacturing process to sustainability: the state variables there used, in fact, allow to quantify the gaps of processes efficiency with respect to the optimal condition. Descending this analysis is, in fact, a clear detection of the optimization opportunities as well as the recognition of products and processes innovation paths.

The thermodynamic analysis consists of five steps, namely: definition of the system to be analyzed, product and production process analysis, exergetic analysis execution, exergetic efficiency computation and improvements [1].

To perform exergy analysis production process have to be analyzed according to a systemic view: the system are intended as composed of several subsystems, where each subsystem is characterized by a corresponding input and output flows. For each subsystem the amount of exergy destroyed is reckoned with following equation:

$$Ex_{M,in} + Ex_{W,in} + \left(1 - \frac{T_0}{T_{in}}\right) Q_{in} = Ex_{M,out} + Ex_{W,out} + \left(1 - \frac{T_0}{T_{out}}\right) Q_{out} + Ex_{loss} \quad (1)$$

where the term $\left(1 - \frac{T_0}{T_{in,out}}\right) Q_{in,out}$ represents the exergy flow of input and output heat transfer in the system.

Ex_{loss} is the destroyed exergy rate, being its value the objective of the analysis.

A second step of the analysis is to calculate exergy efficiency. Exergy efficiency is defined as the ratio between total exergy in input vs the total exergy in output. This ratio is proportional to destroyed exergy. The general equation adopted to compute exergetic efficiency is:

$$\eta = 1 - \frac{Ex_{loss}}{Ex_{in} + Ex_{W,in} + Ex_{Q,in}} \quad (2)$$

2.Exergetic analysis for machine tools

The exergetic analysis of machine tools is performed by evaluating the exergetic efficiency and the exergy loss with respect to the cutting parameters to reduce the exergy loss. To perform the exergetic analysis in case of machine tools the equation of exergetic balance become [2]:

$$Ex_{M,in} + Ex_{W,in} + Ex_{Q,in} = Ex_{M,out} + Ex_{W,out} + Ex_{Q,out} + Ex_{loss} \quad (3)$$

Where the term Ex_{out} is null because the output mass is the same of the thermodynamic state of the environment

The equation adopted to compute Ex_{loss} is follow [3][4][5][6]:

$$Ex_{loss} = \dot{W}_0 \left(t_{setup} + \frac{\pi D_{avg} l}{f v_c} + \frac{\dot{W}_0 t_{t.c.} \pi D_{avg} l v_c^{1/\alpha} f^{1/\beta}}{A} \right) \left(\frac{T_0}{T}\right) + \frac{k\pi l \left(D_i^2 - D_f^2\right)}{4} + \frac{E_{cutting} \pi D_{avg} l v_c^{1/\alpha} f^{1/\beta}}{A} \quad (4)$$

As shown in the equation (4), the exergy lost is due to the three terms: the first term shows the exergy lost as a result of the power consumed by the machine during the non-cutting operations, while, the second and the third term represent the loss of exergy due to the removal of material and energy footprint of the cutting edge.

To compute the exergy lost in case of milling operations the following equation were adopted:

$$Ex_{loss} = \dot{W}_0 \left(t_{setup} + \frac{L}{v_f} + \frac{L v_c^{1/\alpha} f^{1/\beta}}{v_f A} \right) \left(\frac{T_0}{T}\right) + kpA_e L + E_{cutting} \frac{L}{v_f} \frac{v_c^{1/\alpha} f^{1/\beta}}{A} \quad (5)$$

3.Case study

A real industrial case example is considered here to have a test bench and explain how the exergetic analysis may allow to guide the implementation of I4.0 approach. The company in object is "Brovedani S.p.A." located in Bari -Italy. The company is specialized in manufacturing of mechanical components for automotive. In particular, for the sake of simplicity, the study was focused only on a critical product (the piston used in the rear brake calipers). The piston undergoes several mechanical machining (turning, milling and grinding), then an electrolytic deposition of chromium and the final thermal treatment.

Fig. 1. Rear brake caliper piston.

The cycle is made by Brovedani in compliance with the OEM specifications in accordance with the technical drawing. The activities managed by Brovedani are as follows: roughing of the outer diameters (turning t1), the upper and lower facing (turning t1 and t2), roughing throat (turning t2) and the internal chamfering (turning t3). The milling step involves the machining of the slots on the piston head. The milling operation can be decomposed into six substeps: four related to the realization of the slots (t1, t2, t3, t4) and two for burr removal (t5, t6). The grinding is performed to finish the diameter at a given level of surface finish. This latter process is divided into three intermediate steps: roughing (rough grinding wheel), semi-finishing (semi-finishing grinding wheel) and finishing (finishing grinding wheel). Chrome plating operation consists of the electrolytic deposition of chromium and consists of nine steps performed in nine electrolytic baths: electrolytic degreasing, two washing stages, chromic attack, chrome plating, chrome recovery, three final washing steps. The above mentioned machining steps represent the sub-system of the exergetic analysis. The dehydrogenation process allows the removal of hydrogen absorbed during the electrolytic process due to the loss of mechanical strength and brittleness for working metal. In the dehydrogenation furnace parts are stationed for about two hours at a temperature ranging between 200°C and 250°C. The dehydrogenation step is represented by two sub-systems, the heating and the cooling one.

4. The exergetic analysis as a model for Industry 4.0 implementation

The thesis here sustained is that the outcome of the previous exergetic analysis is an excellent guideline to set up an informational flow and thus to set up a smartness model for the transition toward the I4.0 paradigm.

The exergetic view of manufacturing processes allows to recognise the critical sub-systems from the informational flow point of view: this fact is rarely considered in the existing scientific literature, provided the informational flows are typically tied to physical layout or logical operational flows. Provided the industry 4.0 paradigm relies on the use of sensors for the acquisition, processing and analysis of data, the most critical point is the definition and selection of a complete set of parameters in order to effectively control manufacturing processes. The functional view of the process provided by the exergetic analysis thus permit to recognise the sensorization path of the industry 4.0 paradigm. In principle, in fact, exergy analysis allows to:

- Identify the scenario of operation of systems under analysis, as well as the choice of products and the related manufacturing process by defining the thermodynamic model of the systems;
- Split the system in different subsystems;
- Draw a detailed representation of the operation of every subsystem under consideration;
- Define the thermodynamic parameters critical to measure for each subsystem;
- Perform an exergy balance of each subsystem, providing a critical index based on the exergy loss Ex_{loss}.

The optimization criterion in the exergetic analysis is to minimize the term Ex_{loss}, since the exergy loss is proportional to the generated entropy and this latter is responsible for the less-than-theoretical efficiency of the system. This criterion, in Industry 4.0 implementations, may allow to select the critical subsystems as well as their critical parameters, from which the term Ex_{loss} and the exergetic efficiency depends.
In this way, it is possible to define where, what and why to sensorize, as shown in the figure 2 for the case analysed.
In this case, only the grinding and chromium plating subsystems were recognised as critical subsystems from a preliminary analysis (fig. 4).
The term exergy loss depends (see equation 3) on the variation between input and output of material exergy ($E_{x,M}$), work exergy ($E_{x,W}$), and heat exergy ($E_{x,Q}$). Reducing the exergy loss means to predict process behaviour: it is thus necessary to identify and classify the parameters to monitor within the main, derived and non-controllable ones. The above mentioned parameters for the grinding subsystem (see figure 2) are as follows:

- Main parameters are: $T, T_0, t, \dot{W}, \dot{W}_0, N, t_s, t_{c.t}$
- Derived parameters are: $V_c, f, t_{c,} t_{t,}$ k
- Non-controllable parameters are: $V, A, \alpha, \beta, E_{Cutting}$

In this way for the chromium plating subsystem the:

- Main parameters are: $W, m_B, T_{in,b}, T_{out,b}, m_P, T_{in,p}, T_{out,p}, T_0$
- Derived parameters are: $h_P, s_{P,} h_B, s_B$
- Non-controllable parameters are: $c_{p,p}, c_{p,b}$, chemical composition

Descending from the above parameters, the question is which parameter among those recognised is worth to be sensorized for the industry 4.0 approach. Considering that derived parameters are related to the main parameters and that the non-controllable parameters are useless from a process control point of view, our thesis is that the critical parameters to sensorize to implement a predictive manufacturing are the main parameters of the critical subsystems.
In the following paragraph we discuss the numerical outcomes of the analysis permitted by the two subsystems sensorization.

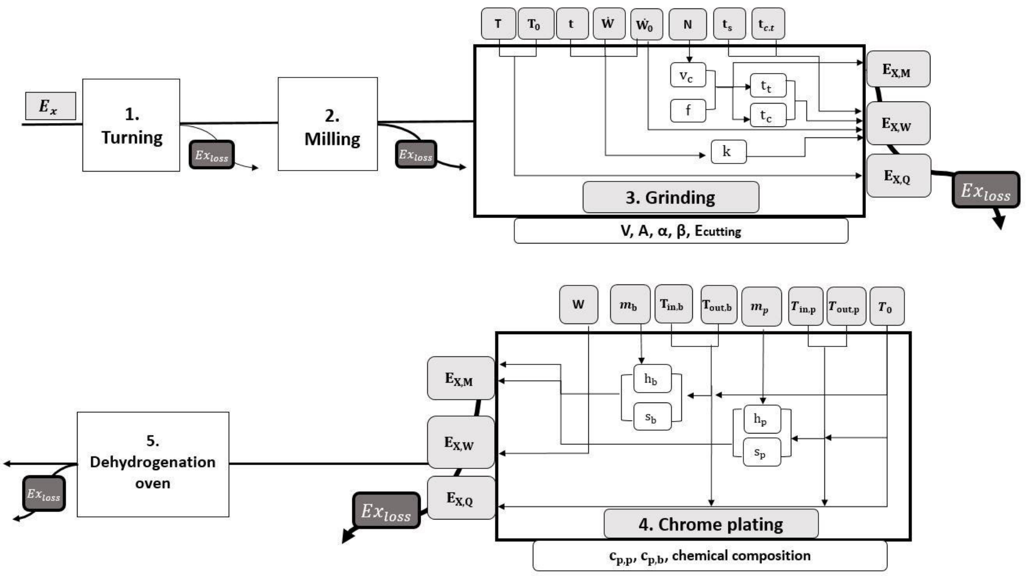

Fig.2 Exergy analysis and the sensing scheme for the case analysed.

5. The exergetic analysis

According to paragraph 3, the manufacturing process consists of five main sub-systems, corresponding to each process step: turning, milling, grinding, chrome plating and dehydrogenation. The on-field information collected from sensors to the scope of intelligent control of the two selected subsystems permitted to predict process performances and also to predict the portion of exergy loss in each of them. The exergetic efficiency of each system was calculated to profile the exergetic efficiency of the plant.

Approach 1

The analysis was conducted in two different ways, to test the informational decomposition strategy of the two process steps (chrome plating and dehydrogenation) and its influence in the exergetic efficiency assessment. Accordingly, this will result significant for the I4.0 paradigm purposes.

In the first way of analysis (approach 1), the chrome-plating plant and the dehydrogenation oven were considered as divided respectively into six and two sub-systems. The data collected (i.e. monitored) for the lost exergy calculation, as well as the exergetic efficiency relative to all the phases of the process, are shown in the following table:

Table 1. Turning parameters monitored (average values)

Operation	Parameter	Value	Tool
Roughing diameters and upper facing	Cutting speed	4,62 m/s	t1
	Feed rate	0,175 mm/rev	
Roughing throat	Cutting speed	2,04 m/s	t2
	Feed rate	0,07 mm/rpm	
Internal chamfer	Cutting speed	1,21 m/s	t3
	Feed rate	0,035 mm/rpm	
Lathe idle power	3,86 kW		
Piston temperature	25 °C		
Heat source temperature	34 °C		

Table 2. Milling parameters monitored (average values)

Operation	Parameter	Value	Tool
Slot realization	Cutting speed	0,49 m/s	t1, t2, t3, t4,
	Feed rate	0,017 mm/rpm	
	Feed speed	1,68E-03 m/s	
Burr removal	Cutting speed	0,55 m/s	t5, t6
	Feed rate	0,07 mm/rpm	
	Feed speed	5,25E-03 m/s	
Milling machine idle power	0,89 kW		
Piston temperature	25 °C		
Heat source temperature	41 °C		

Table 3. Grinding parameters monitored (average values)

Operation	Parameter	Value	Tool
Roughing diameters	Cutting speed	0,38 m/s	RGW
	Feed rate	0,00046E-03 mm/rpm	
Semi-finishing	Cutting speed	0,4 m/s	SFGW
	Feed rate	0,00054 E-03 mm/rpm	
Finishing	Cutting speed	0,4 m/s	FGW
	Feed rate	0,00054 E-03 mm/rpm	
Grinding machine idle power	0,31 kW		

Piston temperature	25 °C
Heat source temperature	42 °C

Table 4. Chrome plating parameters monitored (average values)

Operation	Parameter	Value	Tool
Degreasing bath	T_{in}	298,5 K	
	T_{out}	321 K	
	Q_{in}	322560 kJ	
	Q_{out}	550606 kJ	
Washing bath	T_{in}	305K	
	T_{out}	299 K	
	Q_{in}	463093 kJ	
	Q_{out}	-19295 kJ	
Chromic attack bath	T_{in}	299K	
	T_{out}	312 K	
	Q_{in}	1744416 kJ	
	Q_{out}	153490 kJ	
Chromium plating bath	T_{in}	310 K	
	T_{out}	296 K	
	Q_{in}	444087 kJ	
Chromium recovery bath	T_{in}	297,5 K	
	T_{out}	294 K	
	Q_{in}	431025 kJ	
	Q_{out}	-4354 kJ	
Washing bath	T_{in}	297 K	
	T_{out}	291 K	
	Q_{in}	0 kJ	
	Q_{out}	0 kJ	

Table 5. Dehydrogenation parameters monitored (average values)

Operation	Parameter	Value	Tool
Heating	T_{in}	387 K	
	T_{out}	463 K	
	Q_{in}	758160 kJ	
	Q_{out}	45418 kJ	
Cooling	T_{in}	308 K	
	T_{out}	298 K	
	Q_{in}	0 kJ	
	Q_{out}	246255 kJ	

The temperatures relative to the heating and cooling phases are average values.
Some of the above parameters, such as cutting speed, feed rate, feed speed, has been modified through a multiplication factor for privacy reasons: they still preserve their relative meaning.
For each process operation, the exergy lost and the exergetic efficiency reckoned are reported in the table 6 for a given recording observation time.

Table 6. Exergy values (approach 1)

Operation	Exergy loss value
Turning	1,1572E+04 kJ
Milling	6,3820E+03 kJ
Grinding	3,1960E+03 kJ
Degreasing bath	5,1704E+05 kJ
Washing bath	1,7314E+06 kJ
Chromic attack bath	3,9428E+05 kJ
Chromium plating bath	4,9759E+06 kJ
Chromium recovery bath	6,6568E+05 kJ
Washing bath	1,2103E+06 kJ
Heating	1,6164E+05 kJ
Cooling	6,2659E+05 kJ

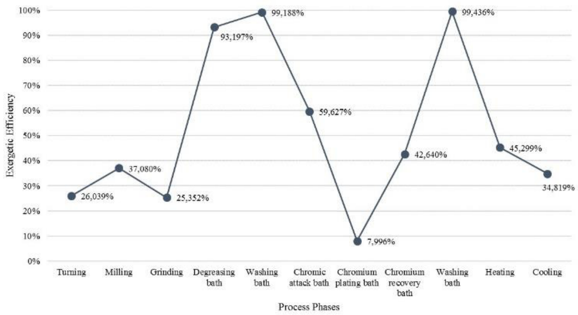

Fig. 3. Performance of exergy efficiency (approach 1).

The analysis highlighted how the chromium-plating bath subsystem has the lowest efficiency (around 8%). This is due to the high amount of heat needed to maintain the temperature.

Approach 2

The exergetic analysis was also performed using another information management strategy by aggregating data coming from chroming subsystems into a single system (treated as a black box); the same was done for the dehydrogenation oven. The number of subsystems thus reduced from eleven to five, corresponding to the number of the process steps.
The purpose of this approach was to proof how the aggregation of the above mentioned information influences the exergetic efficiency performance evaluation.
Different outcome in terms of exergetic efficiency resulted when the chromium-plating plant and the dehydrogenation oven (fourth and fifth macro-system) were not considered as two sub-systems (approach 2), and averaging the relative outcomes. In this latter case, five sub-systems are to be considered, corresponding to five steps of the production process. The exergy lost values and the energy efficiency performance relative to the latter case is shown in the figure below:

Table 7. Exergy values (approach 2)

Operation	Exergy loss value
Turning	1,1572E+04 kJ
Milling	6,3820E+03 kJ
Grinding	3,1960E+03 kJ
Chromium plating	1,5824E+06 kJ
Dehydrogenation	3,9411E+05 kJ

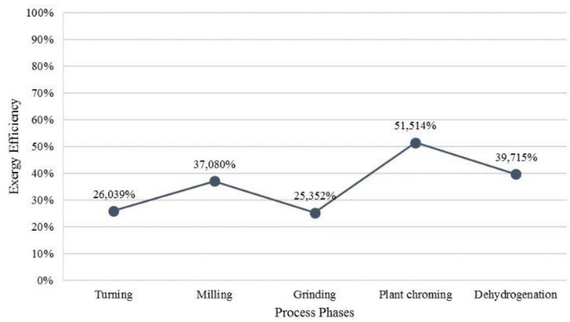

Fig. 4. Performance of exergy efficiency (approach 2).

As the graph in figure 4 shows, the chroming plant –having the lower yield in the first analysis - presents greater efficiency (from 7% to 51.51%). This situation is related to the fact that, by observing the chromium-plating plant as a single black box, no account is taken of the individual mass flows, energy and exergy input and output by the system itself. Similar observations were executed for the dehydrogenation oven in which there was an increase of the overall performance compared to the performance of the subsystem less efficient (from 34,82% to 46,81%).
Considering therefore the chromium-plating plant and the dehydrogenation oven as individual systems, the phase of the process would be less efficient grinding with an about 26% efficiency.
While the first informational approach showed that the subsystem less efficient is the one related to the chromium-plating bath, in this second approach, it is clear that the chromium-plating plant resulted to have the highest yield. This opposite outcome is due to the aggregation of the information coming from the subsystems, neglecting the individual mass flows, energy and exergy exchanged leading to an assessment error.

6. Conclusions

The aim of the present work was to show how the exergetic analysis, while providing a clear view of exergetic efficiencies, is a perfect way of structuring the process knowledge for assuring a correct transition toward the smartness model of I4.0 at job shop level. This was done by referring to an industrial case example.
The exergetic analysis of the individual subsystems provided, in fact, a guideline for collecting information for the control of the production process. The cutting and energy consumption parameters identified for each machine tools, the thermodynamic model built for the chromium-plating plant and the dehydrogenation oven resulted to be key informational elements for the correct control of the core business of the company.
The thermodynamic analysis method, applied to the industrial case, providing the gap from the ideal condition, allowed to identify and recognize the optimization opportunities of the predictive manufacturing based on the appropriate selection of the information infrastructure.
Exergetic analysis for manufacturing processes is, in fact, typically related to the quality of use of resources, with a deeper contextual view of the process. Indeed, the use of state variables, concerning products and processes, allows precisely and objectively quantifying (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.
To a certain extent it is possible to consider the exergetic model of the manufacturing processes a interesting guideline for implementing an information structure for predictive manufacturing. The future developments of the present approach can be to evaluate the sustainability of the I4. paradigm approach designed according to exergetic analysis and to compare with respect to the benefits it may bring with standard I4.0 approaches now under development.

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