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Lifecycle Cost Calculation for Machine Tools in terms of Energy Consumption

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RELATORI

Prof. Ing. Gino Dini
Dipartimento di Ingegneria Civile e Industriale

Dipl. Ing. Karl Doreth
Institut für Fertigungstechnik und Werkzeugmaschinen
Leibniz Universität, Hannover

IL CANDIDATO

Eleonora Geria

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Eleonora Geria

Sommario

Il presente lavoro di tesi, realizzato durante uno stage di sei mesi presso l'*Institut für Fertigungstechnik und Werkzeugmaschinen* (IFW) di Hannover (Germania), è stato orientato allo sviluppo di un approccio innovativo per il calcolo dei costi del ciclo di vita di una macchina utensile connessi al suo consumo energetico. Il motivo di tale ricerca risiede nella necessità impellente, tipica del settore manifatturiero, di rispondere non solo alle esigenze di mercato in termini di progresso tecnologico e riduzione dei costi di produzione, ma soprattutto alle attuali normative ambientali sempre più severe in ambito di risparmio energetico. Il concetto sviluppato, e implementato nella forma di un algoritmo, si pone pertanto come valido strumento per aiutare le organizzazioni a conoscere i flussi di cassa negativi che si susseguono durante l'intero ciclo di vita di una macchina utensile, già nella sua fase di progettazione e sviluppo: attraverso la definizione di uno specifico scenario produttivo, comprensivo di tutti i parametri tecnici ed economici richiesti, il metodo è infatti in grado di esprimere i Lifecycle Cost della macchina in relazione al fabbisogno energetico correlato ai suoi modi di funzionamento e ai suoi compiti operativi, caratterizzandosi pertanto come una soluzione efficace e concreta per una completa valutazione economica d'investimento.

Abstract

The present thesis work, carried out during a six-month stage at the *Institut für Fertigungstechnik und Werkzeugmaschinen* (IFW) of Hannover (Germany), has been addressed to the development of an innovative approach for calculating the Lifecycle cost of a machine tool in function of its energy consumption. The reason behind this research lies in the urgent necessity, typical of the manufacturing industry, of meeting not only the market needs in terms of technological progress and reduction of production costs, but also the current stricter and stricter environmental regulations in the field of energy saving. The concept developed, and implemented through an algorithm, has been proved to be a valid tool for helping organizations in being aware of the negative cash flows characterizing the whole lifecycle of a machine tool, even within its design phase: through the definition of a specific production scenario, including all the technical and economical parameters required, the method is indeed able to express the machine Lifecycle cost in relation to the energy requirements associated with its operating modes and production tasks, establishing itself as an effective and real solution for a complete economic evaluation of an investment.

Institut für Fertigungstechnik und Werkzeugmaschinen

Prof. Dr.-Ing. B. Denkena

Master Thesis

“Lifecycle cost calculation for machine tools in terms of energy consumption”

Author:

Eleonora Geria

Identification number - 2993080

Supervisor:

Dipl.-Ing. Karl Doreth

Garbsen, 31.08.2013

Institut für Fertigungstechnik und Werkzeugmaschinen, Prof. Dr.-Ing. B. Denkena,
An der Universität 2, 30823 Garbsen, Telephone: (0511) 762-25 33, Telefax: (0511) 762-51 15

Abstract

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Written by: B.Sc. Ing. Eleonora Geria
Identification number (Leibniz Universität): 2993080
Identification number (Università di Pisa): 426731

Kenn-Nr.: 13-M 3789 / 5-Do

Due date: 31.08.2013

Supervisor: Dipl.-Ing. Karl Doreth

The continuously increasing technological development and the corresponding always stricter environmental regulations compel organizations to be efficient and effective not only in terms of a good orientation towards the market needs, but also in regards to political and ethical conformity. Manufacturing enterprises, in particular, have faced the imperative necessity to reduce their energy consumptions (especially those relating to electrical energy), and consequentially their costs. This crucial need has led to the development of a good amount of approaches, all addressed to estimate the energetic expenditure of the main actors in production systems: the machine tools. Unfortunately, the actual methodologies are affected by several problems, regarding their complexity and lack of standardization and, most of all, they are not able to directly connect the energy consumption to its equivalent cost. The approach proposed in the present thesis, therefore, is intended to solve this issue, and to provide a valid and appropriate means for estimating all the negative cash flows related to a machine tool during its whole lifetime. The validity of this solution has been confirmed by the results provided by the phases of implementation and evaluation, where some real data have been imported into the model, proving both the algorithm efficiency and the conceptual reliability. In conclusion, given a specific production scenario, the method is able to express the machine lifecycle costs in relation to the energy requirements associated with its operating modes and production tasks, establishing itself as an effective and real solution for a complete economic evaluation of a machine tool investment.

Clarification

I hereby certify that I have written the present thesis without any external help or assistance, and that I have not used any other references except those by me specified.

Hannover, 31.08.2013

Eleonora Geria

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List of abbreviations

Symbol	Description	Unit
AV	Availability	MTTF, MTBF
CM	Corrective maintenance	-
EWH	Effective working hours	WH
HT	Hitch time	-
LCC	Lifecycle Cost	-
MT	Machine tool	-
MTBF	Mean Time Between Failure	-
MTTF	Mean Time to Failure	-
MTTR	Mean Time to Repair	-
OWH	Operative working hours	WH
PM	Preventive maintenance	-
SP	Spare parts	-
TCO	Total Cost of Ownership	-
TVO	Total Value of Ownership	-
WACC	Weighted average cost of capital	-
WD	Working days	-
WH	Working hours	-

1 Introduction

In a dynamic, global and competitive environment, the challenges and risks in meeting and satisfying customer requirements, government regulations and profit goals are several. And this is significant not only in an economic perspective, but above all in the regard of sustainability: to achieve sustainable production, both the aspects of traditional economic results as well as environmental issues must be fulfilled.

Since machine tools play the major role in manufacturing, taking in consideration the progressive dwindling of resources and the resulting rising in energy prices, activities for increasing the energy efficiency of machine tools and production systems have to be set down in order to guarantee productivity, flexibility, cost-effectiveness and ecological respect.

1.1 Initial situation and motivation

Hardly any other topic stirs the German, European and worldwide discussion as intensely, as the question for a sustainable increase of resource efficiency. The world demand for electrical energy in particular has been forecasted to increase by 87% from 2007 to 2035, that is from 18,8 to 35,2 thousands billions of kWh; and in regards to Europe, the amount of electric energy consumptions expected for 2030 has been estimated in 2009 near 3,6 thousands billions of kWh, that is the 24,9% of the European total energy demand. These are really significant values, also considering their impact on energy costs and in particular on electricity prices. The average price of electricity, net of auction payments, is forecasted to increase to 108.4€/MWh in 2020 and to 112.1€/MWh in 2030, a consistent rise compared to current values due to higher capital and O&M (operation and maintenance) costs, and higher fuel and variable costs (the auction payments account for 9.4% of the average pre-tax electricity price). [NEUG11] [FORU13]

In regards to Germany, the electricity consumption for 2030 is expected of 1475 ktoe (that is 17,15 billions of kWh), and considering the actual political plans to abandon nuclear energy in order to embrace the safer and more environmental-friendly solution represented by renewable, some activities to reduce the machine tools energy consumption and to limit the related costs should be developed, especially through some innovative approaches to be applied even at the design phase of the machine tool development process, not only through the improvements of the already existing solutions [ECEU13].

1.2 Objective and purpose

The aim of the present work is to develop an approach to evaluate the Life-cycle costs of a machine tool in function of its energy consumption: through the knowledge of the most likely production scenario to be performed on the machine, and then through the modeling of its power requirement for achieving the production goals, it is possible to estimate the entity of the costs connected to its operative activity, and then its economic impact due to electrical energy requirements. Therefore, considering also all the other costs that are directly connected to the machine tool (acquisition, installation, maintenance, disposal, and so on), and extending the evaluation on its entire lifetime, a general overview of the negative cash flows occurring during its expected life can be derived.

The purpose, in conclusion, is to create the basis for estimating the benefits deriving from energy savings and the consequences on all the other cost components, defining in this way a useful and valid tool for helping organizations in achieving production effectiveness, economic success and environmental regulations compliance.

1.3 Method and procedure

In order to reach the goals declared in the present work, and for which the above described approach has been developed, it has been judged important to set down a formalized procedure, intended to guarantee the respect of all the needed steps for achieving the expected results.

The method suggested (figure 1-1) is composed by seven phases: in the first one, a detailed description of the state of the art relating to the existing approaches both for energy consumption prediction and for Life-cycle costs estimation has been presented, in order to delineate the present level of science and technology concerning the matter of study (chapter 2); the second step is the most speculative one, since it deals with the theoretical and analytical expression of the concept, the mathematical formulation of the problem (chapter 3); the third phase consists in the implementation of the concept by means of a computational algorithm (chapter 4); the penultimate step concerns the validation of the concept, through a set of procedures and methods able to determine its conceptual effectiveness and also to prove the algorithmic efficiency of the implemented software (chapter 6); in the end, the criticalities emerged from the performed approach, the conclusion and the outlook for future development and further improvements have been written down (chapter 6 and 7).

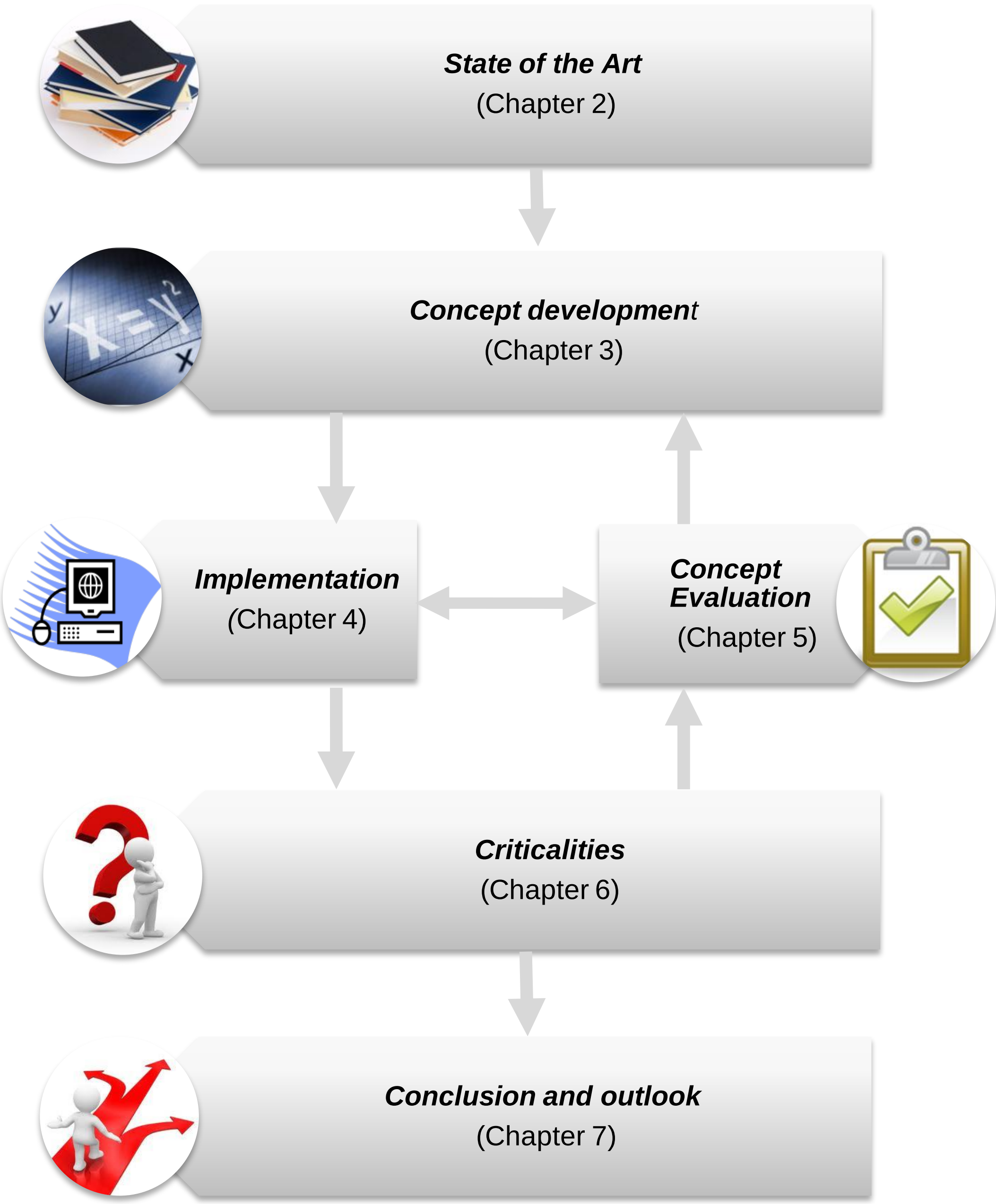


Figure 1-1: Methodological approach

2 State of the art

In order to establish a good balance among all the costs that result from the use of machine tools and to consider also the social and politic regulations on manufacturing systems, some methods have been developed, and they are based both on the assessment of machine tool Life-Cycle costs and on the prediction of electrical energy consumption. This combined evaluation grows out of the proof that costs for the energy of a machine tool, considering all its components, can reach the 20% of its life-cycle costs; then it is consequential the necessity to estimate all the benefits and the drawbacks deriving from the acquisition of a new machine tool, even within the design phase, where the costs for modifying and rearranging the draft are much less expensive than the ones to bear for a wrong evaluation of the production needs, that is for an oversized production system [DENK13].

The aim of this chapter is therefore to outline the existing approaches in machine tools dimensioning, especially in regards to electrical energy consumption and to life-cycle costs: both aspects will be presented and analyzed, and then some considerations and criticalities will be deduced and evaluated.

Nowadays optimizing the efficient use of resources is almost an imperative: quality and flexibility, as well as cost control, are not anymore the only determinants in manufacturing systems. Improper and inadequate decisions in plant dimensioning, so usual in the past, when the costs for material and energy supplies were not so prohibitive to justify such an effort in process planning, have now to be prevented in order to guarantee production efficiency and to meet the increasing demand on environmental impact [ANDE12] [DIET09].

In order to satisfy these requirements, it is essential to evaluate all the components and functionalities of a machine tool: getting a preliminary estimation of their energetic consumption, both independently and within their interactions (for a certain productive scenario), and then using these data in combination with acquisition and operating costs, represents a valid means to find a suitable optimum between productivity and cost regulation [BIAN11].

This impelling necessity in appraising both technical and economical aspects, however, has been not fully translated in a complete and robust method for energy consumption and lifecycle costs calculation: existing models are often complex, hard to parameterize, focused on specific energy, or not integrated with all the other costs affecting the machine tool effectiveness [DENK13] [AIZE12].

For this reason, a separate description of the state of the art will be illustrated in the next paragraphs: first, methods relating to the forecast of electrical energy consumption will be investigated and analyzed; and then an overview on the actual approaches for life-cycle costs quantification will be depicted and examined.

2.1 Existing models for energy consumption calculation

As already mentioned, at present the research community and industry cannot rely on the availability of a concrete and stable method of calculating the energy need for machining a certain product or material: urgent and glaring is the necessity to establish a univocal correspondence between the machine numerical control instructions and energy requirements in processing, so to make process planners capable to elaborate and select the minimum energy machining strategies [AIZE12].

2.1.1 Norms and regulation for energy consumption

Although such an efficient model has not been fully developed, some important norms and regulation have been drawn within the last years, in order to manage and balance the energy consumption with the production quality requirements and the environmental warnings.

These relate to:

– ***ISO 20140*** *"Automation systems and integration – Environmental and energy efficiency evaluation method for manufacturing system"*: it consists of five parts, each one dealing with different aspects of the evaluation procedure [DORN10]:

1) general principles illustration;
2) guidelines description for the application of the procedure;
3) definition of the model for environmental indexes (e.g.: energy efficiency for manufacturing systems index);
4) specification of the data required to the model (e.g.: manufacturing machine/facility, tooling, energy, materials, product, process plan, and production plan data);

5) and, at the end, definition of the facility life cycle impact and indirect impact on the environment.

- ***ISO 22400-1*** *"Key performance indicators for manufacturing operations management"* is the first part of the four constituting the entire standard (ISO 22400 *'Manufacturing operations management —Key performance indicators'*) and describes a "*conceptual overview of an industry-neutral framework for defining, composing, and using key performance indicators that are intended to provide the business domains of an enterprise with a decision support mechanism to manage the manufacturing operations domain of the enterprise*" [ISOW10].
- ***ISO 14955*** *"Environmental evaluation of machine tools"* is a standard in preparation, composed by four parts, which are forecasted to be completed and officially published non before 2014. It is a very demanding but innovative and crucial norm, since it will put the basis for a better management in the use of electrical energy for industrial purposes, and for the creation of a precise and formalized contract system, able to handle and control the energy consumption in a real accurate and demonstrable way [TECH13].
  The standard is so composed [WEIS11]:
  1) ISO 14955-1 "*Eco-design methodology for machine tools*": it deals with the description of the focus and the definition of a standard metal working machine tool, not only in terms of components, but above all of functionalities and operating states.
  2) ISO 14955-2 "*Methods of testing of energy consumption of machine tools and functional modules*": it aims to identify the proper measurement unit for each type of machine tool (previously defined within the application of ISO 14955-1), detecting all the energy flows that govern the machine operations.
  3) ISO 14955-3 "*Test pieces/test procedures and parameters for energy consumption on metal cutting machine tools*": it is not yet outlined the content, because it depends on the conclusions drawn from the first two parts. Then, until the drafts are completed, the third part of this standard cannot assume a defined and precise profile.
  4) ISO 14955-4 "*Test pieces/test procedures and parameters for energy consumption on metal forming machine tools*": it is not yet defined as well. On

the basis of what will be stated at the end of part 1 and 2, then this section will be written down.

- **Ecodesign Directive 2005/32/EC,** sometimes known as EuP (Energy-using Products) Directive, has been issued in July 2005 by the European Parliament and the Council of the European Union, and has been officially acknowledged in all the EU Countries in 2007. It deals with the formulation of the requisites that have to be taken into account in the design of consuming energy products. "*It contributes to sustainable development by increasing energy efficiency and the level of protection of the environment, while at the same time increasing the security of the energy supply*". It is remarkable, indeed, the choice of this directive title: with 'Ecodesign' the necessity of modeling and developing eco-compatible products is emphasized, considering both their energy impact and other environmental aspects during their entire lifetime, before the products themselves are manufactured and brought to market [OFFI05] [ECEE13].
- ***CECIMO*** *"Self-Regulatory Initiative"* for energy-efficient machine tools (MTs) is a preparatory study launched in 2010 in response to the identification of the machine tools as the major critical product in the perspective of environmental efficacy under the European Ecodesign Directive 2005/32/EC. The aim is to achieve the environmental goals established by the EU, through the implementation of a defined and standard method, capable to identify the most suitable improvements in terms of lifecycle costs, economic and market targets and energy-efficiency best technologies. It is a real challenging objective, since the machine tool sector is characterized by a large variety of different products with different technical parameters and functions (around 400 categories and 2000 models), which can be combined in several specific configurations, also depending on the customer's needs. This means that comparing machine tools with different technical characteristics and adopting the same measures to improve their energy efficiency is somewhat difficult, unproductive and futile, since the same measure could lead to a different performance, and even produce a negative effect on some machines. Taking into account these considerations, the aim of CECIMO is then to implement a standardized methodology based on generic, rather than specific requirements, so to evaluate machine energy efficiency in a more rapid, functional and cost-effective way [CECI13].

- Research activities by the ***CIRP CWG EREE***: CIRP stands for ‘College International pour la Recherche en Productique’: it is a “*world leading organization in production engineering research and is at the forefront of design, optimization, control and management of processes, machines and system*”. It gathers many scientific groups operating in different fields in order to collaborate all together in the promotion of a better living and a good economic development. One of these groups is CWG, ‘Collaborative Working Group’, that is composed by scientists and researchers who share the same passion and interest on a certain topic. It is then in this environment that EREE (‘Energy and Resource Efficiency & Effectiveness’) was born: it aims to identify the technologies and methods that could help manufacturers, and industries in general, to better manage their resources and reduce wastes, especially in the use of energy [CIRP13].
- Research activities by ***CO2PE*** (‘Cooperative Effort on Process Emissions in Manufacturing’): it is a research organization focused on the study and analysis of the effects of manufacturing processes on the environment, in terms of energy consumption and CO_2 emissions. The aim is both to implement a model, or better a methodology, for providing data to be included in the Life-Cycle Inventory (LCI) databases and to improve the machine tools performance, elaborating more efficient design processes in collaboration with the machine tool developers [CO2P13].
- Basic research results provided by the ***Cluster of Excellence – eniPROD*** (“*Energy-efficient Product and Process Innovation in Production Engineering”*): it is a research institution which gathers business experts and consultants, mathematicians, physicians, computer scientists and engineers (then people extremely specialized in different fields and branches) in order to develop a methodology to reduce the demand for energy required in industrial production by 30%. The aim of the research is to obtain an “energy-efficient production”, investigating and improving not only the actual industrial processes, but also elaborating proactive strategies for the decrease of energy consumptions and promoting the use of renewable [ENIP13].

2.1.2 Actual models and methodologies for energy consumption prediction

On the basis of the compulsory and mandatory measures established by the European Union in terms of efficient use of resources, different methods and approaches have been developed to improve and optimize manufacturing systems and processes. The majority of the solutions are addressed both to the increase of component efficiency parameters and to the elimination, or at least the reduction, of less efficient components: this is supposed to be achieved through a meticulous and accurate study of the production system defined for the realization of a certain product (then through the examination of the manufacturing planning processes), and/or the implementation of simulative analyses [NEUG11] [ANDE12] [ABEL12].

In regards to process planning, it has been proved that all the environmental and production improvements could be accomplished not only through the design and development of new technological solutions, but also by the use of more effectual process methodologies. Their impact on energy savings, indeed, is not irrelevant: 22% of the measures adopted to increase resource efficiency in CNC machining is related to the ability of making good decisions during the production planning. If lead times, quality requirements, technical constraints and energy use are evaluated and integrated in the process definition, this would lead to a substantial waste reduction, and then to real cost and time savings. Thus, a better selection of process parameters provides a dual good result: the respect of production needs and the fulfillment of environmental and energy requirements [ANDE12].

In order to obtain such a sustainable production, it is then essential to consider the following process factors [ANDE12]:

- *Cost*, as function of machining time;
- *Environment*, in terms of energy use and emissions impact;
- *Quality*, related to scrap rate and process control needs;
- *Time*, in terms of lead-time, rather than set-up or stand-by time;
- *Flexibility*, as the ability to quickly respond to any changes or evolution in the production needs.

According to these aspects, the process capability is then fairly connected to the analysis of machining parameters of a CNC machine tool: excessive tool wear, chip breaking, vibrations or ineffective lubricant usually lead to the realization of faulty pieces, the intensification of maintenance activities and then to the increase of cycle times and rework, that leads to a consequential increase of waste, and so of energy and resources cost. In order to make it clearer the relation between process planning decisions and machining outcome, the following figure is presented (figure 2-1):

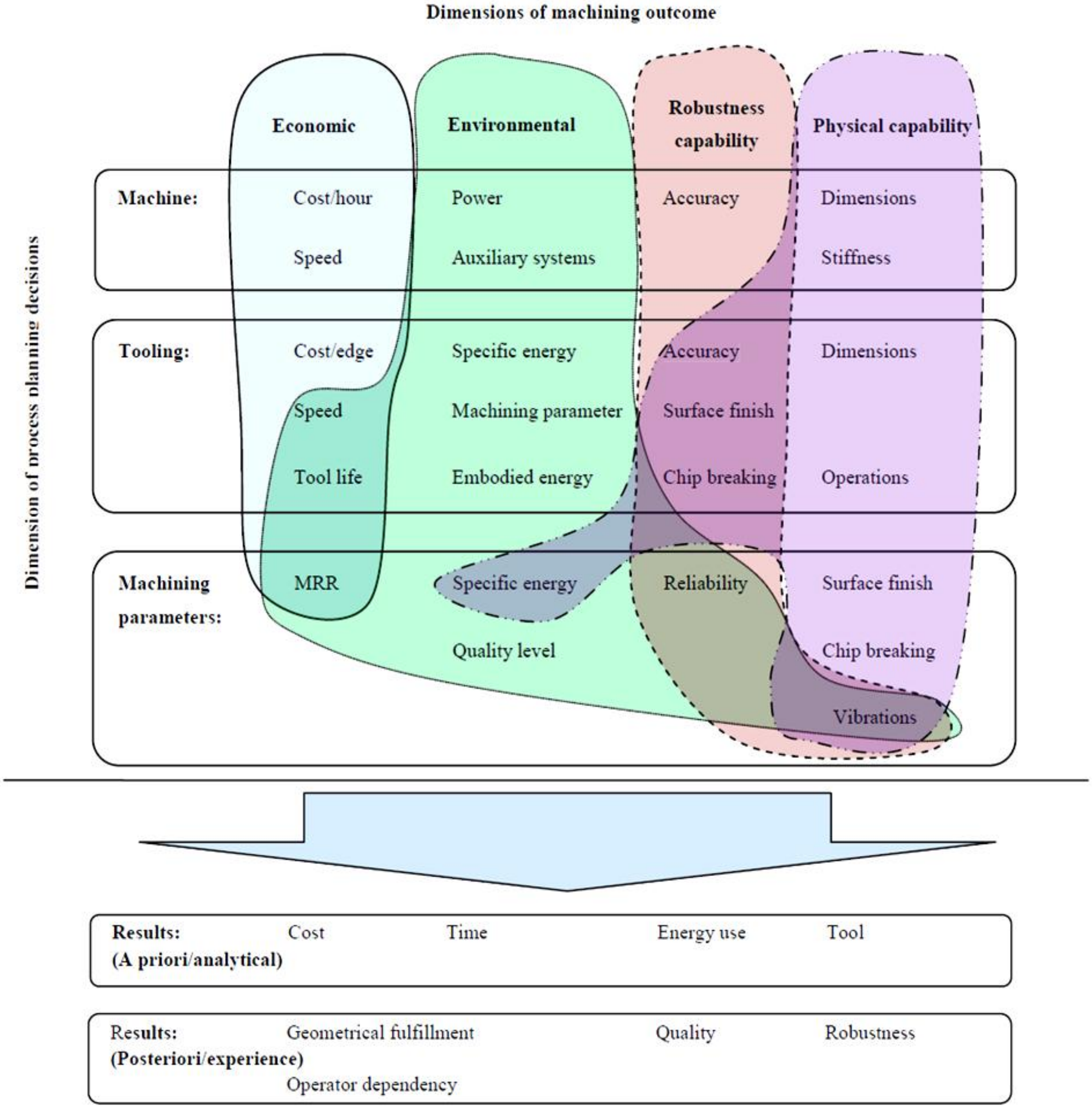


Figure 2-1: Relations between process planning decisions and machining outcome [ANDE12]

It is evident how low process capability can directly affect quality levels and costs in general, as well as having some bearing on environmental aspects [ANDE12].

In order to analytically understand the effect of the machining parameters on the process efficiency, the total energy used by the machine tool and by all its components and auxiliary equipment per volume of removed material is investigated. It is usually considered as “specific energy”, even if the definition of “specific” could be indeed wide. It could be the energy required to allow the actual formation of the chip, and then to remove material; or it could be the energy that has to be provided to the machine for the same purpose; or again, the total energy employed during the entire machining process, and then including also all the activities which do not add value to the product, like spindle start, tool repositioning or piece change. Of course, from an environmental perspective it is more interesting the focus on total energy, so to permit process planners to elaborate and implement a “green machining strategy”: as shown in the picture below (figure 2-2), thanks to a wide, but proper range of information regarding the specific cutting energy, as well as material properties, rather than tool material and geometry, it is possible to enhance not only the process planning, but also the R&D activities, in order to move from a short-term perspective to a long-term one, and then guarantee an healthy and efficient manufacturing system, in line with the aims of resources and energy optimization [ANDE12].

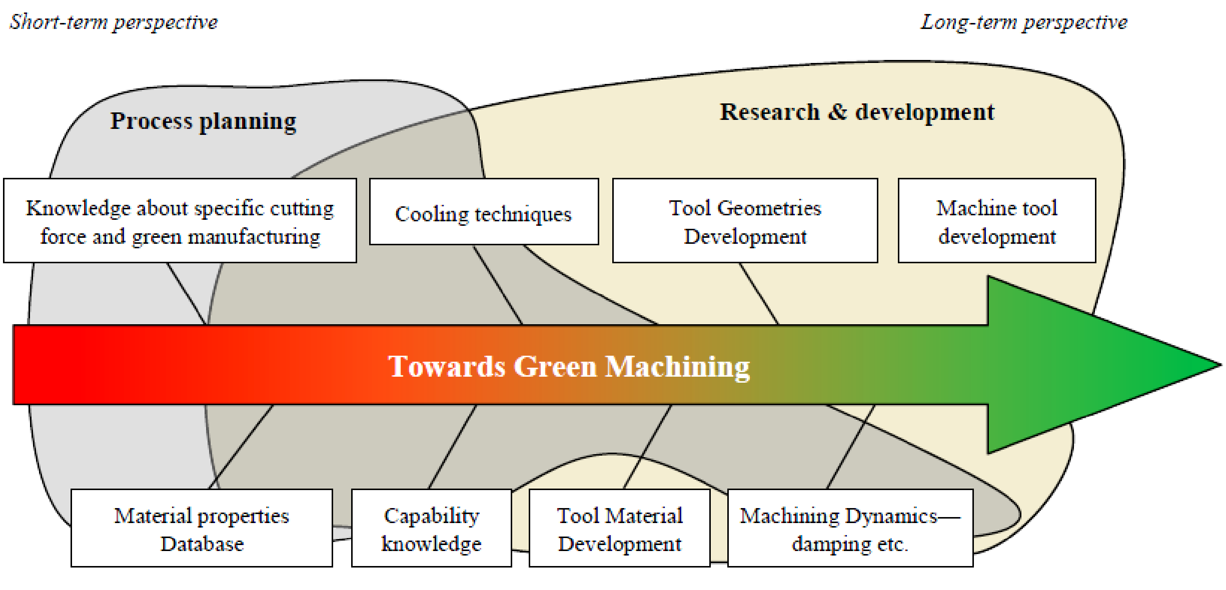


Figure 2-2: A green machining strategy [ANDE12]

In relation to this global vision of machine tools and production systems, also the approach proposed by Neugebauer, Wabner, Rentzsch, Ihlenfeldt is based on the consideration that the most important share of energy consumption in production is due to the complex and articulated dependences among components evaluated at a system level. In particular, the aim is to develop a method for the design of energy efficient production systems, analyzing in details where, and at which level, to implement the activities needed to reach the goal, that is energy optimization [NEUG11].

What is required, then, is a sort of manufacturing and technological analysis, really structured and standardized, in order to recognize the main sources of energy consumption in the process that leads from the definition of a particular product to the configuration of the suitable production system [GÖTZ12] [NEUG11].

Then, the elements that should be taken into account are the following [NEUG11]:

- *Product definition*: not only the main characteristics (like functions and life cycle), but above all the secondary aspects (like material, geometry, dimensions and volume series) influence the production needs, then the technological processes and therewith the electrical power required.
- *Process definition*: it has a direct impact on energy efficiency, since the choice itself of the most adequate process for the realization of the defined product is a matter of trade-off among productivity, cost effectiveness, quality, time and regulations compliance. It is necessary, then, to develop of a good machining strategy which optimizes the selection of the best efficiency measures.
- *Machine tool components*: since they are the direct responsible of energy consumption, both the enhancement of the actual components and the development of more efficient ones is requested to suppliers.
- *Machine tools*: the right choice of good components is not sufficient in terms of energy efficiency. It is in fact important to consider the interactions among them and then to arrange them into an optimal task-dependent configuration, considering secondly all the operation modes and strategies. It would be proper, therefore, to design the machine tools in order to be flexible and compatible with possible re-configurations, so to adapt themselves to different productive scenarios.
- *Production line*: at this level, the machine tool efficiency is considered as a global value, no more divided into all its components, and it is integrated with automation and handling systems, in order to evaluate all the contributions to

energy waste affecting the whole production line. It is then possible to manage idle energy and power peaks through good balance among the resources.

- *Factory*: this level is specifically set to detect all the production relevant elements. At this point it is possible to improve the energetic balance of the entire production system, considering not only electrical energy, but also the thermal losses and investigating the ways to implement an effective use of them.

A synthetic but immediate representation of this procedure is provided in figure 2-3.

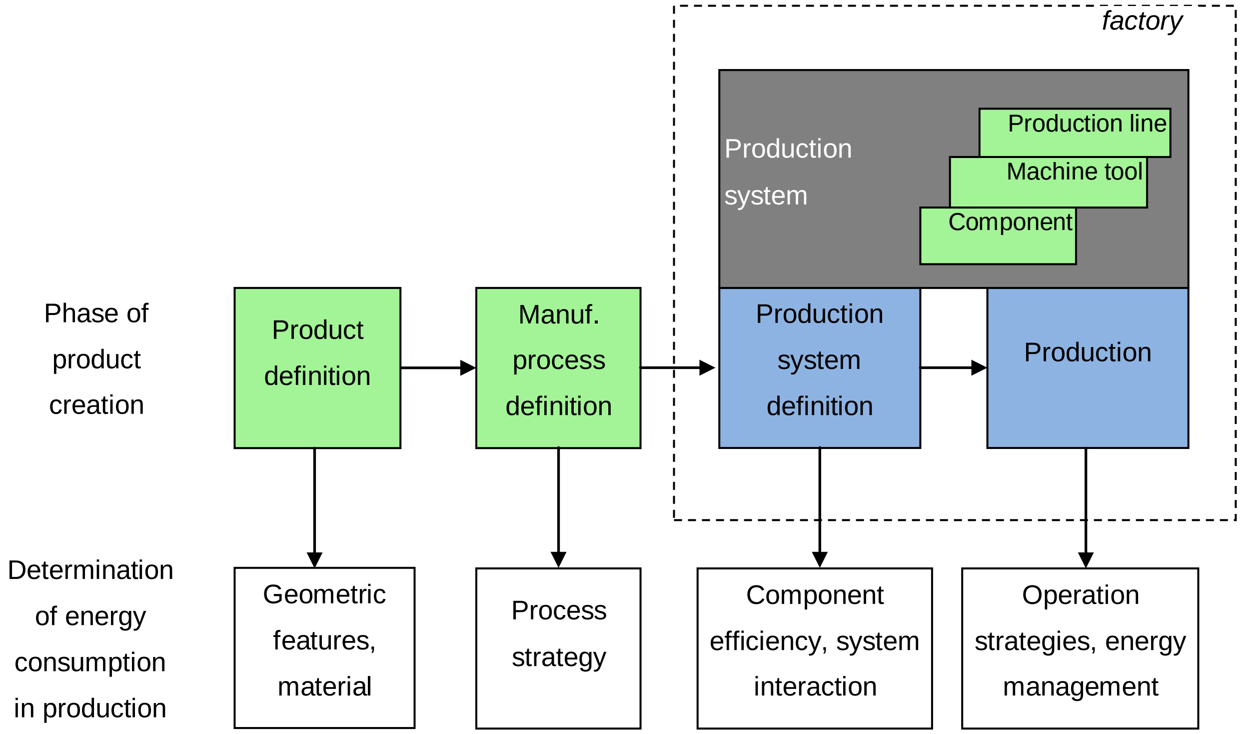


Figure 2-3: Energy relevant aspects in production [NEUG11]

According to this hierarchical portrayal of production system, sometimes it could be arduous and demanding to exactly individuate the main consumers of energy and then to allocate to them the proper share of that consumption. The solution proposed by the authors is then to define the boundaries, or better the interfaces which characterize the production system, that are [NEUG11]:

- The factory, as energy provider (input);
- The process, as energy consumer (output).

The purpose is to delineate the energetic flow in a discrete way, evaluating the actual portion of energy that is transferred to the process, net of losses. In this way it is possible to distinguish the "useful" energy, called primary demand, from the secondary demand and the energy losses [NEUG11] .

The *primary demand* is the percentage of energy needed to accomplish the manufacturing process itself, and then required for the shaping operations (e.g.: speed of the drives requested for the realization of a certain piece) and the process mastering (e.g.: hydraulic performance required to obtain the optimal component cooling). The *secondary demand* is constituted by all the energetic contributions which do not add any value to the product, nor to the machining process itself. And they are not only represented by the energy amount requested by the machine tool to simply operate, but also by the so called logistic processes, that are those including the activities of handling and piece clamping, as well as the operations of process control and measurement. Finally, the *losses* are composed by all the energetic dissipations due to the inefficiency of the machine tool components themselves (and they are referred to as load-dependent losses), or to the secondary systems (load-independent losses) [NEUG11].

The representation of these flows is shown in figure 2-4.

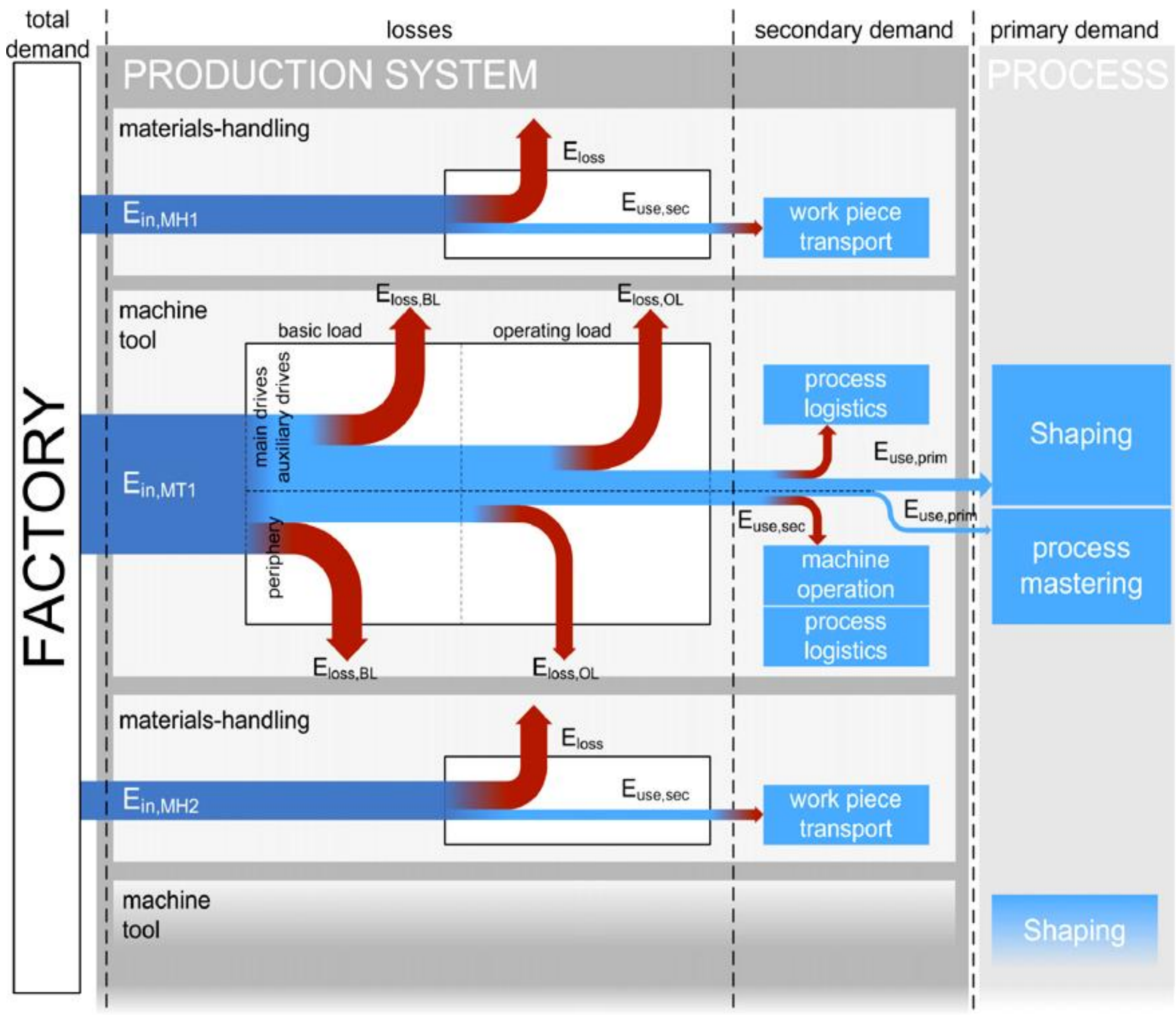


Figure 2-4: Demands, losses and interfaces on production system level [NEUG11]

It is then evident how of the total amount of energy provided by the factory, only a little percentage is used to satisfy the primary demand. Consequentially, the efficiency of the whole production system is unsatisfactory in its turn, since it is expressed as the ratio of useful energy to the total energy demand [NEUG11]:

$$\eta = \frac{E_{useful}}{E_{total}} = \frac{E_{useful}}{E_{useful} + E_{seconday} + losses} \qquad (2.1)$$

Where:

- E_{useful} is the energy required for satisfying the primary demand;
- $E_{seconday}$ is the energy required by the processes necessary for the machine working, but which do not directly contribute to the shaping of the piece (such

as handling and clamping operations, control and measurement activities, etc.);

- $losses$ are represented by the waste of energy due to the inefficiency of components or process (such as friction, damping, electrical losses, flow losses).

The conclusion drawn is that energy optimization can be achieved through the enhancement of the system efficiency, in particular through the reduction of the secondary demand and of the influence of components and system on losses [NEUG11].

Consequentially, efficient machine tools are the result of the designers ability to distinguish between component optimization and system optimization: the first one in fact can be achieved by the implementation of more efficient components on the machine; the second one, instead, is more complex and requires a further effort in the analysis of the several solutions and principles existing to increase the overall efficiency. Some of these relate to: robustness; “adaptivity”; stiffness; the good trade-off between multifunctionality and specialization; and mobility, intended both as general transportability of the machine to the specific site of production, and as the ability to place the machinery on the work piece, instead of the traditional placement of the piece inside the machine [NEUG11].

Especially these last aspects are truly interesting for an energetic evaluation. The dimension of the workpiece, indeed, is a crucial parameter for the machine sizing: as much bulky the piece is, so much large the workspace has to be dimensioned. And this has a direct effect on energy consumption, because it implies the necessity to install an higher power to accelerate components which are heavier than those actually and theoretically needed. The result, therefore, is an oversized production system, which is always, under every point of view, a source of resource waste and sub-optimization [NEUG11].

In regards to transportability, instead, the main effect produced by large machines and facilities lies in the more expensive production and maintenance activities. Small machines, indeed, can simply be transported to the facility location for processing or machining a certain component, drastically reducing the facility downtime, because nor the transportation of the piece to another service point neither possible intermediate storage (buffers) are longer needed. Moreover, if the machining is realized on built-in components, then even the activities of assembly and disassembly are reduced to zero, as plainly shown in the picture below (figure 2-5) [NEUG11].

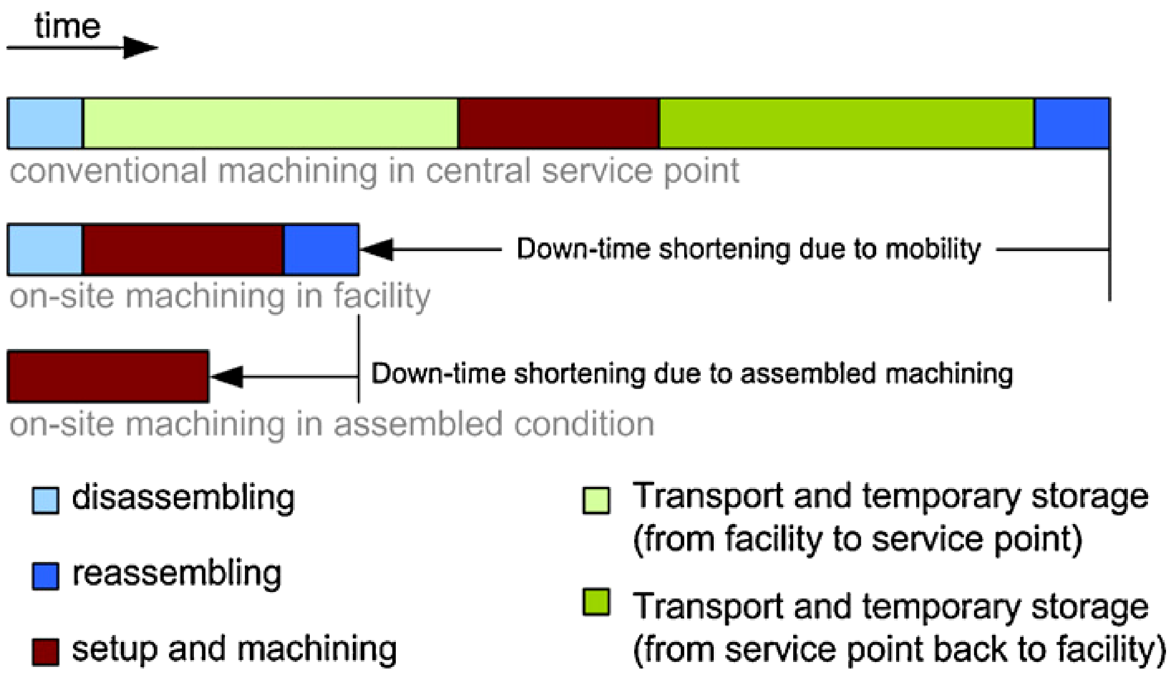


Figure 2-5: Downtime shortening through on-site machining (qualitative display) [NEUG11]

At the beginning of the paragraph, two guidelines for the prediction of energy consumption have been introduced: the investigation of manufacturing process planning and the simulative analysis. In regards to the second one, different models have been developed, aiming at reproducing in a virtual environment the behavior of a machine tool in the use and management of electrical energy. With the data related to the measurement of energy consumption, indeed, it is possible to detect which components of the machine tool are the main energy consumers, and in this way a prioritization of the actions to be implemented for enhancing energy savings, and thus the machine efficiency, can be set down [GÖTZ12].

The simulative analysis is therefore a valid means to identify and assess different design alternatives of a machine tool, also considering the impact of the most energy-efficient solutions on the operational costs, and then comparing the technical parameters with the economic implications. Moreover, the real advantage of simulative models is the opportunity to analyze all the various configurations through a virtual approach, and then in a time and cost-efficient way [BRAU12].

The method proposed by Götze, Koriath, Kolesnikov, Lindner and Paetzold is based on the evaluation of both technological and cost-oriented aspects and it is combined and adapted to the problem solving procedure (figure 2-6). First, the measurement of energy consumption allows the identification of the major energy flows existing among the machine tool components, modeling in this way the basis for the formulation of the problem (design of more energy-efficient machine tools); secondly, the data are arranged into a simulative scenario, considering different operation times and modes, and so different power requirements (and this step corresponds to the system analysis phase of a problem solving procedure); finally, economic data are imported into the simulative model in order to get a complete and extensive evaluation of the machine tool performance, in terms of both efficiency and effectiveness (evaluation and decision phase) [GÖTZ12].

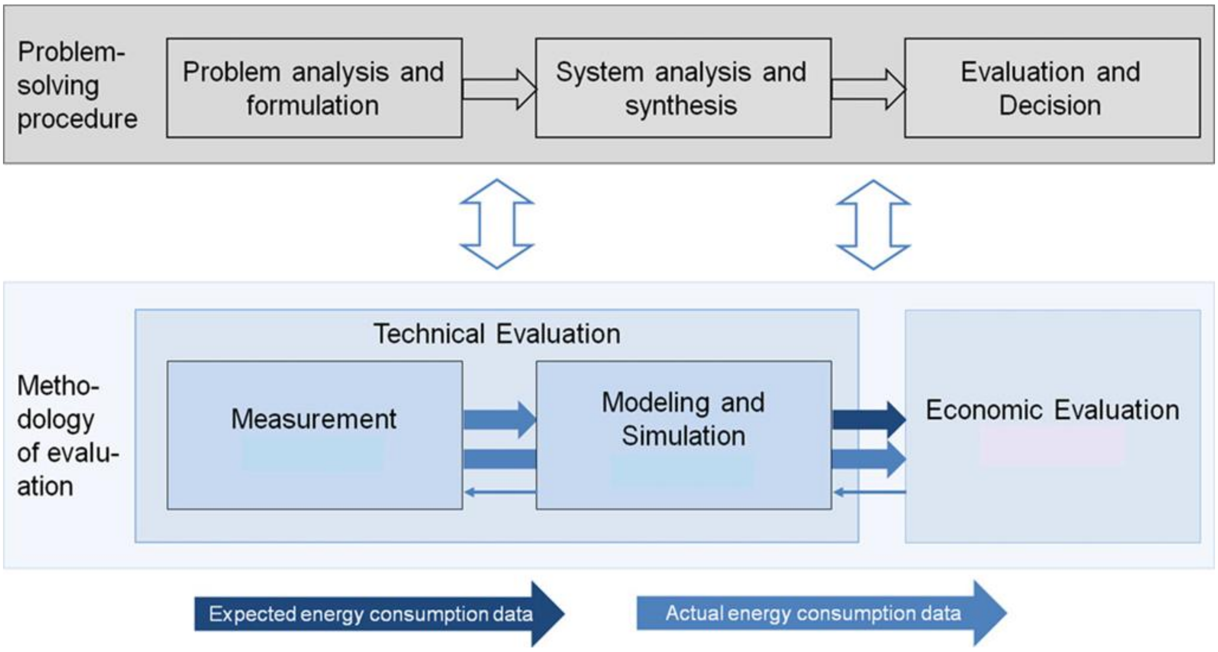


Figure 2-6: Methodology for the technical and economic evaluation of machine tools [GÖTZ12]

Since this kind of appraisal is quite ample and extensive, the model is implemented at two levels: the machine tool-level and the submodel-level. The first one considers the machine as a global system to be analyzed in its entirety, while the second one focuses on the technical/energetic and economic factors of its single components and/or relates to the specific manufacturing processes carried out by the machine tool. It is important to underline, however, that this method aims only to the detection of the major energy consumers within the machine tool or the production process, in order to set an energy-reduction prioritization strategy, and it is in no way addressed to the optimization of manufacturing processes or of process time [GÖTZ12].

This methodology has been implemented taking into consideration the energy consumption of a milling machine, and adopting an input-throughput-output (ITO) standard in the modeling of the energy flow (figure 2-7): the input is represented by the energy supplied by the factory; the output is constituted by process energy and energy losses absorbed by the environment; and the throughput is the part of the machine tool system devoted to the transformation and distribution of the energy needed to support the cutting process [GÖTZ12].

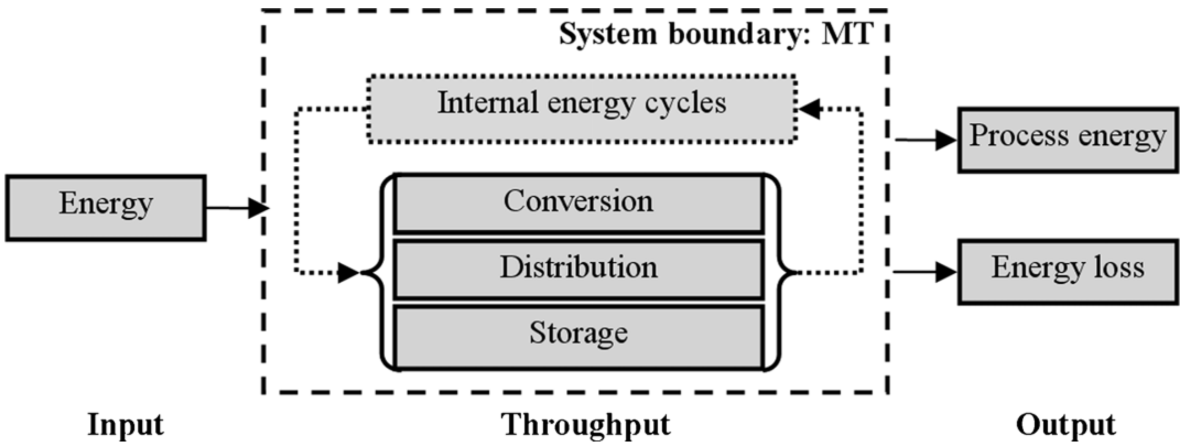


Figure 2-7: ITO-model with boundaries for energetic analysis of a machine tool (MT) [GÖTZ12]

The method presented is therefore based on measured input data, which implies that the machine tool, or better its components, must be physically implemented, effectively built in the machine in order to conduct the experiments and register the measurements. This automatically precludes the possibility to use this method during the development phase of a machine tool, because the components are here not yet accessible, they do not actually exist. Even for the assessment of optimization measures addressed to present machines in an industrial environment this method is not suitable, since it takes a long time to install the measurement equipment and then an onerous expenditure of financial resources .

The method proposed by Eberhard Abele, Christian Eisele, and Sebastian Schrems, instead, allows to estimate the energy requirements of all the different components of a machine tool simply making use of pure simulation models, and then without any need of former measurements [ABEL12].

The model is specifically focused on the optimization of existing machine tools, so it is not addressed to the implementation of new technological solutions. Its main element is the machine model, which only collects simulation models for every individual component and the description of the overall energy requirement of the machine tool. A better and more intuitive explanation of what the machine module is, is offered in figure 2-8.

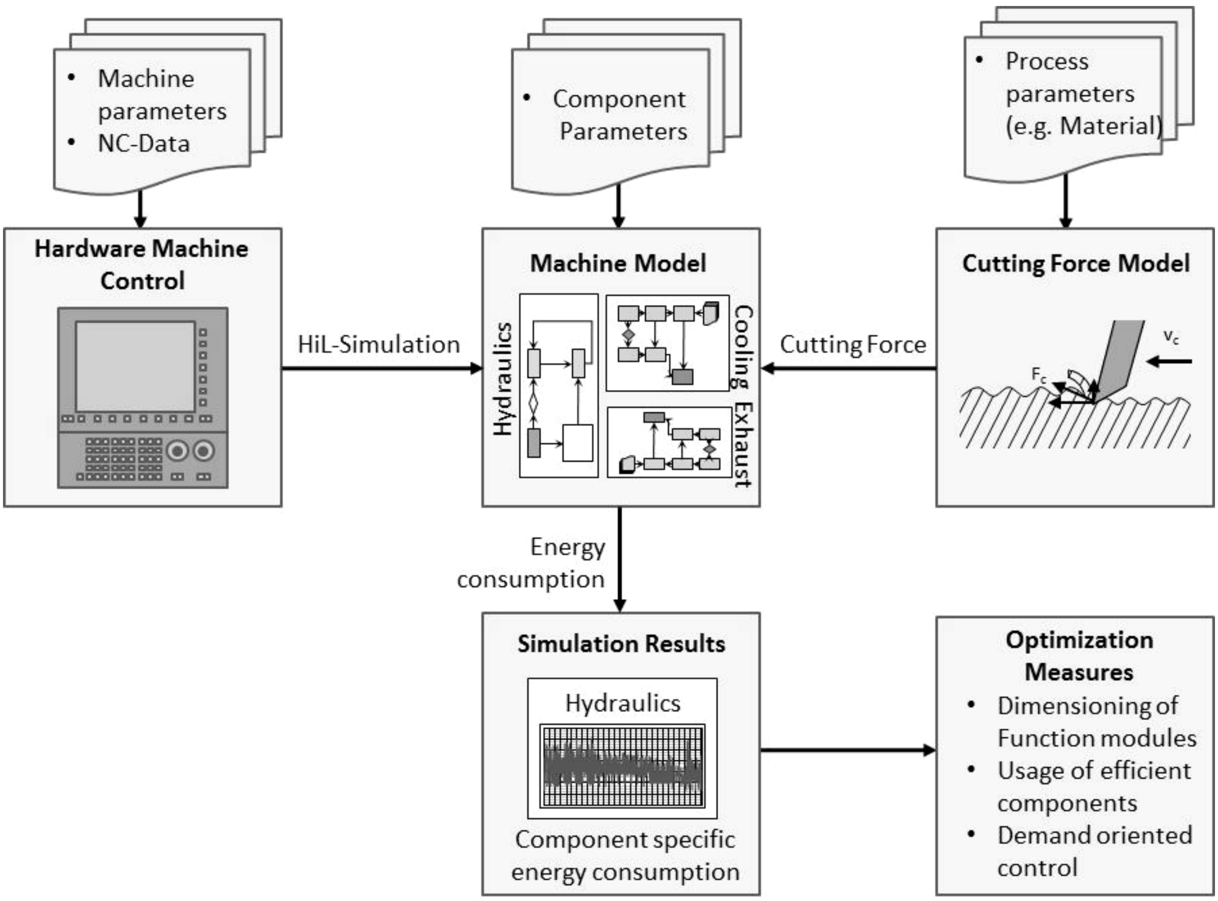


Figure 2-8: Conceptual structure of the simulation of the energy consumption of machine tools [ABEL12]

The simulation environment which characterizes this model, and in which the real machining process is replicated, is implemented through the concept of Hardware-in-the-Loop-Simulation (HiL-Simulation), consisting of a physical machine control which is connected via Field or Profibus to the simulation computer. The bus interface permits the exchange of PLC or NC signals, so that the machine control signals could be coupled with the corresponding simulative scenario, transferring in this way to the simulation computer all the real information about the functions and the behavior of the different components in the various operating condition states. The main advantage of this methodology consists in the possibility to run the NC program for a certain manufacturing process on the machine control, reproducing in this way the real machining operation, in real time, since the data about the axis speed, the movement path and the process operations, as well as the energy consumption of the different components or of the overall machine tool, are already available in the machine control [ABEL12].

In order to have a good estimation of the energy consumption, anyway, it is fundamental to import into the simulation model also the information related to the cutting forces applied in a certain machining process. In this regards, the less expensive, but not less effective way to predict the cutting force is to use empirical models, which express it in function of the width of cut, the angle of cut, the chip thickness and of some other factors relating to the material, rather than to the tool wear [ABEL12].

Finally, the last observation concerns the effectual operation of the simulation model so implemented: this can be verified by evaluating if the result of the simulation matches the real energetic output of a machining process. Actually, some appreciable deviations are noticeable, especially in regards to the machine cooling and the hydraulic system, as shown in figure 2-9.

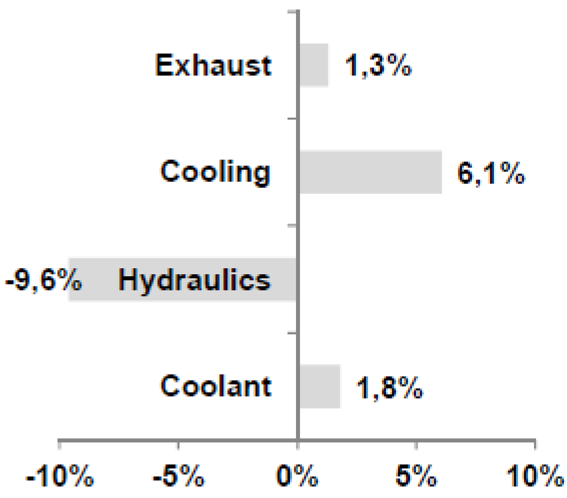


Figure 2-9: Function module specific average deviation of simulation results [ABEL12]

Anyway it has to be said that it is not a deficiency of the simulation model, but of the lack of efficient methods to calculate the power losses in terms of heat transfer, for the machine cooling system; and it is the consequence of the exclusion of the hydraulic oil temperature raise from the simulation model, for the hydraulic system. Then, it is possible to conclude that simulative analyses are quite faithful to the effective behavior of a machine tool in terms of functions, components and energetic consumption, but it is extremely important to evaluate the results obtained in view of the parameters included in the model and of the accuracy level of the analytical formulas used [ABEL12].

It is worthy to note, moreover, that, although simulation models permit to evaluate in advance and in a cost-effective way the impact of different decision alternatives in terms of process requirement and energy efficiency for even very complex production systems, they are sometimes not so flexible in following the continuous dynamic changes which affect modern manufacturing systems. Therefore, it is necessary to optimize the models of simulative analysis, in order to let them consider in their implementation also all the potential variable system conditions and requirements: if new models have to be created every time a change occurs, indeed, the benefits of energy optimization and cost control stemming from simulation would be much more expensive than the actual economic benefits deriving from energy savings. Moreover, it is fundamental not to lose sight of the main goal, that is minimizing the use of energy in manufacturing processes, but without compromising the process quality, and then ensuring performance, stability and robustness in all machining conditions [BRAU12].

In order to solve this problem, S. Braun and U. Heisel of the University of Stuttgart have been working on a project, called “Ecomation Project”, in which they try to develop a modular approach for modeling the machine tool energy consumption, through the use of a scalable generic model structure combined with generic prototypes of typical resources and components, so that each model can be reused adapting it to every different scenario, simply by modifying the parameters in accordance with the measured data. In this way, of course, the accuracy of the simulation becomes quite rough and approximate, since considering the effects of all the variable process parameters in each machining strategy implies the necessity to design pretty simple and schematic models of the process and the machine tool, so to handle and predict the energy consumption in a wide spectrum of alternative operative conditions [BRAU12].

Taking into account the substantial difference between the energy provided during the process (and so devoted to the production of manufactured pieces), and the energy consumed by the machine, the model implemented by Braun and Heisel is structured on two levels: the *Process Model*, in which the cutting force is the parameter used to assess the electrical power required by the spindle and the axes to carry out a defined cutting operation; and the *Machine Tool Model*, in which, instead, the energy required by the machine tool different components, depending on their state and on the process conditions, is calculated [BRAU12].

The simulative environment proposed by the authors is illustrated in the picture below (figure 2-10):

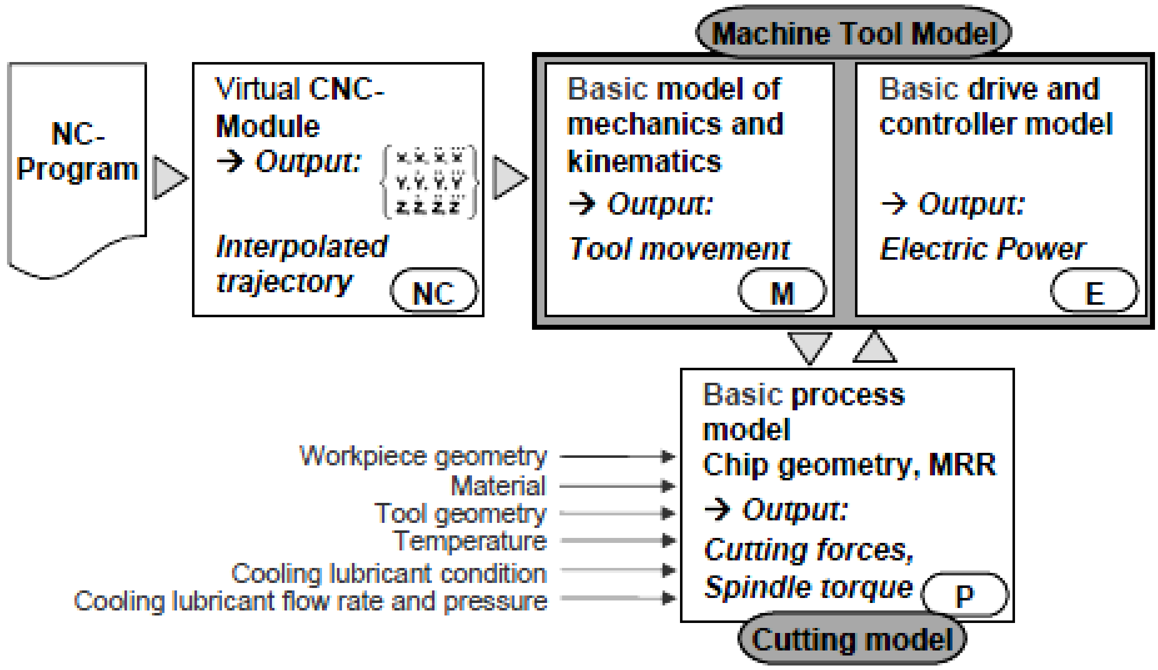


Figure 2-10: Structure of the simulation environment [BRAU12]

2.2 Existing models for Life-Cycle Costs calculation

In the following dissertation, the definition of Life-Cycle costs (LCC) will be presented making no difference with the concept of Total Cost of Ownership (TCO): both the terms, indeed, refer essentially to the economic valorization of all the resources employed not only in the production of a material or immaterial asset, but also in the operating states that characterize its entire lifetime [BUSI13a] [BUSI13b].

Therefore, what is provided by a Life-Cost analysis is a comprehensive depiction of the product economic impact “from cradle to grave”, and the method of TCO evaluates this impact as well, but only in the perspective of the customer’s interests, ignoring the costs for the product design, development and production, since included in the acquisition costs (figure 2-11) [GÖTZ08].

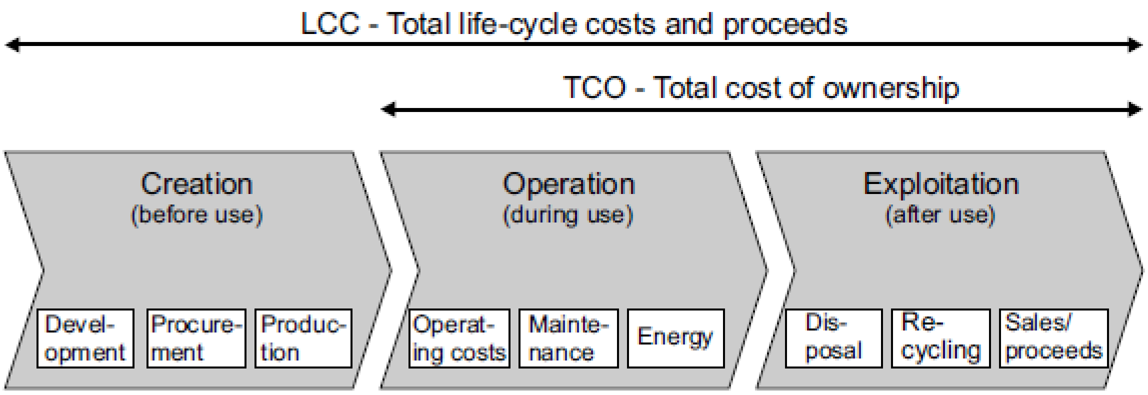


Figure 2-11: Differences between TCO and LCC [GÖTZ08]

2.2.1 Norms and regulation for LCC definition and quantification

As for the energy consumption, also for the calculation of LCC some regulations and norms have been drawn in order to formalize the procedures to be applied and guide the users to a standardized cost quantification. They refer to:

- **DIN EN 60300-3-3**: it represents the most comprehensive description of the elements involved in lifecycle costing and is based on the concept of reliability management. It considers all the direct and indirect costs which are correlated with the reliability of an asset, so to provide a good basis for the evaluation of the convenience of an investment. This standard is then structured into six steps, each respectively related to the concept and definition of a product, to its development, production, installation, operation and maintenance and, finally, to its disposal. Moreover, the data are evaluated not only under a quantitative point of view, but above all qualitative information are taken into account [HOFF11].
- **VDI 2884:2005 - Purchase, operation and maintenance of production equipment, using Life Cycle Costing**: it is specifically addressed to the manufacturing industry, and in fact it provides an adequate guideline both for the customer, to select among different industrial options and alternatives, and for the vendor, in order to develop new technological and innovative solutions. The methodology proposed for LCC calculation is quite detailed, and it offers a very good framework for supporting the decision-making process, also by evaluating the risks connected to the LCC quantification, such as the utilization of unreliable sets of data, and recommending the application of sensitivity analysis. Anyway, an

important defect can be recognized to this norm, which is the lack of a specific example, the absence of a concrete guidance, and then the consequently possibility to misunderstand and badly apply the principles of this standard [HOFF11].

- **VDMA 34160:2006**: it is an engineering-specific standard for the calculation of lifecycle costs, and it is addressed both to the customer (machine owner) and to the seller (machine manufacturer), under the dual perspective of providing respectively a proper aid in the evaluation of capital investment and a marketing tool in the cost estimation and price quotation.

  The total lifecycle costs are represented by the sum of all the cost contributions during the utilization of the machine, from its acquisition up to its disposal, and it is important to underline that VDMA 34160 is the first model to take into account any kind of revenue (given by recycling, rather than by the sale of the asset) obtained in the exploitation phase.

  The model is structured in a way that all the costing elements of each phase (development, operation and exploitation) are systematically subdivided into their constituent parts, except from development, design and production costs which are not included into the analysis, revealing a clear inclination of the norm towards the customer's side.

  The VDMA approach considers all relevant costs (but not indirect ones), based on quantitative data and related to the period under consideration, explicitly defined once again as the portion of the machine's lifetime comprehended between its procurement and the ending of its useful life. The model introduces here a factor of ambiguity, since costs before or after the so defined period should be included only if they "have a cost influence on the service life", but no details are given on how identify and assess this kind of influence [HOFF11].

2.2.2 Actual models and methodologies for LCC calculation

Once presented the standards existing in literature to regulate the lifecycle costs quantification, it is now important to illustrate and describe in details which cost components are supposed to be effectively considered in the definition of Life-Cycle.

In this regard, a valid and significant analysis can be sketched out by distinguishing between the manufacturer's perspective (and then referring to the pure concept of

LCC) and the customer's one (giving more emphasis to the concept of TCO) [EHRL07].

On the manufacturer's side, it is strictly important to quantify the impact of the market requirements and the technical constraints on the realization of a product, and this implies the consideration of the manufacturing costs (material and production), in addition to environment and disposal costs, as well as overheads. The sum of all these factors will lead to the definition of the purchase price for the customer, which represents their first step for the calculation of the costs that they will bear during the product lifetime, and which comprehends one-time costs, as well as operating and maintenance ones (figure 2-12) [EHRL07].

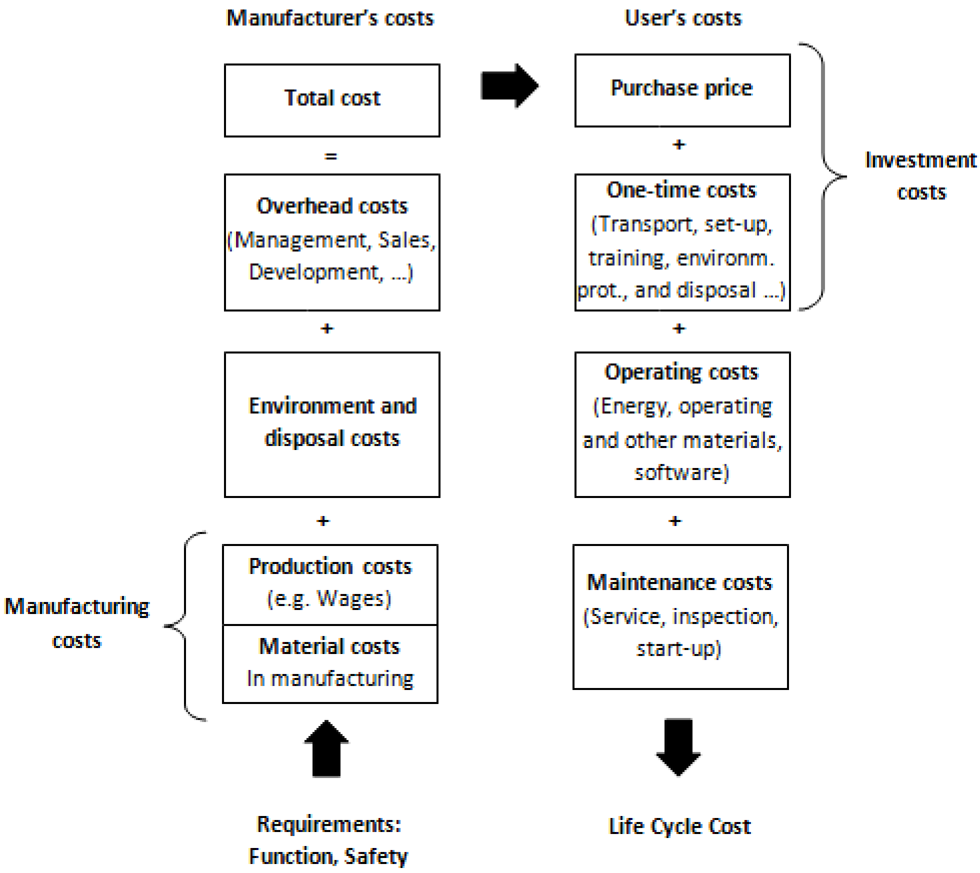


Figure 2-12: Composition of lifecycle costs [EHRL07]

It is also possible to evaluate the concept of lifecycle costs under the perspective of product life span: according to the different phases of the design and development process for the realization and for the future utilization of a manufactured piece, a different and progressively increasing composition of costs will constitute the economic structure of the product in exam, independently from the responsibilities that the manufacturer or the customer have on these costs. In this way, moreover, it is possible to consider the lifecycle costs not as a discrete sum of single costs, but as a continuous domain, to be integrated in time (figure 2-13) [EHRL07].

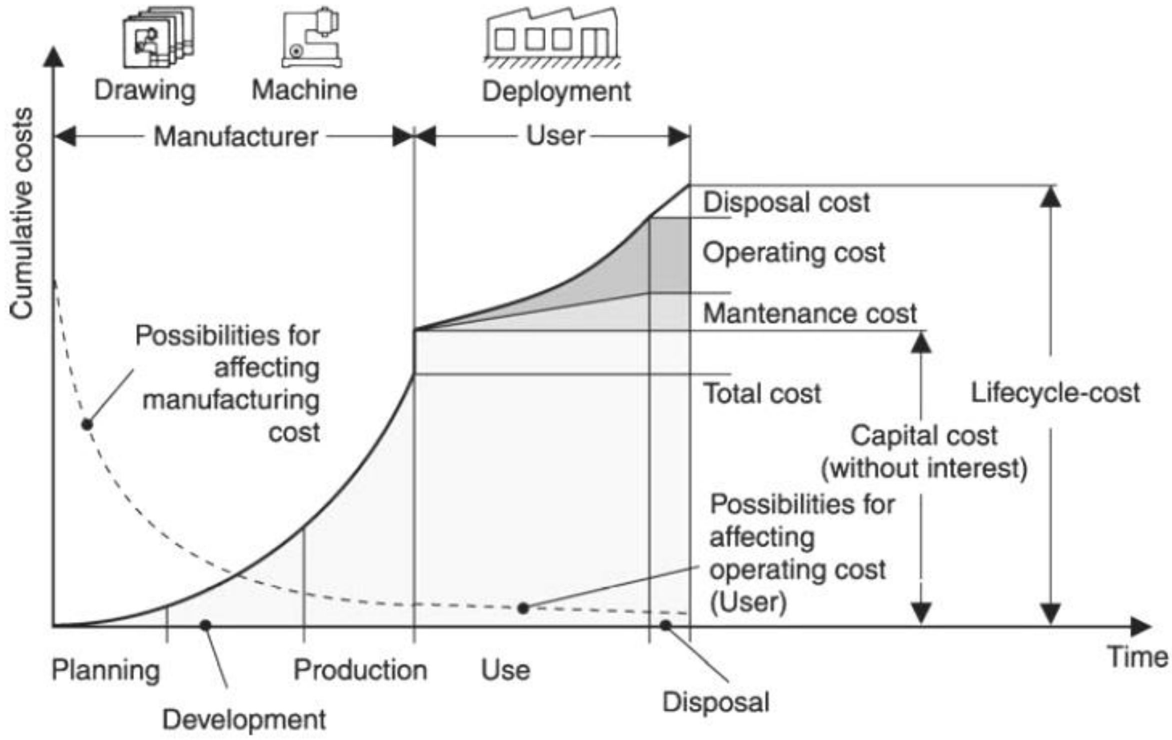


Figure 2-13: Lifecycle costs during the individual product life span [EHRL07]

It is worthy to note, however, that a uniform and coherent calculation for the lifecycle costs is available only in parts: all parties (manufacturer, user and disposer) calculate them according to their individual schema. Particularly in regards of TCO, a common complaint is that calculations can easily become very sizeable and complex, and that is the reason why different methods have been developed or are still in elaboration [WYNS05].

In summary, two are the alternatives mainly applied for the analytical quantification of lifecycle costs: one refers to a monetary-based method and the other one to a value-based method [ELLR95].

The most renowned method is the monetary-based one, which allocates the costs of purchasing a product or service to the different cost components based on real costs. This is often done with management accounting methods (as Activity Based

Costing), and for this reason it is extremely time-consuming, but also very precise and quite easy to interpret [WYNS05].

The value-based method, instead, combines monetary data with qualitative performance information, with the aim, as the denomination suggests, of estimating the value of an offer, and then to consider in the cost quantification also all the parameters that are hard to be expressed in monetary terms, but which are definitely important to valorize the product or the service to be supplied. Therefore, on the basis of non-monetary and historical information (such as vendor-rating scores of several suppliers) a total cost factor is calculated [WINS05].

In the application of one method, rather than of the other one, it is necessary of course to consider both benefits and limitations: when glaring is the need to evaluate the cost of a complex and flexible offer, more suitable is the monetary-based method, though the time for implementing it could be substantial; when, instead, an overall appraisal of the asset, under both merely economic and qualitative point of view is requested, the value-based method is the most adequate, though high is the risk to be too subjective, and then not effective (table 2-1) [WINS05].

METHOD	***STRENGTH***	***WEAKNESS***
Monetary-based method	– Numbers of factors (complexity) can be adjusted to situation; – Flexible; – Useful in identifying cost drivers.	– Time-consuming; – Not useful for straight re-buys; – Not cost effective for small expenditures.
Monetary formula-based method	– Easy to apply after initial development; – Effective for straight re-buys.	– Development of formulas time-consuming; – Formulas need changes periodically.
Value-based method	– Suitable for more qualitative aspects; – Uses the relative importance of existing performance criteria to determine weights; – Easy to use for straight re-buys.	– Development time-consuming; – (Possible) subjectivity in determining weights.

Table 2-1: Comparison of TCO calculation methods [ELLR95]

The quantification of LCC (or equivalently of TCO), however, is not always proper or requested as a practice for the supplier selection and appraisal or as a means to evaluate the economic convenience of an investment for all the types of product. A good selection of the most suitable situations in which this is effectively opportune can be based both on the evaluation of the economic configuration of the product in comparison to the criticality of its procurement; and on the consideration of its life-cost structure [WYNS05].

In regards to the first point, it is possible to utilize the Kraljic's portfolio matrix to detect in which region the product is collocated: a LCC analysis, in fact, is worthy only if it is positioned in the upper half of the matrix, and so if it has a substantial economic impact on the enterprise revenue and, at the same time, it is quite hard and/or risky to be supplied (figure 2-14) [WYNS05].

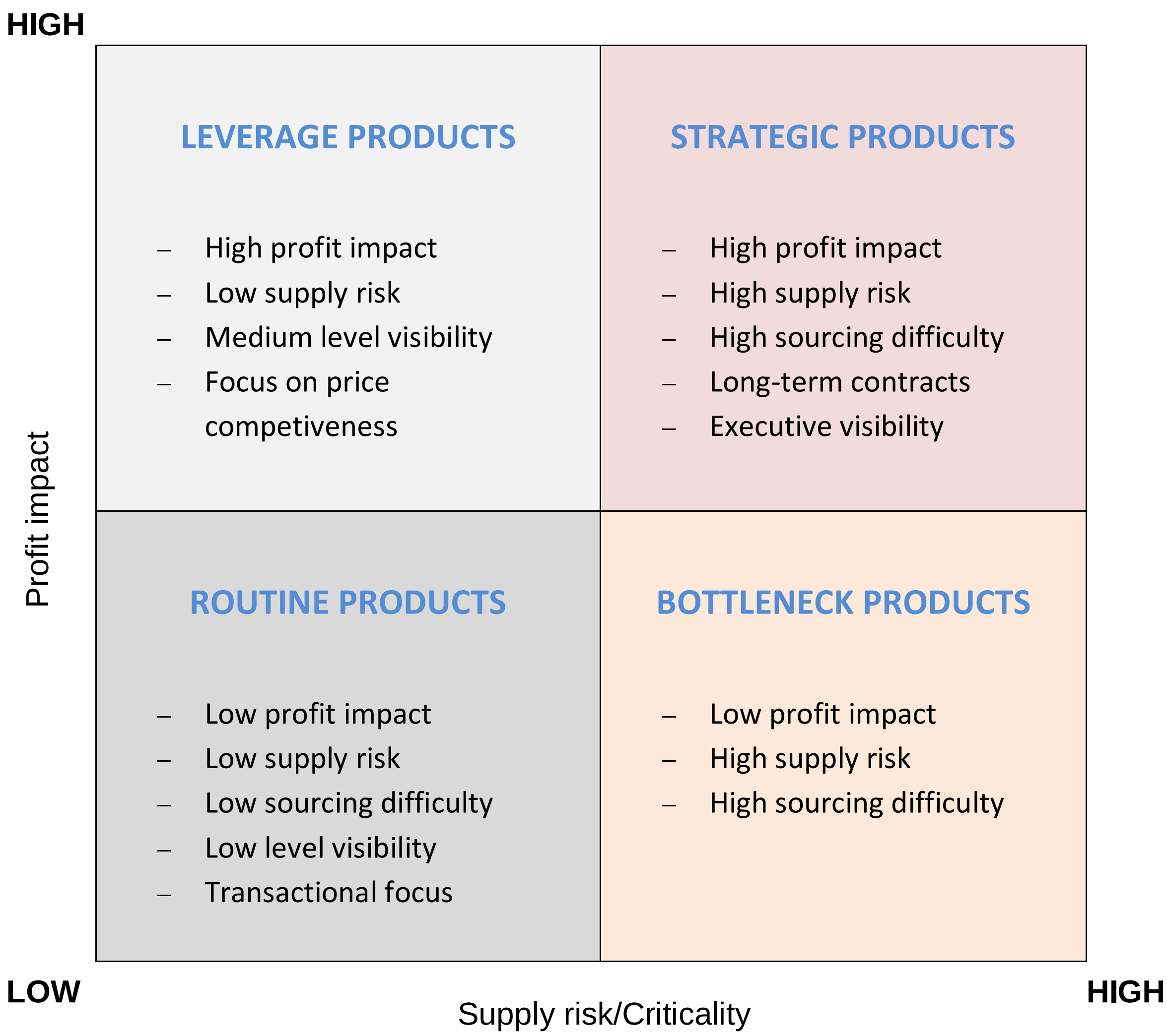


Figure 2-14: Kraljic's Portfolio Matrix [ZVYA12]

On the other hand, it is possible to evaluate which kind of costs effectively affect a certain product, referring of course to its life-cycle cost structure and functionalities. If simple devices in fact, like wrenches or tool, are taken into account, the only cost typology that has to be considered is the initial capital expenditure: no operating or maintenance costs will be incurred during their lifetime. Different, instead, is the assumption if more complex products in terms of functionalities and/or components number are analyzed: for a vehicle, or better a water pumps for example, all the cost categories as acquisition, operating, maintenance and disposal costs are fundamental, and finding the good trade-off among all of them could be a real demanding task (figure 2-15) [EHRL07].

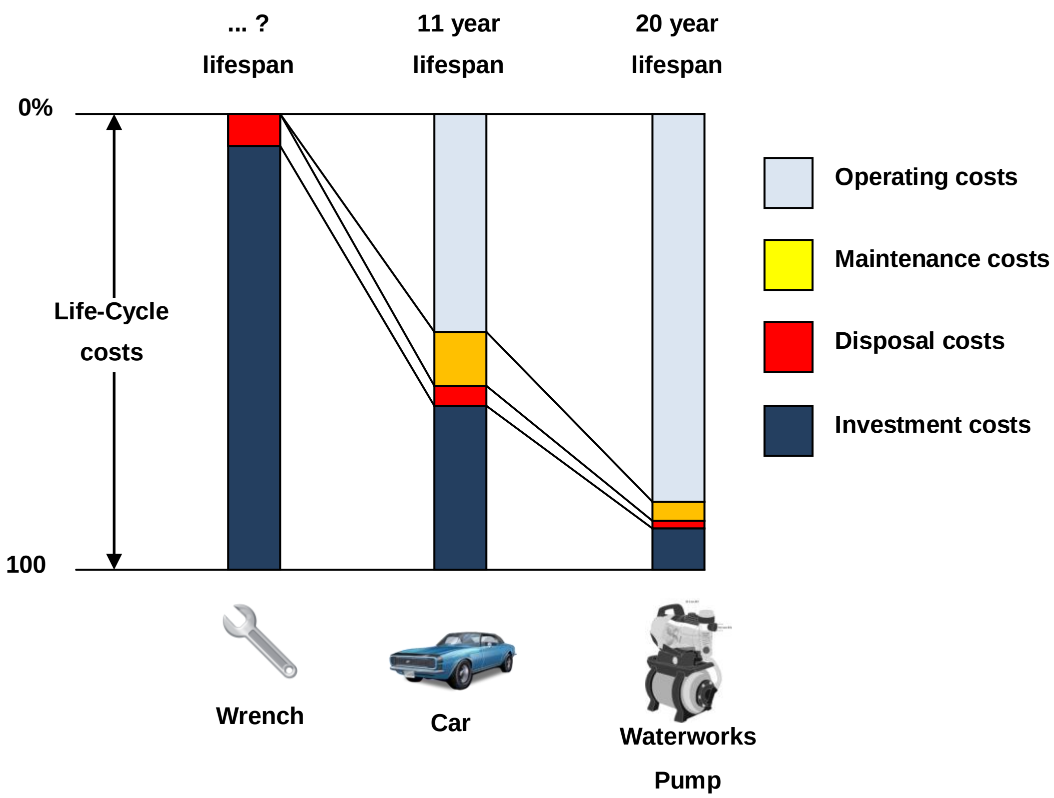


Figure 2-15: Lifecycle cost structure [EHRL07]

Making reference to a water pump, for example, it is evident how the operating costs, which are clearly represented by energy consumption, are the most considerable component of its life-cycle costs. Energy costs, indeed, constitute 96% of the lifecycle costs for a 2000 kW pumping set, with an annual running time of 8000 hours and a service life of 20 years. This implies that a potential buyer should consider the eventuality to purchase pumps of higher initial cost, but with an higher level of efficiency as well: the initial price, in fact, could be even twice bigger than the average market price, if the efficiency were only 0,2% higher, since it would lead to the exactly identical life-cycle costs structure [EHRL07].

Anyway, customers would reasonably switch to a more expensive offer only if the TCO savings are substantial and demonstrable. Some studies concerning the supply process in the United States have proved in fact that purchasers are more susceptible to a higher purchase price than to (possible) cost savings, and this is explainable also in terms of enterprise incentive programs [ANDE00]. As deducible, managers subjected to a system that rewards price savings will be oriented to accept only low purchasing prices; managers who are evaluated instead on the basis of the

TCO savings obtained with their purchasing decisions, will be more susceptible to higher-value investments. Moreover, it has been proved that a reduction by only 2,5% in the life-cycle costs of a product compared to its corresponding current purchase price could be sufficient to accept an higher acquisition cost [WYNS05].

Therefore, there could be different levels of sensibility towards Life-Cycle costs (or TCO equivalently), and this is also reflected in the degree of detail applied to the costs evaluation of a certain product. It is indeed possible to make a purchasing choice on the basis of [WYNS05]:

1) *Just price*, if the product is not complex and satisfies only minimum requirements and specifications.
2) *Intuition*, when aspects other than the price are important and in trade-off between each others, and no objective information is provided in order to evaluate if the cost of the product is then worthy to be paid.
3) *Informality*, if still different aspects have to be considered besides the price, but objective information are available for purchasing decisions.
4) *Ad-hoc*, when the impact of different performances (due to different levels of efficiency of some product parameters) can be calculated on a monetary basis;
5) *Formality*, if an effective process to calculate TCO has been set down and lots of information and precise rules are available for its implementation.
6) *Monitoring*, when the process for TCO calculation is not only active and effective, but regular feedback concerning the TCO of different purchasing items is included and evaluated.

The last point, only briefly mentioned in the previous lines, refers to the consideration of the lifetime of an asset. Indeed, besides the definition of the product type, what is really crucial in the determination of life-cycle costs is the product lifespan. If a car is taken as an example, its initial acquisition cost has a considerable impact only on the first few kilometers driven, but over the long term, it is the fuel, and then the operating costs in general, which dominate in the quantification of LCC [EHRL07].

What is then important to consider before developing any new product are the different cost focal points that characterize its lifetime, since as these focal points change over time, the conception and design of a product could sensibly vary accordingly (figure 2-16) [EHRL07].

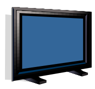
Product		Annual use	Significant cost item		
			Write-off + interest	Energy costs	Service, Personnel costs
	Car	10000 km	●		
		40000 km		●	
	Television	700 h	●		
	Fire engine pump	50 h	●		
	Waterworks pump	8000 h		●	
	PC (business)	1600 h			●
	PC (private)	700 h	●		

Figure 2-16: Focal points of Life-Cycle costs [EHRL07]

In summary, during the product development phase, extremely important is to consider all the parameters that affect life-cycle costs, above all if the customer is disposed to buy an asset, only under the condition that the acquisition costs would be reasonably well proportioned with its functionalities and lifecycle costs. These parameters are the following [EHRL07]:

– *Product type,* referring also to the quality and quantity produced (e.g., single unit or in series production);
– *Design principle,* consisting in the evaluation of the most suitable working principle (as mechanical, hydraulical, electrical) for the specific product (mechanical transmissions, for example, are more efficient than hydrodynamic ones);
– *Product use,* referring to length of use, life span and environmental conditions (as dirt, corrosive substances, temperatures, etc.);

- *Service and maintenance,* influenced both by users, and by manufacturers or others (e.g., availability of spare parts);
- *Cost structure of the user,* that is considering the boundary conditions in which the product is developed (e.g. automation expense could be not justified if there is low labour in a country);
- *Cost for energy and materials used,* such as fuels, process materials, lubricants, wear parts, etc.;
- *Product life span and reliability,* since long lasting products with corresponding reliability are often cheaper with regard to life-cycle costs;
- *Long-term trends,* e.g., relative increase of service and maintenance costs, of purchase costs, of energy costs, of competition pressure, and so on;
- *Legal requirements, ordinances,* e.g., taxes on cars, oils, inspection and disposal requirements;
- *Time span,* since in general, shorter processes are effectively cheaper (“Time is money”);
- *Price policy* in a sector or with a customer. The actual purchase is often important for monetary or psychological reasons.

Finally, in order to provide a practical guide for the development and implementation of LCC methods, the following table (based on practical experience and aimed at achieving lifecycle target costs) is presented [EHRL07]:

Has the problem been clearly defined? NO

I. Clarify the problem and procedure

a. Plan the **procedure**. Form the **team**. Name the **responsible** persons.
b. Establish the total **lifecycle costs**: profit goal for the customer/operator, economic target from the market. **What is the customer wish?**
c. **Analysis** of similar machines: cost structure according to lifecycle costs and types of costs, influences related to functions.
d. Search for **focal points** for cost reduction. What can be changed? What cannot? Establish **possibilities for cost reduction** with customer/operator.
e. Split up target costs according to types of LCC (e.g., energy and material use costs, wear costs) for functions, assemblies. Divide the task into individual parts.

Is the solution effective and inclusive of all the information? NO

II. Search for solutions

a. **Functions**: fewer or more functions? Function integration of processes, product modules? Function separation (e.g., special wear protection)?
b. **Principle**: other principle (concept)? More automation? More software?
c. **Shape design**: fewer parts (integral design)? Higher reliability? Longer life span?
d. **Material**: less material? Less waste? Wear/corrosion resistant material? Material easier to dispose off?
e. Right **solutions** for each **individual process** of the lifecycle (e.g., set-up, training, operation, service and maintenance, organization of training and service, disposal).

III. Decide on solutions

a. Analysis and evaluation of alternatives: **cost estimation, calculation** (according to types of costs), **testing, experiments**.
b. **Choose one solution**.

Table 2-2: Procedure for a correct Life-cycle cost appraisal [EHRL07]

2.3 Deficiencies and issues of the actual approaches

Although the methodologies developed to predict energy consumption and to calculate lifecycle costs are quite various, distinctive and detailed, some criticalities can be highlighted and recognized under the perspective of both performance and usability.

In regards to energy consumption, it has been illustrated and analyzed the relation existing between machining outcome and process planning decisions: even though this is a good achievement in the comprehension of how machining costs can be influenced and determined, it puts in evidence the subjectivity and complexity of the issue. It is not only a matter of equations and energetic flows dimensioning, but it involves also a considerable amount of parameters and aspects that refer to economic, environmental, market, politic and strategic areas. Moreover, even circumscribing the analysis to the mere calculation of the energetic expenditure, the necessity to clarify which basis should be taken as a reference for the electrical energy consumption measurement has been revealed: specific energy (which is the one to be provided to the machine for removing the material, and then for accomplishing its core task) can be calculated analytically, or using piezo-electric dynamometers directly assembled on the cutting tool holder; but if total energy is taken into account, it is no more sufficient to consider only the cutting process parameters, but also all the auxiliary systems and machinery must be analyzed, in order to optimize the complex energetic dependences inside the whole production system [ANDE12].

Another critical factor is that most of the approaches are focused on evaluating the energy consumption of machine tools in different states, scenarios and operation modes, but always relating to the same present process. What is carried out, then, is the research of the best machine configuration, without an insightful and deep analysis of other manufacturing processes. This means that the actual methodologies are often devoted only to the optimization of the present solution, without considering if the energy consumption can be reduced simply by adopting more efficient technological processes, able to dwindle the process time and/or increase the machine performance [GÖTZ12]. It has been proved, for example, that dry and near dry machining solutions can potentially reduce the specific energy, even if further studies and experimentations are necessary to understand which are the real savings (both in environmental and in economic terms) and the trade-offs in regards to surface roughness problems, tool wear, process capability, and so on [ANDE12].

Finally, what is hidden behind all these considerations and criticalities is the glaring and evident need to have reliable data on the factors that influence the energy consumption as well as on the environmental impact of manufacturing processes. This implies the effective availability of data, the assessment of their quality (in terms of completeness, consistency and time frame), and also the usefulness of their format, in order to be easily and confidently manipulated by experts and machine designers [KELL11].

If the reliability of data is a fundamental condition in order to estimate the energy consumption, it assumes an even more crucial connotation in the definition and quantification of machine tool lifecycle costs. Also in this case the adequacy of information should be evaluated under the point of view of data availability and reliability: if an organization, or better the organizational functions most involved in LCC estimation (as Purchasing and Accounting) have a fairly small amount of available information, it can be difficult and demanding to calculate a complete Total Cost of Ownership; secondly, if the information contained in the data is too vague or imprecise or ambiguous for a correct appraisal of certain cost savings, the confidence will decrease, and consequently also the robustness and coherency of the TCO [WYNS05].

Anyway, although the issue of data effectiveness and plausibility represents a significant constraint, what makes really complex and problematic the implementation of LCC in the evaluation of investments is the lack of experience, familiarity and confidence with this kind of calculation. It has been proved, indeed, that organizations generally do not consider the LCC method particularly difficult or conceptually intricate, even if they often get confused or disorientated in identifying which costs are effectively relevant and worthy to be included in the analysis. Related to this implicit uncertainty in the cost components evaluation, and even leading to further ambiguity, is the fact that the TCO approach is typically project-oriented (ad hoc), and so, even if the logic is plain and clear, the results obtained from different applications cannot be taken as reliable references for a standardized model: each case has its individual cost composition, and then it is quite hard to parameterize the results and make an absolute example [WYNS05].

Beyond these considerations, quite technical and evidence-based, also some psychological and social reasons prevent organizations from adopting the LCC method, especially in the logistic and supply issues: purchasers sometimes do not feel confident in using those methods that undermine their personal position and capability of making autonomous decisions, especially in situations in which higher organizational and predictive skills, more than technical ones, are requested (such as supplier selection and evaluation, and/or outsourcing decisions). Moreover, in order to implement such method, it is fundamental an effective communication system with the financial and accounting department, and this means that, before any attempt of adopting a LCC approach, an evaluation of the effectiveness and adequacy of internal processes is required and recommended, in order to eventually renovate and enhance the crucial relations and dependences between organizational functions [WYNS05].

Another aspect that is rarely considered and partially highlighted is the possible "revenue-enhancing" factor deriving from a particular investment decision, or from the acquisition of a certain item. In fact, since markets change dynamically and competition becomes increasingly fierce, considering only the costs and not the increase of value could be rather erroneous and deceptive: a cost-effective solution may actually be not so successful and effectual in terms of value for the customer. And this is even truer if the market life of a product, and not simply its lifespan, is taken into consideration: it is possible, indeed, to find many other functionalities or alternative uses for a certain item at the end of its lifecycle, simply by investigating and evaluating the potential benefits and revenues deriving from the activities of redesign and restyling (figure 2-17) [EHRL07].

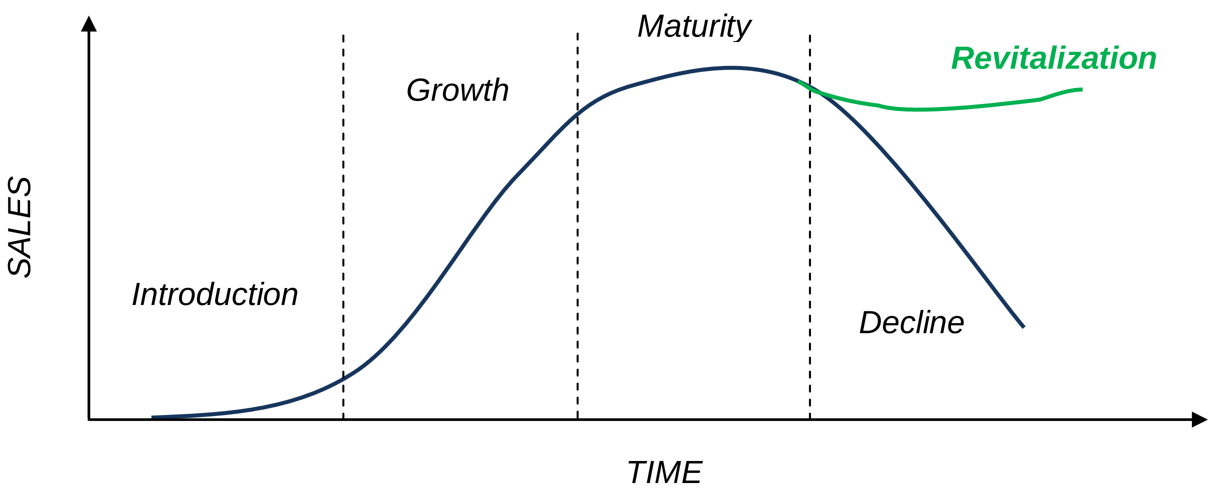


Figure 2-17: Lifecycle and market life of a product

In this way, the perspective and the logic characterizing the described approach change radically: no more the meaning of total cost of ownership, but of total value of ownership (TVO) is proposed and emphasized [WYNS05].
The actual drawback of this proposal, however, is the even more uncertainty and ambiguity connected to its implementation, compared to the traditional TCO methodology: explicitly quantifying the enhanced value in terms of revenues or extra-profits is definitively less direct and immediate than considering the effects of cost reduction [WYNS05].

Finally, the very critical aspect that has been noticed (since it affects the whole literature in general) is that there is no appreciable integration between the method of LCC quantification and all the other methods adopted for the calculation of the costs characterizing every different typology of investment. The lack of precise information related to some operative, technical, economic, or logistic process is reflected in the inability to obtain valid and credible results: taking commercial costs as an example, it is evident the significant difficulty in evaluating them, if no suitable techniques to estimate, for instance, the impact of advertising on a product have been developed. And this is generally true for all the activities and factors affecting costs: energy consumption, resource requirements, IT services, and so on.

2.4 Summary

In this chapter an overview on the actual approaches existing in regards to energy consumption and LCC calculation has been presented. It has been shown as urgent and evident is the necessity to meet the strict legal requirements in terms of environmental impact, as well as the constantly increasing demand of a dynamic and continuously changing market.

The methods concerning the energy consumption prediction have been analyzed in their main representative characteristics, distinguishing between the norms and regulations to be respected in machine tools design for decreasing their consumption and waste in general; and the actual methodologies used for quantifying the energetic expenditure of a machine tool. In this last case, the approaches described refer principally to two different ways of analysing the question: increasing the component efficiency parameters through the enhancement of the manufacturing process planning; or implementing simulative analysis to predict the energy consumption.

In regards to LCC quantification, some norms for regulating and standardizing the procedures to be used as a reference for costs calculation have been presented, as in the previous case. Then, an overview on the actual methodologies for identifying and classifying all the costs to be included in an LCC analysis have been illustrated and commented, referring in particular to the monetary-based and value-based methods, and underlining that the only difference between LCC and TCO lies in the perspective (both that of the manufacturer and the customer).

Finally, for both methods (energy consumption and LCC calculation) some criticalities have been deduced and analyzed, finding that the most significant issue consists in the necessity of a good amount of reliable data and in the lack of integration between the different methods that concur in quantifying all the costs affecting a product.

In the next chapter, a new approach to solve the critical aspects emerged from the actual existing methods will be presented: the aim is to find a direct relation between energy consumption and lifecycle cost, so to develop a unique and distinctive methodology for correlating the impact of operating (energy) costs on the whole economic profile of the machine tool.

3 Concept development for the estimation of a machine tool Life-Cycle Costs

As underlined and emphasized by the conclusions drawn from the analysis of the actual approaches concerning energy consumption prediction and LCC calculation, the evident exigency in finding a valid relation and a univocal analytical connection between these two methods is examined in depth in this chapter. The aim is to develop a single concept that, on the basis of precise input data related to the machine tool energetic expenditure and to economic, enterprise-based and manufacturer-based information, is able to calculate, with a certain degree of confidence, the lifecycle costs of the machine, and then to let the customer become aware of its outflows and of their impact on the final product. This implies the possibility for the user to dimension in advance its manufacturing system, according to its actual production needs, and then it constitutes also a proper reference to support decisional and planning processes.

3.1 Definition of required output data

In order to consolidate itself as a valid means for a well-managed process planning and as a reliable method for energy and lifecycle costs prediction, the concept should be based on the identification of all the relevant costs that could affect the choice of a particular machine tool. It is a really complex and sensitive aspect to exactly individuate the factors that directly impact on the machine (and then on the product), since their erroneous identification would lead to a bad evaluation of the production and economic resource requirements, and then to the eventual decision of renouncing to the investment project.

The machine tool taken as a reference for the concept development is a traditional milling machine, which is supposed to process only one type of material during its entire lifecycle, but in various possible shapes and configurations (assuming in this way the eventuality of planning the production of different batches on the same machine). Moreover, another significant hypothesis for the development of the concept concerns the initial conditions of the customer's industrial plant: the aim is to evaluate its actual performance over time, and so in the definition of the machine tool requirements for lifecycle costs calculation, the same parameters of efficiency and process capability related to the existing machines will be adopted. In summary, the assumption is that any investment for the acquisition of a new machine tool will be carried out respecting the present level of effectiveness and performance.

On the basis of these considerations, the lifecycle costs supposed and required in output have been initially classified in five categories, whose definition and description is concisely provided in table 3-1:

Life-cycle costs	***Cost components definition***
Acquisition costs	They relate to the initial purchase price, perhaps less the resale value, evaluated at the end of the machine lifecycle.
One-time costs	They refer to the costs that the user has to pay only once during the entire machine lifecycle, and they are composed by: a. Transportation; b. Installation and Set up; c. Personnel training; d. Disposal.
Operating costs	All the costs which relate to the operative resources required to satisfy the production needs, and classified in: a. Quality costs ; b. Ongoing costs for energy; c. Supplies (materials); d. Storage costs.
Maintenance costs	They are defined as the resources needed to maintain the intended level of efficiency and performance and to protect the facilities and the equipment from damages and malfunctioning. So they are divided into: a. Service; b. Inspection; c. Reparation; d. Spare parts costs.
Other costs	In this section, all the costs that were not classified into a particular category are considered, and, according to the present purpose, they are only represented by: a. Wages for the operating staff; b. Room rent.

Table 3-1: Lifecycle costs composition

After this first classification, anyway, a general review in order to assess the congruence and coherence of all the cost components identified has been carried out: in particular, what has been analyzed is the effective responsibility of the machine tool on the costs generation.

In this regards the following costs have been excluded from the concept development:

1. _Personnel training_: according to the hypothesis already mentioned about the initial conditions of the customer's plant, the investment in a new machine tool won't involve the necessity of updating the personnel skills, since the new machine will run in the same conditions and with the same operating modes of the previous one.

2. _Disposal_: this voice is in contrast with the resale value proposed in the definition of the acquisition costs. Since the usual practice in manufacturing enterprises is to resell the machine tool (or its single components), according to its residual value, it has been assumed that if this operation took place at the end of the machine lifecycle, then the resale value and the disposal costs would be coincident in modulus, except from the fact that the first is an income (then a positive cash flow), and the second is an expense (negative cash flow). For this reason, there is no need to consider a negative component, when a possible revenue is expected.

3. _Quality costs_: they usually refer to the extra-costs due to the production of faulty pieces, and are generally divided into costs for rework and costs for waste products. They have been excluded from the analysis, since they do not directly impact on the machine operating costs: what has indeed a substantial influence on them is simply the number of produced pieces and the time required for their production, independently from the fact that they are congruent or not with their functional and technical requirements. This aspect, in fact, will exclusively affect the costs per part, and not the machine lifecycle costs as a whole.

4. _Supplies (materials)_: what has been assumed at the beginning for the definition of this kind of costs was the possibility for the machine tool to process some raw materials already designed in a productive optimizing shape, then aimed at reducing the percentage of swarf. For instance, if the need were the one of processing an hexagonal piece, a considerable cost reduction would take place if raw materials with a circular section, rather than a squared one, were supplied

(figure 3-1). Anyway, also in this case, the hypothesis is to keep the same design parameters in the acquisition of a new machine tool, considering also the fact that this kind of analysis notably complicates the model, and is itself subject of further independent studies.

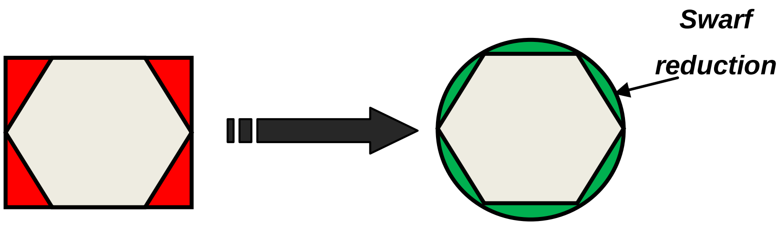


Figure 3-1: Raw material differences

5. *Storage costs*: they generally refer both to the raw materials warehouse and to the end-products storehouse. Their exclusion from the concept is the consequence of their being dependent on the enterprise supply policy, and not on the productive activities carried out by the machine: as already mentioned, the machine is involved only in processing the pieces, independently from the fact that they have been or will be stored for a long or short period. It can be argued, however, that the necessity to hold a considerable amount of products in store is fairly connected to the machine tool capacity of being flexible against rapid changes in the products demand; but it is still a strategic decision that one to dimension the plant on the basis of a certain productive capacity, and then also in this case exclusion of these costs is reasonably justified.

6. *Wages for the operating staff*: as for the other costs already mentioned, also this cost component does not directly affect the machine tool: even if the number of required workers could vary on the basis of the machine functionalities, their wages are anyway established by law and regulated by strict union contract.

Then, at the end of this preliminary review, the costs that will be object of the concept development for the estimation of a machine tool Life-cycle costs are the following:

– *Acquisition costs;*
– *One-time costs (transportation and installation);*
– *Energy costs;*

– *Maintenance service costs;*
– *Preventive maintenance costs;*
– *Corrective maintenance costs;*
– *Room rent.*

A complete and comprehensive definition of each cost category will be provided in details in the next paragraphs.

3.2 Description of machine use and machine states

In order to assess the entity of the costs previously defined, it is essential to define and understand the operative framework in which the machine tool is expected to perform its tasks. This implies not only the need to individuate the different productive scenarios characterizing the machine daily schedule, but also the necessity to define how the production time is managed by the enterprise. What is indeed relevant and significant is the actual amount of hours in which the machine is supposed to run, in order to evaluate in this way also the different operating states which characterize its lifecycle, such as real processing, rather than waiting between processes (the topic will be further analyzed in details).

In this regards, the time model proposed by the norm VDMA 66412-1:2009-10 ("*Manufacturing Execution System (MES)*") has been taken as a reference and adapted to the present context, obtaining in this way the following time picture (figure 3-2):

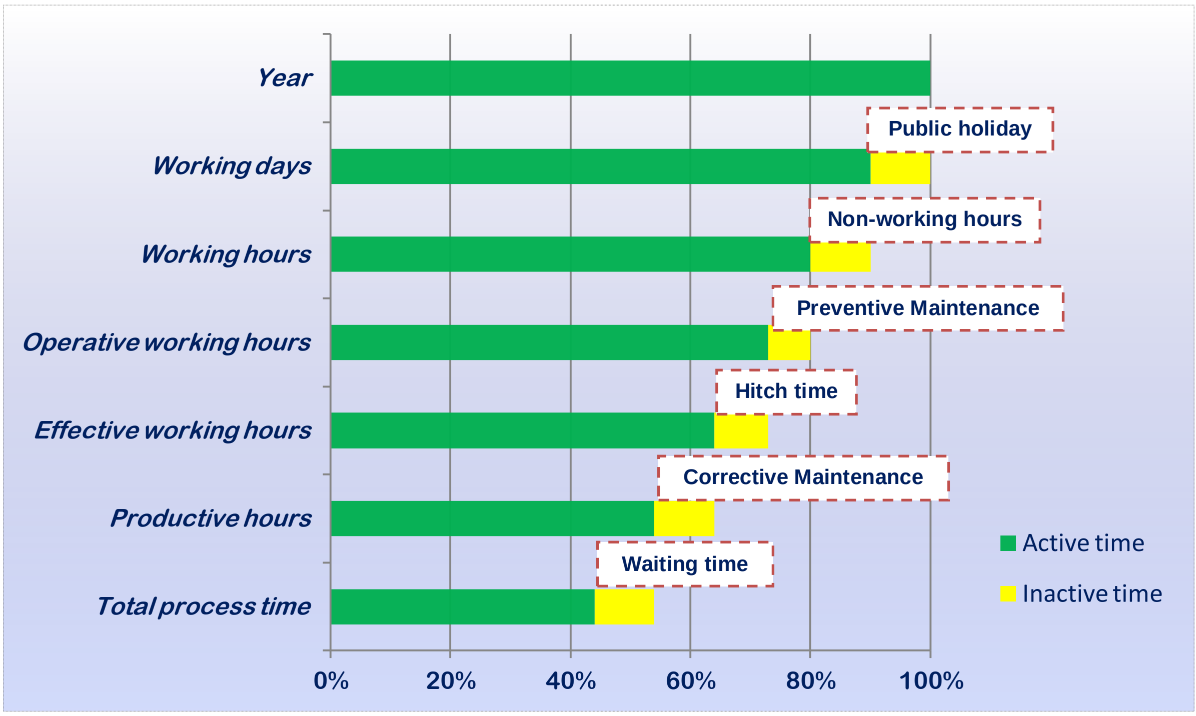


Figure 3-2: Enterprise time management

As immediately noticeable, the time in which the machine tool could actually process a piece (*Total process time*) is only a fraction of the total time available; what influences this percentage is either the result of prefixed time management decisions (such as the choice to increment the number of hours spent in preventive maintenance), or the consequence of contingent negative events, depending for instance on a malfunctioning of the handling system (that can cause an increase of the waiting time for the machine), or on the breakdown of a machine component.

In order to specify the meaning of each time definition and to correctly outline how the total process time has been deduced, the following description is provided:

- **Year:** it is the traditional solar year composed by three hundred and sixty-five days, and then it represents the actual physical time available.
- **Working days:** they are defined as the total amount of days in a year in which work is allowed and regulated by law. They are then obtained through the exclusion from the solar year of public holiday and of all the non-working days established by the specific enterprise policy.
- **Working hours:** they are represented by the hours per year in which the plant is open and is supposed to be productive. This value depends on the factory

production planning, and in particular on the number of planned shifts per day and on the duration of each shift.

- **Operative working hours**: this is the time in which the machine tools are at least switched on and ready to accomplish their task, and so it is the result of the working hours minus the time spent in preventive maintenance. The **Preventive maintenance** is strongly recommended to keep equipment working and/or extend the equipment lifecycle; it is a planned activity and its frequency and duration usually depends on the customer maintenance policy.
- **Effective working hours:** they are the hours in which the machine tools are expected to run, with the exclusion of all the possible events in which they are in an idle state, waiting for the piece to be processed. This time in which the machines are on, but are unfortunately forced to be unproductive (as when a bottleneck or a general unexpected production halt occurs) has been called **Hitch time.**
- **Productive hours:** they are the actual hours in which the machine tools are expected to process a piece. In order to have a good estimation of this time it is necessary to assess the real availability of all the components which the machines are made of. Therefore, what is important to know is how much time per year is spent in **Corrective maintenance**, that is in the activities to identify, isolate, and correct a failure so that the failed equipment and/or machine can be restored to its normal operating state.
- **Total process time**: it is the time in which the machine tools are actually processing, and so it represents the real productive time. The **Waiting time**, instead, comprehends the typical production activities in which the machine is normally not operative, and it is composed by:
    - **Set-up time**: time required to prepare the machine tools for the production of a certain batch;
    - **Piece changing time**: it is the time related both to the placement of the material on the machine and to the removal of the piece, once the material has been processed.

As already mentioned, this classification is extremely useful in order to identify and categorize the different operating states that progressively and periodically occur during the machine tool lifecycle.

The working conditions of a machine tool are indeed substantially different depending both on the production planning and on the efficiency of the secondary equipment of the specific factory in which the machine is installed. In particular, the operations that are supposed to be performed by (or on) the machine are essentially three:

1. Processing the piece;
2. Waiting for the piece;
3. Accomplishing maintenance activities (planned or unexpected).

For each of them, a different requirement of electrical energy is expected, and this is the reason why a precise distinction and classification of these operating conditions in different “standard” states has to be provided, so to find the direct relation between the energy consumption and its cost. In order to respond to this necessity, the following machine states have been identified:

1. ***Process state****;*
2. ***Idle state****;*
3. ***Hibernation state***.

The first, as deducible, is the cumulative time in which the machine processes a piece, and it is then expressible in function of the piece process time and of the number of pieces produced per year. The idle state is the global time in which the specific machine is running, but unfortunately no piece is going to be worked, independently from an eventual unexpected halt of the production system or simply because of the time required for changing the piece. The Hibernation State, in the end, is the one characterized by the complete inactivity of the machine tool, with the exception of its being only switched on.

With this classification and with the model for time management previously introduced, it is possible to quantify the entity of the different machine states, identifying at which level the time (and then energy) losses are placed (figure 3-3).

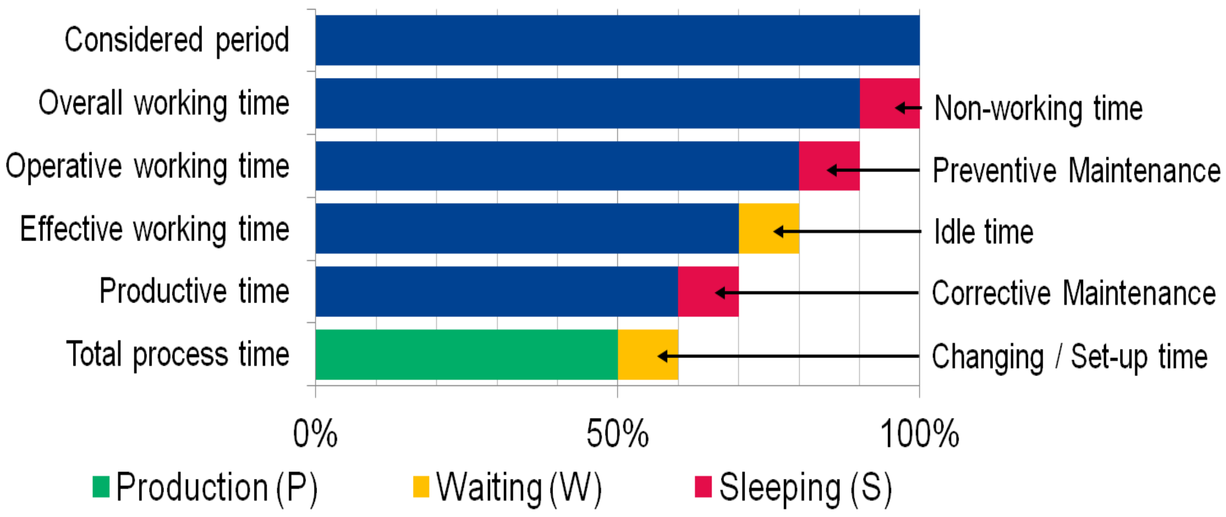


Figure 3-3: Relation between enterprise time management and machine states [NOSK13]

The reason why such classification is absolutely essential lies in the will to express the operative lifecycle costs of the machine tool in function of its energy consumption. As shown in the second chapter (chapter 2, “State of the art”, par. 2.3), one of the criticalities emerged from the actual approaches is the lack of integration between methods for costs identification and quantification: with the proposed methodology, instead, a linear relation between energy consumption and its impact on costs can be set and defined.

On the basis of the energy measurements obtained during several experiments, it has been shown that not only the distinction between the different operating states of the machine tool is central and crucial for the energy consumption quantification, but especially the identification of the most relevant energy-consuming components is fundamental to assess their responsibility on costs and to validate the method effectiveness. The most innovative aspect of this approach, indeed, consists in expressing the lifecycle costs as a sum of the economic impact of the different components, allowing the eventual comparison between various machine configurations, and then providing the basis for a better evaluation of the investment.

Therefore, in order to consider in the concept development all the possible components configuration, with different performance and power requirements, and so with distinct cost effects, the machine tool has been decomposed in some "standard" parts (table 3-2), so to be flexible to different production processes and acquire the relating energy consumption.

#	Components
1	Axes and spindle cooling
2	Axes and spindle drives
3	Numeric control
4	Ventilation
5	Chip conveyor
6	Axis lubrication

Table 3-2: Machine tool components

The classification of the components is then more "functional", than mechanical: the single machine parts have been aggregated in function of their main role in machining processes, in order to guarantee the applicability of the concept also to machine tools characterized by different internal structures. In this way, it is possible to associate to every component the relating energetic performance through the quantification of the electrical energy requirement for each defined state (Process, Idle and Hibernation state), as plainly illustrated in figure 3-4.

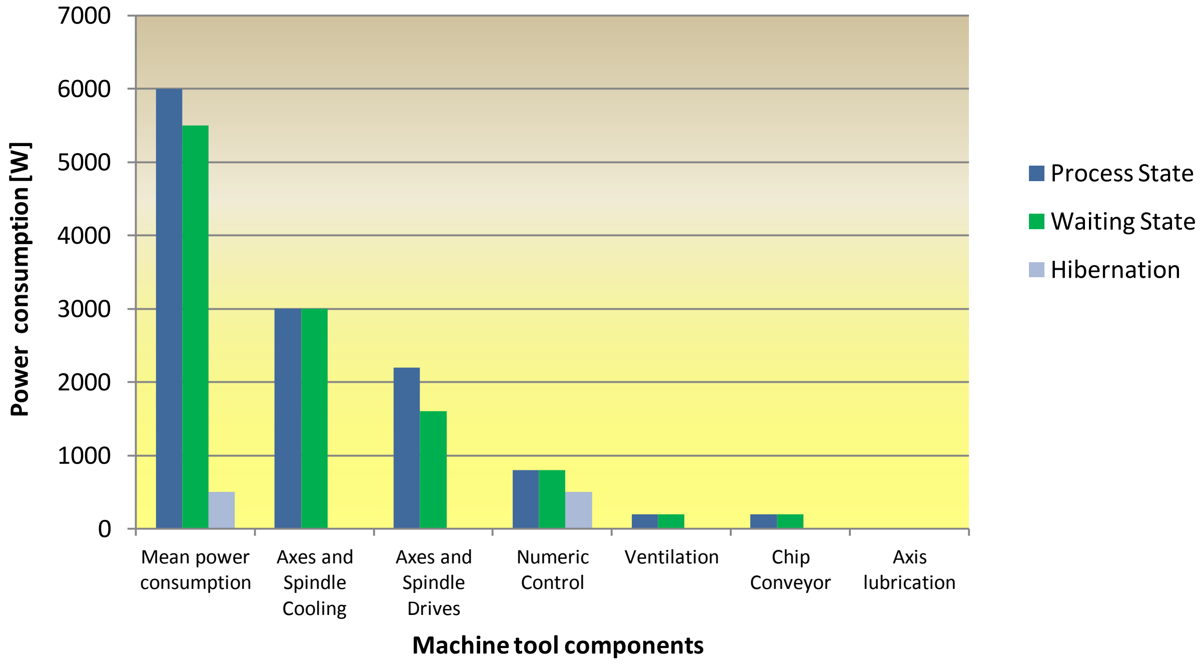


Figure 3-4: Energy consumption of measured machine tool within different operating states [DENK13]

Finally, on the basis of the machine tool decomposition in its main components and on the distinction between Process State, Idle State and Hibernation state, an analytical description of the lifecycle costs related to energy consumption (together with all the other categories of LCC) will be presented in the next paragraph.

3.3 Mathematical and analytical formulas

Since the aim is to create a unique relation between energy consumption and lifecycle costs, the first subject that will be presented is the way such correspondence has been obtained, and then all the other costs will follow in the description.

The actual energetic expenditure of a machine tool, as previously said, can be derived from the identification and quantification of the time spent by the machine itself in one of its three main operating conditions (Process state, Idle state, Hibernation state).

In regards to Process state, the following analytical expression has been deduced:

$$\boldsymbol{t\_Process\ State}_{\boldsymbol{year}} = \sum_{\boldsymbol{i=1}}^{\boldsymbol{n}} PT_i \cdot nP_i \qquad (3.1)$$

Where:

- $\boldsymbol{t\_Process\ State}_{\boldsymbol{year}}$ is the time per year in which the machine is processing [h/year];
- PT_i is the process time required to process a piece belonging to the batch i [h/piece];
- nP_i is the number of pieces produced per each batch i per year [piece/year];
- n is the number of batches processed on the machine;

As intuitively deducible, in fact, the active time of the machine is simply dependent on the time required for each piece to be manufactured. The assumptions made in regards to the batches is that the pieces they are composed of differ only in the shape, but the material to be processed is always the same (generally titan or steel).

Less intuitive, instead, is the way to exactly formalize the time in which the machine is in an Idle State: several are the parameters to consider, and they refer not only to the expected activities of changing the piece and set up the machine (planned activities, then easily quantifiable and controllable), but also to all the possible unexpected events which will inevitably induce the machine to be inoperative. This is the reason why the definition of "Hitch Time" has been previously introduced, and now a way for its appraisal is presented.

On the basis of the time model proposed by the norm VDMA 66412-1:2009-10 (and rearranged in paragraph 1.2), it is possible to identify some key performance indicators (KPI), through which each enterprise could assess its performance in terms of productivity and time management. So, making reference to the "Operative efficiency" of an enterprise ($\eta_{operating}$) it is possible to correlate the operative working hours (OWH) with the effective working hours (EWH), and then to estimate the percentage of operating time lost for unexpected occurrences:

$$\eta_{operating} = \frac{EWH}{OWH} \qquad (3.2)$$

$$EWH = OWH \cdot \eta_{operating} \tag{3.3}$$

Where:

- $\eta_{operating}$ is the enterprise operative efficiency [%];
- EWH are the effective working hours [h/year];
- OWH are the operative working hours [h/year];

Being the Hitch time (HT) exactly the difference between the operative working hours and the effective ones, it is possible to write:

$$HT = OWH - EWH \tag{3.4}$$

Where:

- HT is the hitch time [h/year];
- EWH are the effective working hours [h/year];
- OWH are the operative working hours [h/year];

And so:

$$HT = OWH\left(1 - \eta_{operating}\right) \tag{3.5}$$

Where the OWH are calculated by means of the input data related to the time spent in preventive maintenance (PM), and then:

$$OWH = WH - PM \tag{3.6}$$

Where:

- OWH are the operative working hours [h/year];
- WH are the working hours [h/year];
- PM is the preventive maintenance time [h/year];

It follows:

$$OWH = (nSH \cdot SH \cdot WD) - PM \tag{3.7}$$

Where:

- nSH is the number of shifts per day established by the enterprise [n°];
- SH is the shift duration [h/day];
- WD are the working days per year [day/year];
- PM is the preventive maintenance time [h/year].

Then, the analytical representation of the Idle State is the following:

$$\boldsymbol{t\_Idle\ State}_{\boldsymbol{year}} = \sum_{\boldsymbol{i=1}}^{\boldsymbol{n}} (CT_i \cdot nP_i + (ST_i \cdot nST_i \cdot WD)) + HT \tag{3.8}$$

Where:

- $\boldsymbol{t\_Idle\ State}_{\boldsymbol{year}}$ is the time per year in which the machine is waiting [h/year]
- CT_i is the time required to change a piece belonging to the batch i [h/piece];
- $\sum_{\boldsymbol{i=1}}^{\boldsymbol{n}} CT_i \cdot nP_i$ is the total time per year spent in changing the pieces for all the batches [h/year];
- ST_i is the time required to prepare the machine for the production of the batch i [h/batch];
- nST_i is the number of set up per batch i per day [n° batch/day];
- WD are the working days in a year [day/year];
- $\sum_{i=1}^{n} ST_i \cdot nST_i \cdot WD$ is the total time per year spent in set up [h/year];
- n is the number of batches.

Finally, since the operating states supposed for the machine are three, and two of them have been already defined, the Hibernation State is automatically deduced by the detraction of the Process State and Idle State from the total time available (the year), according to the assumption that the machine control unit is always switched on:

$$\boldsymbol{t\_Hibernation\,State}_{\,\boldsymbol{year}} = Year - t\_Process\,State_{\,year} + \\ - t\_Idle\ \ State_{\,\boldsymbol{year}} \tag{3.9}$$

Where:

- $\boldsymbol{t\_Hibernation\,State}_{\,\boldsymbol{year}}$ is the time per year in which the machine is only switched on [h/year];
- $t\_Process\,State_{\,year}$ is the total processing time for the machine [h/year];
- $t\_Idle\ \ State_{\,\boldsymbol{year}}$ is the total waiting time for the machine [h/year].
- $Year$ is intended as the amount of hours existing in a year, and then:

$$Year = \left(365\frac{days}{year} \cdot 24\frac{h}{day}\right) = 8760\ \frac{h}{year} \tag{3.10}$$

Where:

- 365 are the days existing in one year;
- 24 are the hours per day.

In order to estimate now the machine energetic impact, it is important to know exactly which is the power requirement for each of these states. The method to calculate and quantify these values has been the subject of another project, and it has been based on a sample of empirical information deduced thanks to the application of a series of sensors on a machine tool operating in a real manufacturing context. Those sensors were able to detect the energy consumption for all the components in function of the process parameters characterizing a defined productive scenario, and then those information were used as a feedback to set and improve the method for the energy consumption prediction [DENK13].

Then, given the power absorbed by the components in all the three different states, and indicating it as $P_{process}$, P_{idle}, and $P_{hibernationn}$, the energy needs per year can be expressed in this way:

$$\boldsymbol{Energy\ needs} = P_{process} \cdot t\_Process\ state_{\ year} + \\ + P_{idle} \cdot t\_Idle\ state_{\ year} + \\ + P_{hibernation} \cdot \\ \cdot t\_Hibernation\ state_{year} \tag{3.11}$$

Where:

- $\boldsymbol{Energy\ needs}$ is the energy requirement per year considering all the three machine states [kWh/year];
- $P_{process}$ is the power required by a machine component for processing [kW];
- $t\_Process\ state_{\ year}$ is the time per year in which the machine is processing [h/year];
- P_{idle} is the power absorbed by a machine component during waiting between processes [kW];
- $t\_Idle\ \ State_{\ \boldsymbol{year}}$ is the time per year in which the machine is waiting [h/year];
- $P_{hibernation}$ is the power absorbed by a machine component in stand-by mode [kW];
- $t\_Hibernation\ State_{\ year}$ is the time per year in which the machine is only switched on [h/year].

This last mathematical expression, however, refers only to the quantification of the power required for each state by a single component (spindle, axis, coolant system, …), and then it is not representative of the total amount of energy consumed by the whole machine yet. The aim, in fact, is not only the one to assess the energetic and economic impact of the machine in its entirety, but also to understand which are the most energy-consuming components in all the three states, and then to outline eventual opportunities for improvement.

Therefore, in order to calculate the total power need per year, a simple summation on the number of components (m) is required:

$$\boldsymbol{P_{process_{machine}}} = \sum_{j=1}^{m} P_{process_j} \quad (3.12)$$

Where:

- $\boldsymbol{P_{process_{machine}}}$ is the power required by the whole machine for processing [kW];
- $P_{process_j}$ is the power required by the machine component j for processing [kW];
- m is the number of components of a machine tool.

$$\boldsymbol{P_{idle_{machine}}} = \sum_{j=1}^{m} P_{idle_j} \quad (3.13)$$

Where:

- $\boldsymbol{P_{idle_{machine}}}$ is the power absorbed by the whole machine while waiting [kW];
- P_{idle_j} is the power absorbed by the machine component j while waiting [kW];
- m is the number of components of a machine tool.

$$\boldsymbol{P_{hibernation_{machine}}} = \sum_{j=1}^{m} P_{hibernation_j} \quad (3.14)$$

Where:

- $\boldsymbol{P_{hibernation_{machine}}}$ is the power absorbed by the whole machine in stand-by mode [kW];
- $P_{hibernation_j}$ is the power absorbed by the machine component j in stand-by mode [kW];
- m is the number of components of a machine tool.

In this way, the total amount of energy required by the machine is:

$$\begin{aligned}\boldsymbol{E_{total}} = \; & P_{process_{machine}} \cdot t\_Process\ state_{\ year} + \\ & + P_{idle_{machine}} \cdot t\_Idle\ state_{\ year} + \\ & + P_{hibernation_{machine}} \cdot t\_Hibernation\ state_{year}\end{aligned} \quad (3.15)$$

Where:

- $\boldsymbol{E_{total}}$ is the total amount of energy required by the whole machine per year [kWh/year];
- $P_{process_{machine}}$ is the power required by the whole machine for processing [kW];
- $t\_Process\ state_{\ year}$ is the time per year in which the machine is processing [h/year];
- $P_{idle_{machine}}$ is the power absorbed by the whole machine while waiting [kW];
- $t\_Idle\ state_{\ year}$ is the time per year in which the machine is waiting [h/year];
- $P_{hibernation_{machine}}$ is the power absorbed by the whole machine in stand-by mode [kW];
- $t\_Hibernation\ state_{year}$ is the time per year in which the machine is only switched on [h/year].

Once assessed the procedure through which appraising the machine tool energy consumption, the calculation of the respective lifecycle costs is quite intuitive. The cost of energy per year is indeed given by the simple multiplication of the already defined energy requirements and the unitary cost of energy, as in the formula below:

$$C_{energy} = E_{total} \cdot \frac{€}{kWh} \quad (3.16)$$

Where:

- C_{energy} is the annual energy cost [€/year];
- E_{total} is the total amount of energy required by the whole machine per year [kWh/year];
- $\frac{€}{kWh}$ is the unitary price for energy;

Then, considering the lifetime of the machine tool, it becomes:

$$\boldsymbol{C_{energy}} = E_{total} \cdot T \cdot \sum_{t=1}^{T} \frac{€}{kWh} \left(\frac{1+g}{1+i}\right)^{t} \qquad (3.17)$$

Where:

- $\boldsymbol{C_{energy}}$ is the lifecycle cost for energy [€];
- E_{total} is the total amount of energy required by the whole machine per year [kWh/year];
- $\frac{€}{kWh}$ is the unitary price for energy;
- T is the machine lifetime [year];
- g is the annual growth rate of the cost of energy [%];
- i is the annual discount rate [%].

In regards to the other lifecycle costs previously defined, their analytical representation is here provided.

- **Acquisition cost**

It is represented by the purchase price and, eventually, by the resale value, which contributes to reduce the initial capital expenditure, in the perspective of a lifecycle analysis. In regards to the purchase price, it is nothing but the sum of the components cost, maybe increased by a certain percentage (α) that takes into account the work required to assembly them in the final configuration requested for the machine tool.

In formulas:

$$Price_0 = \alpha \cdot \sum_{j=1}^{m} Cost\_component_j \qquad \alpha \geq 1 \qquad (3.18)$$

Where:

- $Price_0$ is the purchasing price at time 0 [€];
- α is the mark-up on the sum of the costs of components [%];

- $Cost\_component_j$ is the acquisition cost for the component j [€/piece];
- m is the number of machine components.

The acquisition cost is then expressed as:

$$\boldsymbol{C_{Aquisition}} = Price_0 - \frac{RV_T}{(1+i)^T} \tag{3.19}$$

Where:

- $\boldsymbol{C_{Aquisition}}$ is the lifecycle cost for buying the machine [€];
- $Price_0$ is the purchasing price at time 0 [€];
- T is the machine lifetime [year];
- RV_t is the resale value at time T [€];
- i is the annual discount rate [%].

- **One-time costs**

They are represented by the costs requested for transporting the machine to the industrial plant and installing it in accordance with the existing manufacturing system (transportation and installation costs). Both are not analytically calculated, since they are generally established by supply contract, and then they will be taken as predetermined input.

- **Maintenance service cost**

It responds to the annual base fee that the enterprise has to pay simply to benefit from the services of an external and specialized maintenance company. It is expressed as:

$$\boldsymbol{C_{maintenance\ service}} = C_{contract} \cdot T \cdot \sum_{t=1}^{T} (1+i)^{-t} \tag{3.20}$$

Where:

- $\boldsymbol{C_{maintenance\ service}}$ is the lifecycle cost for maintenance contract [€];

- $C_{contract}$ is the annual base fee paid to the maintenance company, in relation to the single machine tool at analysis [€/year];
- *T* is the machine lifetime [year];
- i is the annual discount rate [%].

- **Corrective maintenance cost**

This voice comprehends all the costs that the enterprise has to bear when some malfunctioning or failure occur, and then when the restoring of the machine to its normal state is required. It is therefore important to consider both the costs related to reparation and the cost for spare parts, in case a substitution of the failed part is requested.

Then, the lifecycle costs for corrective maintenance have been so formalized:

$$\boldsymbol{C_{corrective\ maintenance}} = CM \cdot C_{labour} \cdot T \cdot \sum_{t=1}^{T} \left(\frac{1+g_{labour}}{1+i}\right)^{t} + \\ + \sum_{t=1}^{T} \sum_{j=1}^{m} SP_j \cdot C_j \cdot \left(\frac{1+g_{c_j}}{1+i}\right)^{t} \qquad (3.21)$$

Where:

- $\boldsymbol{C_{corrective\ maintenance}}$ is the lifecycle cost for corrective maintenance [€];
- *CM* is the corrective maintenance time per year [h/year];
- C_{labour} is the cost per hour for the maintenance personnel [€/h];
- g_{labour} is the growth rate of labour cost [%];
- i is the discount rate [%];
- *T* is the machine lifetime [year];
- g_{spc_j} is the growth rate of spare parts cost for the component *j* [%];
- C_j is the cost for a single spare part of the component *j* [€/piece];
- SP_j is the number of spare parts for each component *j* [piece];
- m is the number of components.

In regards to the corrective maintenance time, since it is defined as the total time in which the machine is out of service due to a component breakdown, the key parameter required to calculate it is the component availability (AV), defined as the ratio of the mean time to failure (MTTF) to the mean time between failure (MTBF):

$$AV_j = \frac{MTTF_j}{MTBF_j} \tag{3.22}$$

Where:

- AV_j is the availability of the component j [%];
- $MTTF_j$ is the Mean Time To Failure of the component j [h];
- $MTBF_j$ is the Mean Time Between Failures of the component j [h].

In this way it is possible to assess how many times per annum a component would fail and how much time is needed to fix it. Then, the corrective maintenance time (CM) has been so defined:

$$\boldsymbol{CM} = WH \cdot \left(1 - \prod_{j=1}^{m} AV_j\right) \tag{3.23}$$

Where

- $\boldsymbol{CM}$ is the time spent per year in corrective maintenance [hour/year];
- WH are the working hours per year [hour/year];
- AV_j is the availability of the component j [%];
- m is the number of components of the machine tool.

A little digression has now to be made in regards to the number of spare parts required. It has been assumed that the spare parts policy of a particular enterprise is the one to buy a spare part only when it is needed, so when it is statistically possible the imminent breakdown of a component. Of course it is not a general hypothesis, although plausible and common, but other assumptions would have meant the need to enlarge and complicate the model with some sophisticated considerations, as the differential analysis between the storage costs and the economic consequences for the eventual halt of production due to the absence of the required spare part.

Finally, the number of spare parts for a general component is calculated as the ratio of the working hours (that is the time in which the component must work to guarantee the respect of the production needs) and its mean time to failure (that is the time interval in which the component is expected to work, before its breakdown). Then:

$$SP_j = \frac{WH}{MTTF_j} \tag{3.24}$$

Where:

- SP_j is the annual number of spare parts required for the component j [piece/year];
- WH are the working hours per year [hour/year];
- $MTTF_j$ is the Mean Time To Failure of the component j [h].

- **Preventive maintenance cost**

Since the preventive maintenance is a periodical activity, generally daily performed by the enterprise workers themselves at the beginning of the first machine shift, the only costs that have to be taken into account are constituted by the portion of the personnel wage predisposed to remunerate the time spent in this kind of activities.

In analytical terms:

$$\boldsymbol{C_{preventive\ maintenance}} = t_{PM} \cdot C_{labour} \cdot T \cdot \sum_{t=1}^{T} \left(\frac{1+g_{labour}}{1+i}\right)^t \tag{3.25}$$

Where:

- $\boldsymbol{C_{preventive\ maintenance}}$ is the lifecycle cost for preventive maintenance [€];
- t_{PM} are the hours per year devoted to the activities of control and prevention of the machine tool efficiency [h/year].
- C_{labour} is the cost per hour for the maintenance personnel [€/h];
- g_{labour} is the growth rate of labour cost [%];
- i is the discount rate [%];
- *T* is the machine lifetime [year].

– **Room rent cost**

It is normally a null value, since the machine dimension can be considered standard, above all if the initial hypothesis of a non-innovative investment (same performance parameters) is recalled. Anyway, it has been introduced to take into account the eventuality to expand the productive capacity and then the need to install more powerful components, which generally require a major space, and consequently a bigger room.

The rent costs, finally, are so defined:

$$\boldsymbol{C_{room}} = \sum_{\boldsymbol{j=1}}^{\boldsymbol{n}} SR_j \cdot C_{rent} \cdot T \cdot 12 \cdot \sum_{t=1}^{T} \left(\frac{1+g}{1+i}\right)^t \qquad (3.26)$$

Where:

- $\boldsymbol{C_{room}}$ is the lifecycle cost for renting the room in which the machine is placed [€];
- SR_j is the space required for each component j [m^2];
- n is the number of components of a machine tool;
- C_{rent} is the unitary cost for rent [€/(m^2 · month)];
- 12 are the months per year [month/year];
- g is the growth rate of rent cost [%];
- i is the discount rate [%].

Once assessed the extent of all the machine tool costs, it is then possible to quantify their impact on the different pieces processed by the machine. Through their summation and division by the machine lifetime, indeed, the “average” cost per year can be derived, and consequently, also an estimation of the cost per part needed to recover the entire investment can be provided. It is worthy to note, however, that the cost per part is here intended only in relation to the machine tool LCC, and then it is not inclusive of all the other costs that can affect it (such as commercial and logistic costs). Moreover, since the hypothesis of processing different batches on the same machine has been adopted for the concept development, it is necessary to evaluate the impact of the LCC on the specific batch, and then on the number of produced pieces.

In order to respond to these requirements, the incidence of each batch on the machine operative activities has to be considered, and this has been determined on the basis of the share of the process time required for the production of a certain batch in respect to the total process time estimated (that is, the Process State); therefore, the weights through which the correct quota of the annual costs has been allocated to the corresponding batch have been so calculated:

$$w_i = \frac{PT_i \cdot nP_i}{Process\ State} \tag{3.27}$$

Where:

- w_i is the weight for calculating the cost per part of the batch i [%];
- PT_i is the process time per piece [h/piece];
- nP_i is the number of pieces produced for the batch i [piece/batch];
- $Process\ State$ is the total time per year in which the machine is processing [h/year].

Then the theoretical cost per part (formula 4.2) and the actual cost per part (formula 4.3) have been so calculated:

$$C_{unitary\ Teoretical_i} = \frac{Annual\ cost \cdot w_i}{nP_i} \tag{3.28}$$

$$C_{unitary\ Actual_i} = \frac{Annual\ cost \cdot w_i}{nP_i\ (1 - \%_{faulty\ pieces})} \tag{3.29}$$

Where:

- $C_{unitary\ Teoretical_i}$ is the theoretical cost per part for the pieces belonging to the batch i [€/piece];
- $C_{unitary\ Actual_i}$ is the actual cost per part for the pieces belonging to the batch i [€/piece];
- $Annual\ cost$ is the annual share of the machine tool LCC [€/year];
- w_i is the weight for calculating the cost per part of the batch i [%];

- nP_i is the number of pieces produced for the batch i [piece/batch];
- $\%_{\text{faulty pieces}}$ is the percentage of faulty pieces for the batch i [%].

The last clarification regards the $Annual\,cost$. It has been expressed in average, simply dividing the total lifecycle costs by the number of years at the basis of the calculation: it won't correspond, then, to the actual portion of LCC registered at each year, because in that case it has to be considered the exact year taken as a reference, and estimate all the costs specifically for that year, with its corresponding actualized discount rate. The purpose, then, is only to obtain an average annual value so to calculate the average cost per part for each batch.

3.4 Definition of required input data

As highlighted by the analysis of the issues and criticalities of the actual approaches for LCC calculation (see chapter 2, "State of the art", par. 2.3), and as also evident from the analytical examination of the concept, the amount of data needed for a good and realistic costs evaluation is really significant and considerable. Specifically for the concept at issue, the most critical aspect is related to the necessity to get reliable data from all the subjects who are involved in the supply chain:

- the manufacturer, as regards the components and their technical characteristics;
- the customer, in relation to their production needs and economic requirements.

Moreover, this is also complicated by the fact that the analysis is performed on the whole machine lifetime, and then it is important to have not only reliable, but also updated information about the economic parameters involved in this calculation.

In order to guarantee that all the required and essential information are included into the lifecycle costs analysis, a classification of the input data in function of their affinity in terms of reference source has been done, and the result is their subdivision in four categories:

I. *Manufacturer-based*;
II. *Customer-based*;
III. *Product-based*;
IV. *Market-based*.

The manufacturer-based data include all the information related to components and to the manufacturer services, as shown in table 3-3:

Manufacturer-based
Component cost [€]
Mark-up on acquisition price [%]
AV (component availability)
MTTF (mean time to failure)
Cost for transportation and installation [€]
Cost for maintenance contract [€]
Cost for maintenance labour [€/h]

Table 3-3: Manufacturer-based data

All the information referring to the enterprise production policy are instead gathered in the Customer-based data (table 3-4):

Customer-based
WD (working days [day/year])
nSH (number of shifts per day [n°/day])
hSH (hours per shift [h/n°])
Lifetime [years]
nST (number of set up per piece per day [n°/day])
$\eta_{operating}$ (operative efficiency [%])
Number of batches [n°]
Number of pieces produced per batch per year [n°/batch year]
Percentage of faulty pieces produced [%]
Preventive maintenance time

Table 3-4: Customer-based data

The Product-based data refers to the parameters and characteristics of the specific productive processes, and they are illustrated in table 3-5:

Product-based
$P_{process}$ (power required for processing [kW])
P_{idle} (power absorbed while waiting [kW])
$P_{hibernation}$ (power absorbed in stand-by mode [kW])
SR_j (space required for each component j [m^2])
PT (process time [h/piece])
CT (piece changing time [h/piece])
ST (setup time [h/piece])

Table 3-5: Product-based data

The last category, Market-based data, includes all the required information for the implementation of a lifecycle analysis (table 3-6):

Market-based
Resale value [€]
Cost of energy [€/kWh]
Cost for room rent [€/m^2]
Growth rate of energy cost [%]
Growth rate of maintenance labour cost [%]
Growth rate of rent costs [%]
Growth rate of spare parts cost [%]
Discount rate (cost of capital) [%]

Table 3-6: Market-based data

Starting from these data, all the other intermediate results (as the working hours, the hitch time, the corrective maintenance time, and so on) and the final output can be derived.

In order to directly and physically visualize the complex relationships among all the data, a series of partial diagrams regarding different data dependences will be provided.

The first delimited graph (figure 3-5) describes the result of the interactions among the data related to:

- preventive maintenance;
- number of shifts;
- shift duration;
- operative efficiency;
- component availability;
- component MTTF,

which leads to the definition of the following auxiliary data:

- working hours (WH);
- operative working hours (OWH);
- hitch time (HT);
- corrective maintenance time (PM);
- number of components spare parts.

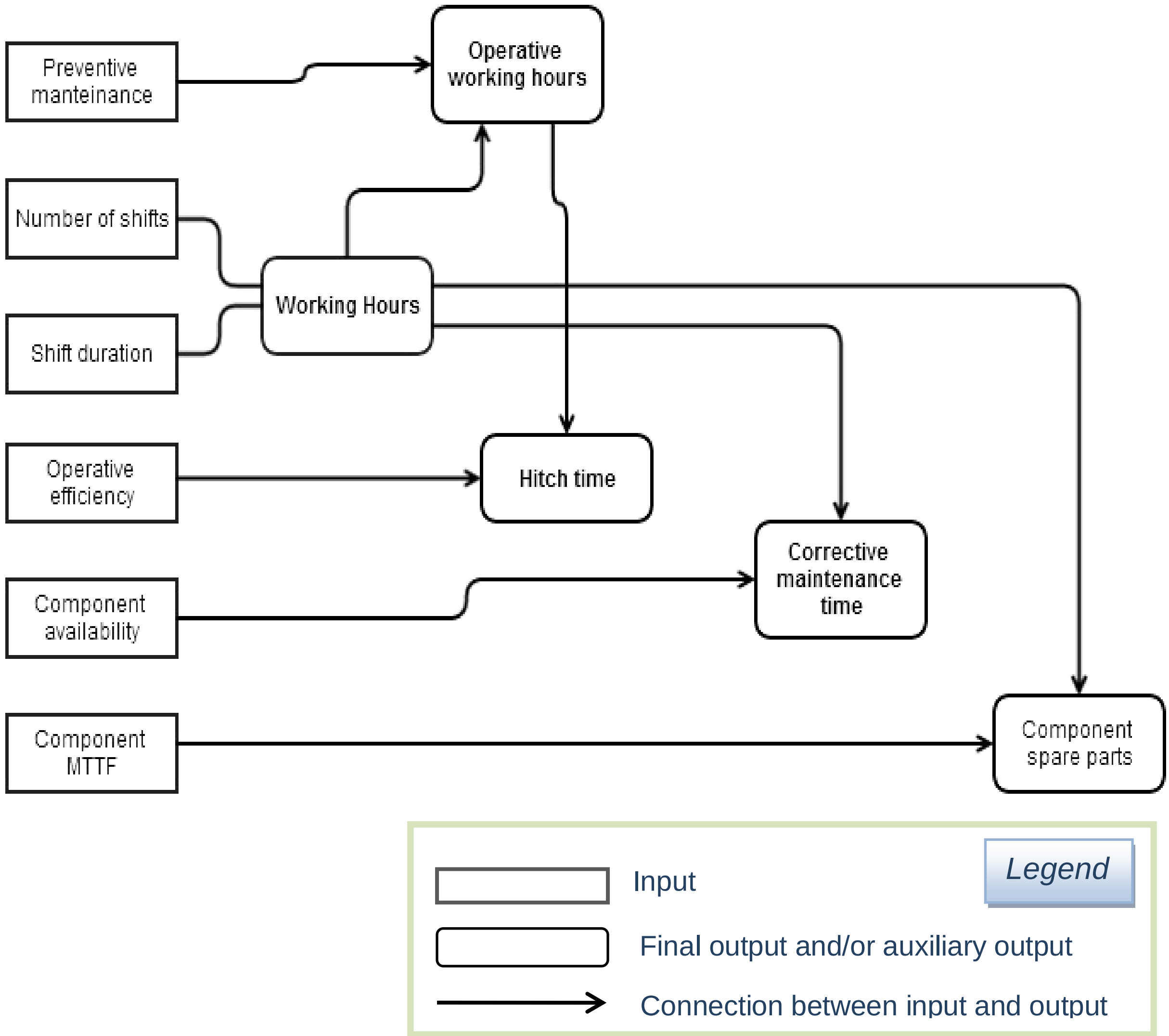


Figure 3-5: Partial representation of the concept data relationships

Within this diagram, therefore, some of the initial input and sensitive intermediate output necessary for the calculation of the machine tool lifecycle costs have been defined: the Corrective maintenance time, for instance, will be used in the third diagram (figure 3-7) for the quantification of the LCC relating to inspection and reparation, while the Hitch time, as a second example, is one of the input for the quantification of the machine idle state, as noticeable in the next diagram (figure 3-6).

The second diagram, indeed, is related to the depiction of the three different states defined for the energy consumption prediction and to their interaction in the characterization of lifecycle costs for energy (figure 3-6), and then it includes all the data which are necessary for the definition of:

- Process state;
- Idle state;
- Hibernation state;
- Total energy consumption;
- Energy lifecycle costs.

This diagram shows the most critical relations for achieving the goals for which the concept has been developed (calculating the machine tool LCC in function of the energetic impact of its tasks), therefore it represents the core reference for the comprehension and the application of the method.

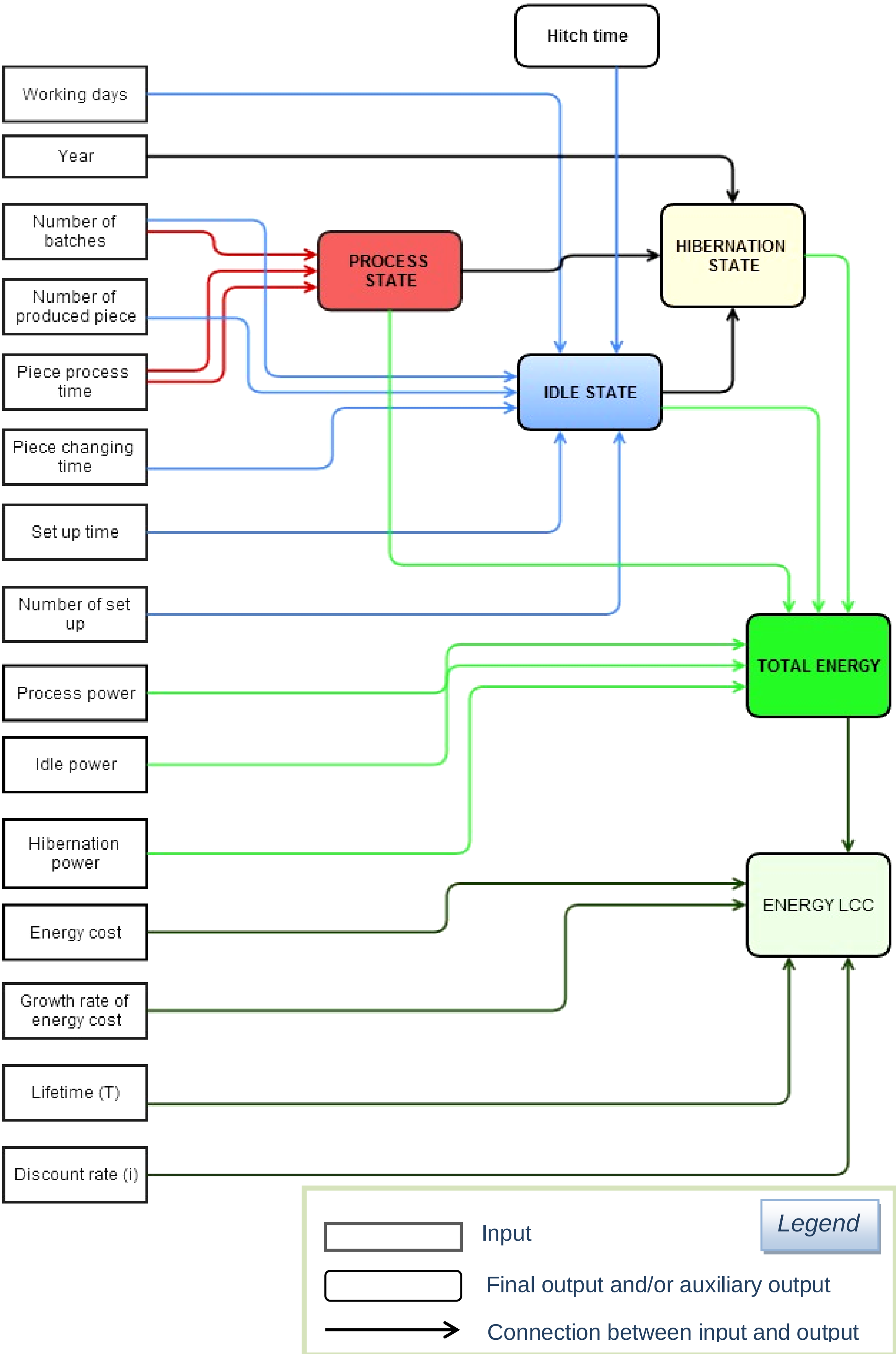


Figure 3-6: Data relationships for the calculation of energy LCC

The third partial diagram, finally, depicts the rest of the lifecycle costs related to the machine tool (figure 3-6), that are:

- Acquisition costs;
- One-time costs;
- Maintenance service;
- Corrective maintenance;
- Preventive maintenance;
- Room rent.

It illustrates then the information and data required for the quantification of all the other costs relating to the machine tool investment, beyond the consideration of the operating costs.

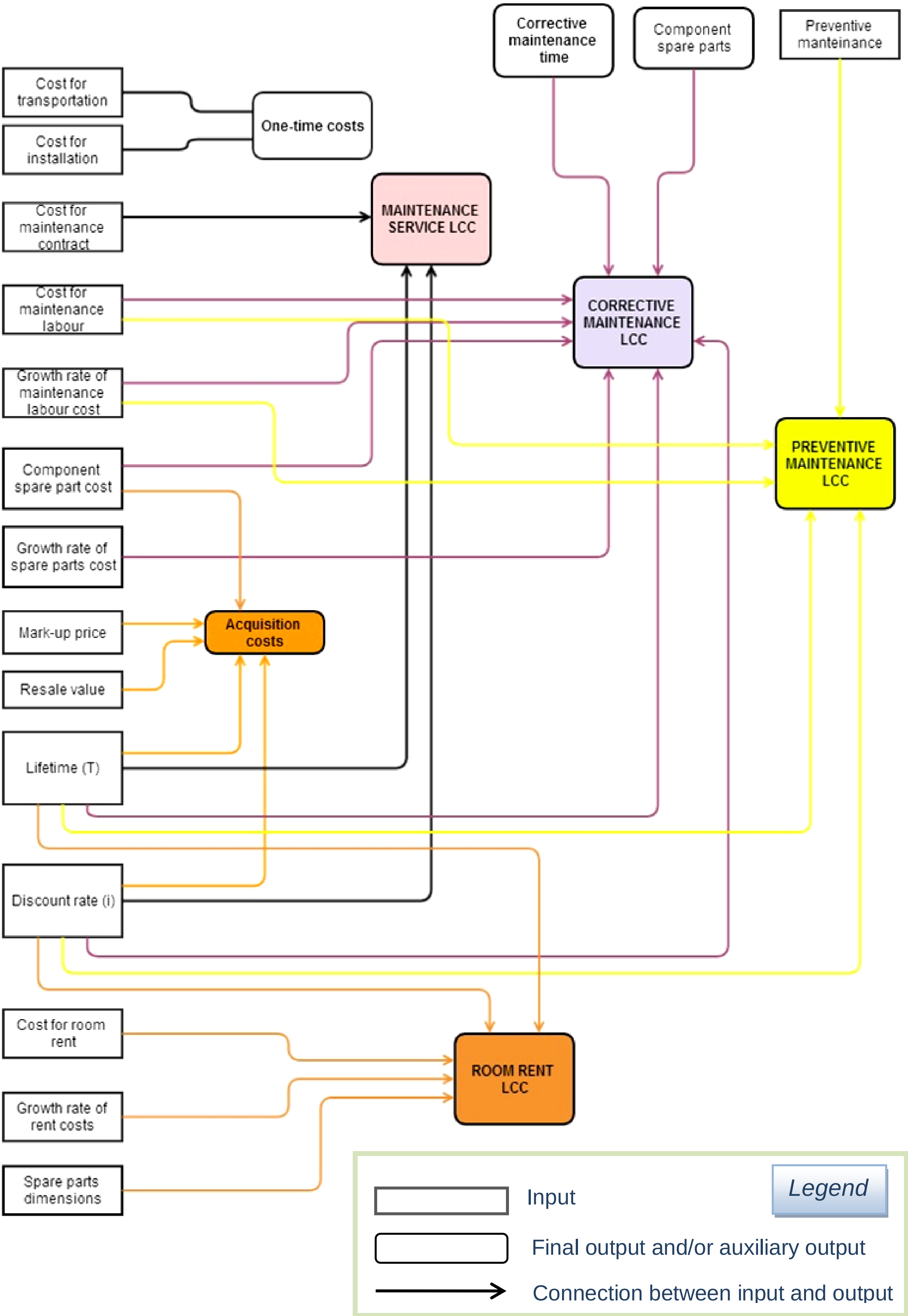


Figure 3-7: Data relationships for the calculation of all the others LCC

3.5 Summary

In the present chapter a concept for the estimation of the lifecycle costs related to a milling machine and to its energetic consumption has been proposed.

As a first step, the required outputs in terms of measurable costs during the entire machine lifetime have been individuated and plainly defined; then, in order to clarify the procedure, a description of the model whereby the productive time is managed has been illustrated, defining in this way the different time components that contribute to the quantification of the requested machine lifecycle costs, and in particular to the determination of the three operative states established for the machine tool: Process state, Idle state, Hibernation state. Then, given the exact power consumption for each component of the machine and for each defined state, the total energy consumption has been quantified, obtaining in this way the energy lifecycle costs simply through the consideration of the machine lifetime and the cost of energy, with its corresponding annual growth rate.

The same logic has been applied in the calculation of the other lifecycle costs, assessing the time interval devoted to a particular operation or condition (transportation, installation, preventive maintenance, corrective maintenance, and so on), and its relating cost over time.

In the end, a classification of all the required data in different categories according to their reference source has been suggested, emphasizing the complex relationships among all the input data and the corresponding output, also through a graphical representation of their connections and dependences.

In the next chapter, the present concept will be described and analyzed through its implementation in a software, outlining in this way the structure and the functionalities of the developed solution, whose validity will be further examined during the evaluation phase.

4 Implementation

In this chapter the concept previously developed for the calculation of a machine tool lifecycle costs is presented through its practical and concrete implementation into a computational algorithm. The aim is to create a useful and tangible tool to help enterprises in quantifying the costs connected to their production activities, and then to lead them towards a simpler achievement of the hard and demanding goals related to the reduction of their energy consumption and to the increase of their own environmental performance. An introduction to the integrated development environment (IDE) in which the algorithm has been implemented will be then provided, and an explanation of the most peculiar and distinctive characteristics of the algorithm itself will follow in the dissertation.

4.1 Development of an algorithm for a machine tool LCC calculation in function of its energy consumption

The integrated development environment (IDE) that has been chosen for the implementation of the algorithm for calculating the lifecycle costs connected to the energetic expenditure of a machine tool is represented by Microsoft Visual Studio 2010. It is a multiplatform which supports different programming languages (as C, C++, C#, F#, Visual Basic .Net and ASP .Net), and that allows the development of GUI applications, web sites, web services and web applications. It includes, a code editor, a debbuger and a designer and it is specifically designed for programmers who work on platforms like Windows and .NET Framework 4.0 [HALVO12].

The algorithm developed on this IDE in this research work has been named "*LC€nergy*" and is written in C# language. It is composed by three forms: in the first one, the user is initially invited to enter the data relating to their enterprise labour policy in terms of productive and unproductive hours; the second one is specifically designed to show to the user the technical characteristics of the machine tool at analysis, in regards to power consumption, components reliability, and acquisition cost for the spare parts; and also a table relating to the required economic data for LCC calculation (as the actual energy cost, actual growth rate of energy cost, labour cost, rent cost, and so on) is displayed; in the end, the third form includes the results in terms of machine lifecycle costs, cost per part (theoretical and actual), and of component energy states.

In order to provide a plain explanation of the algorithm structure, a brief description of the classes created, the functions implemented and the different forms used (comprehending their interface and main operations), will be presented in the following paragraphs.

4.1.1 Classes and functions

Besides the program class, that is responsible of the algorithm running, and the main class in which all the required operations have been entered, other two classes have been built in order to facilitate the code writing and implementation. These are:

- “Variables”: it is the class in which all the public variables (those needed for every operation and event) are stored;
- “Procedures”: it contains some functions implemented to formalize the most used and frequently required operations.

The most useful functions developed in this second class are those relating to the calculation of the spare parts cost and to the determination of the actualized discount rate for each entry of the LCC. In regards to the first one, the function has been called “CalculateSPcost” and requires in input:

- the enterprise working days;
- the machine tool lifetime;
- an array with the MTTF of all the components;
- an array with the cost of each component;
- an array with the growth rate of the cost of each component;
- the interest rate.

Once inserted all these data in the argument of the function, it returns the total cost to be borne for the spare parts during the whole machine lifespan. In particular, the procedure has been structured so that, when a spare part is required, its cost is actualized to the corresponding year in which it would be purchased. The code through which such result is obtained is provided in figure 4-1:

lures.cs* × Variables.cs FormLcc.cs FormLcc.cs [Design]

ndowsFormsApplication2.Procedures CalculateSPcost(float WH, uint T, uint[] MTTF

```
public float CalculateSPcost (float WH, uint T, uint[] MTTF, float[] SPcost,
                              float[] gSP, float interest)
{
    float WHtemp = WH;
    float SPtotal = 0;
    int n = MTTF.Length;

      float[] actual = new float[n];

      for (int j = 0; j < n; j++)
          actual[j] = ((1 + gSP[j]) / (1 + interest)); // actualization rate

      double[,] SPyear = new double[T,n]; // Spare parts cost per year

      for (int j = 0; j < n; j++)
      {
          for (int i = 0; i < T; i++)
          {
              if ((WHtemp / MTTF[j]) < 1)
              {
                  SPyear[i, j] = 0;
                  WHtemp = WHtemp + WH;
              }

              else
              {
                  double nSP = System.Math.Round ((WHtemp / MTTF[j]),0,
                               MidpointRounding.AwayFromZero);

                  SPyear[i, j] = nSP * SPcost[j] * Math.Pow (actual[j], (i+1));
                  WHtemp = WH;
              }

              SPtotal = SPtotal + Convert.ToSingle (SPyear[i, j]);
           }

          WHtemp = WH;
      }

      return
          SPtotal;
  }
```

Figure 4-1: Function for the calculation of the spare parts cost

The function “Actualization”, instead, given the discount rate, the machine lifetime and the growth rate of a certain variable, returns the sum of all the actualized rates corresponding to each single year of the whole machine lifespan (figure 4-2):

```
public float Actualization (float i, int T, float g)
{
    double temp;
    double actual= 0;
    double rate = ((1 + g) / (1 + i));
    for (int h = 1; h < T+1; h++)
    {
        temp = System.Math.Pow (rate, h);
        actual = actual + temp;
    }

    return
        Convert.ToSingle (actual);
}
```

Figure 4-2: Function for the calculation of the actualized discount rate

In regards to the main class, called “FormLcc”, the major methods involved are those for acquiring the input by the user (and checking their validity), and also the events connected to the click of a button. In the first case, in order to assess the correct insertion of data, the function “TryParse” provided by Visual C# has been used and a message box which notifies the eventual error to the user (called by the function “Error” in the “Procedures” class) is soon displayed on the screen (figure 4-3):

```
class Procedures
{

    public void Error(TextBox x)
    {
        MessageBox.Show("Invalid number. Please insert a correct number", "Attention",
                        MessageBoxButtons.OK, MessageBoxIcon.Warning);
        x.SelectionStart = 0;
        x.SelectionLength = x.Text.Length;
    }
```

Figure 4-3: Function for the notification of an error on input data

As concerns the real computational activity, instead, all the required operations for the calculation of the machine tool lifecycle costs are handled by the event “`BatchDone_Click(object sender, EventArgs e)`”, which is called once the button “Done” in the first form is clicked. By this method, indeed, all the input data are acquired, both those directly inserted by the user (and relating specifically to some enterprise production parameters) and also the ones regarding the technical characteristics of the machine tool at analysis and the economic data needed for the LCC calculation. These last two sets of data are directly provided to the program in the form of a pre-compiled .csv file, and then they are shown to the user through their insertion into a data grid. In regards to the machine components, for instance, the file “Component Parameters.csv” has been given as a reference for the algorithm, and here it is shown the code needed to separate the values and add each of them in a DataGridView (figure 4-4):

```
DataGridView ComponentGrid = new DataGridView();
StreamReader Data = new StreamReader("Component Parameters.csv");
string line = Data.ReadLine();
string[] tmp = line.Split(';');

for (int i = 0; i < tmp.Length; i++)
    ComponentGrid.Columns.Add(tmp[i].Substring(0, tmp[i].Length),
                              tmp[i].Substring(0, tmp[i].Length));

int j = 0;
line = Data.ReadLine();
while (line != null)
{
    ComponentGrid.Rows.Add();
    tmp = line.Split(';');
    for (int i = 0; i < tmp.Length; i++)
        ComponentGrid.Rows[j].Cells[i].Value = tmp[i].Substring(0, tmp[i].Length);
    j++;
    line = Data.ReadLine();
}
Data.Close();
Component.Controls.Add(ComponentGrid);
```

Figure 4-4: Algorithm code for file .csv reading and creation of a DataGridView

Finally, the last method of the code is the one related to the button “Calculate LCC”, handled by the event “`Calculate.Click += new System.EventHandler(Calculate_Click)`”, that only opens a new form in which the results (LCC) are presented to the user, together with the calculation of the cost per part and of the energy states of the machine components.

4.1.2 Presentation of the Graphical User Interface

The implemented algorithm is composed by the three forms, whose content is here presented.

The first form, as already mentioned, is purposely designed to acquire the parameters relating to the specific enterprise in relation to its time management efficiency and process requirements. The user, then, is firstly asked to compile the boxes relating to the enterprise working days, the number of shifts per day and the duration of each shift (figure 4-5).

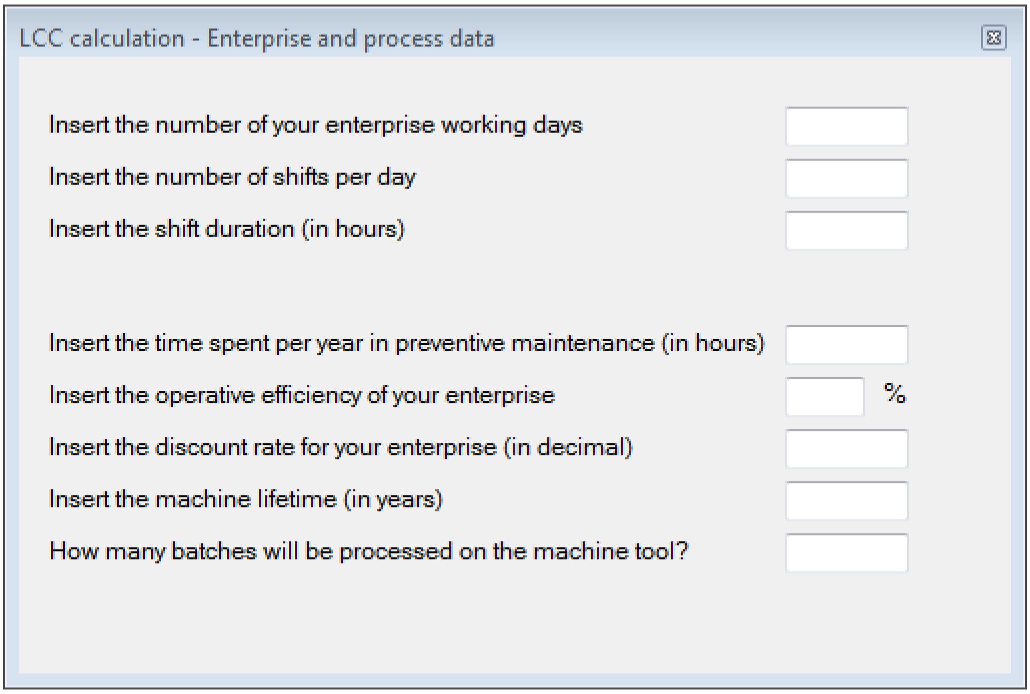


Figure 4-5: Initial form: enterprise and process data

The algorithm, then, will calculate the corresponding working hours in which the industrial plant is supposed to be operative (figure 4-6).

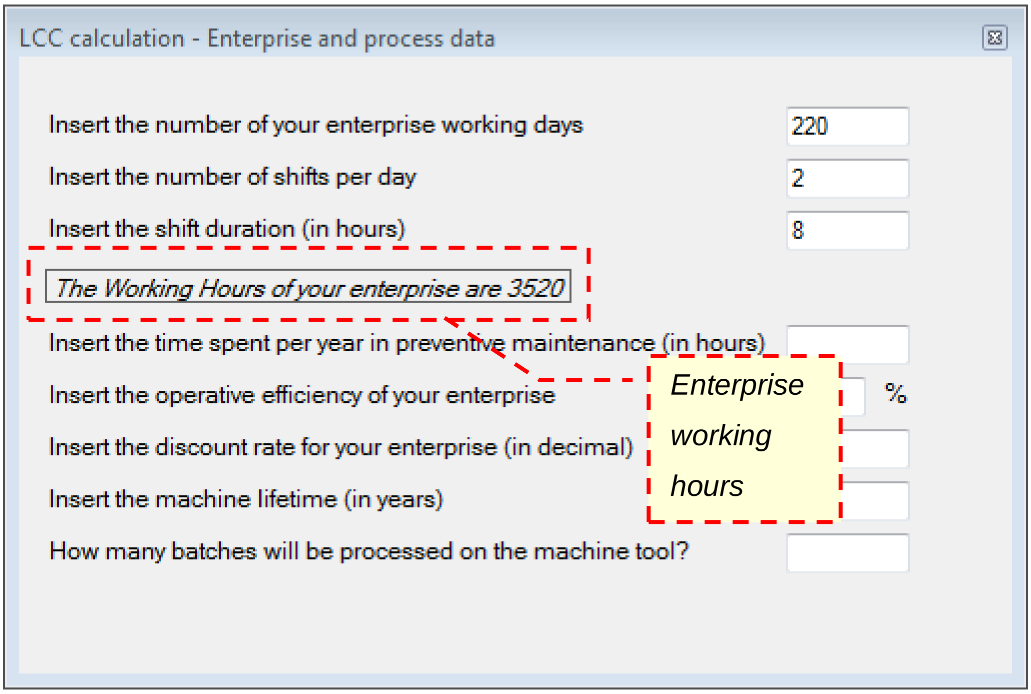


Figure 4-6: Example of data insertion: calculation of the enterprise working hours

The following boxes to be filled in refer instead to some other specific data (such as the time spent in preventive maintenance, the discount rate, the planned machine lifetime, etc.), and include also the definition of the process conditions in which the machine is demanded to run (number of batches, number of pieces per each batch, percentage of faulty pieces, process time per piece, set-up time, and so on…).

Once the user has inserted the number of batches that will be processed on the machine, a table with all the parameters required for each batch will be instantly displayed, together with the button “Done”, predisposed to acquire all the values in the form, and to open the second form in which the technical data are contained (figure 4-7).

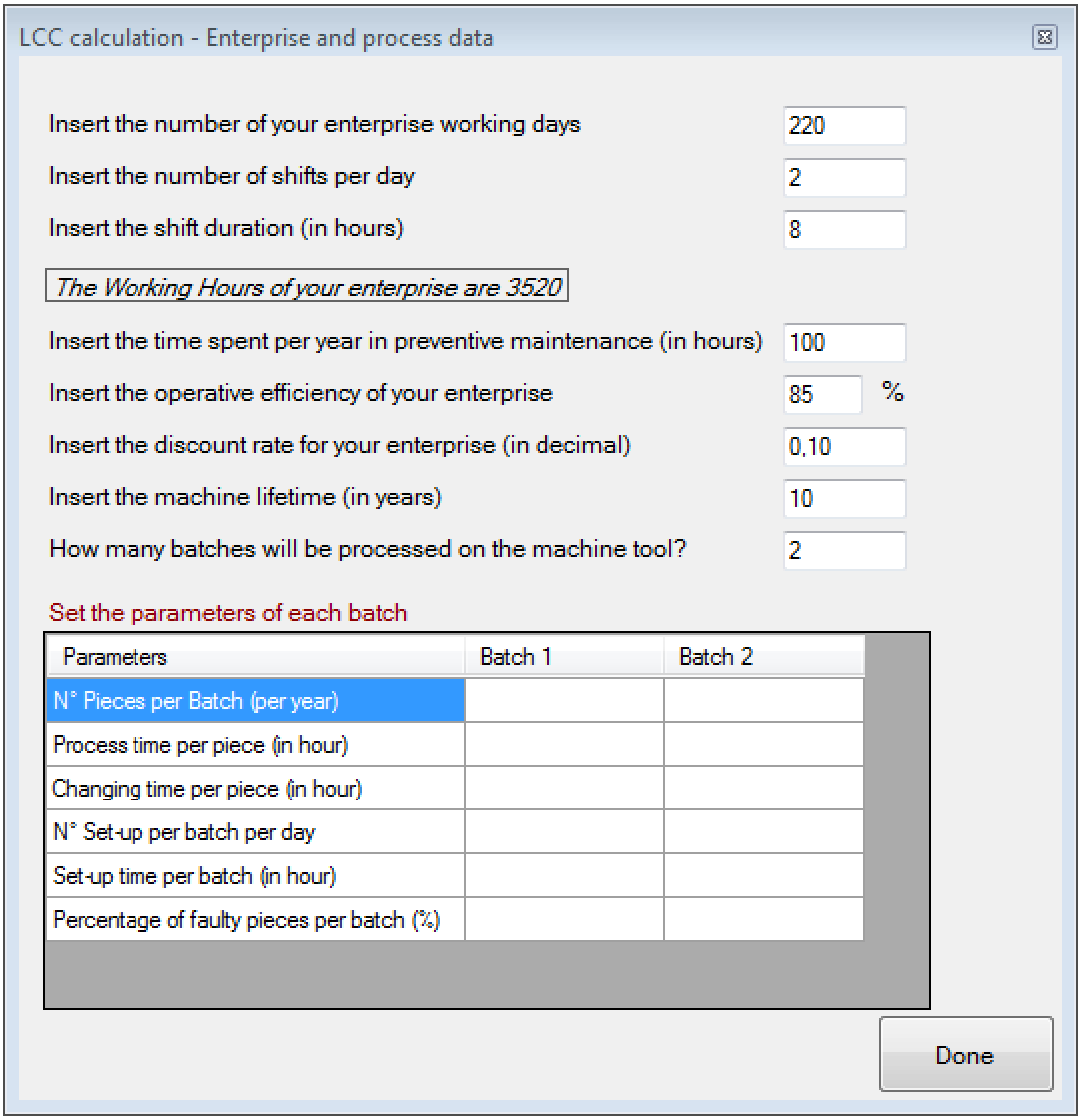


Figure 4-7: Initial form: insertion and completion of all the required data

Since the first form is designed for having a complete and essential interaction with the user, a formal control on the input data is absolutely required, in order not to generate code exceptions. Then, once the invalid input has been entered, as already mentioned, a message box which notifies the error to the user is soon displayed on the screen (figure 4-8).

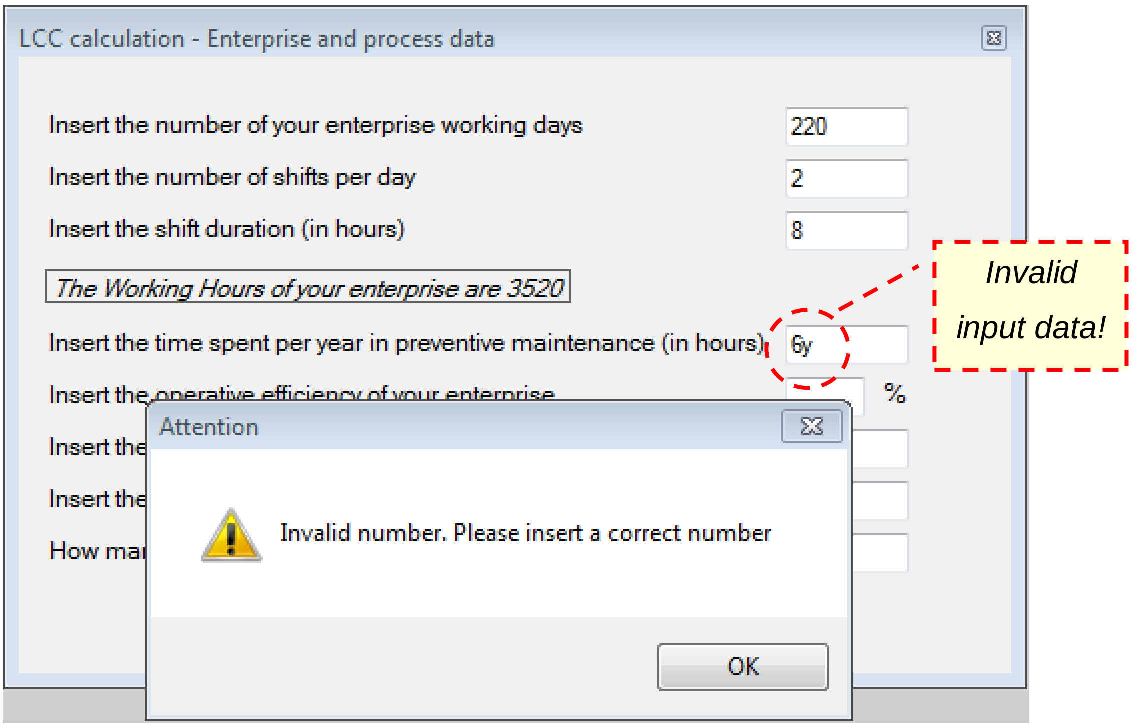


Figure 4-8: Example of data insertion: error message for invalid input

After having pushed the “Done” button, the second form appears on the screen: here the parameters of the machine tool components relating to their energy consumption and to their technical, logistic and economic aspects (such as component MTTF, dimension and cost) are grouped in a table (figure 4-9).

Components	Pprocess	Pidle	Phibern	AV	MTTF	g Cost	COST	Space
Axes and spindle cooling								
Axes and spindle drives								
Numeric control								
Ventilation								
Chip conveyor								
Axis lubrication								
Machine frame								

Figure 4-9: Machine components parameters

It is worthy to note that the initial list of machine components presented in the third chapter of this thesis (see table 3-2, p.52) has been modified, including another element, the “Machine frame”. The reason of this additional component lies in the will to take into account its eventual influence on the lifecycle costs, even if it is not related to any energetic consumption, but only to logistical needs. The hypothesis behind is to evaluate, for instance, the impact of the necessity to enlarge the machine structure for some production reasons (considering major component dimensions in virtue of a major power required and installed), or better for some safety reason (enhancing the frame dimension to better isolate the machine).

In the end, also the economic and supplier-based data, needed for the estimation of the machine lifecycle costs, are shown to the user in this second form through a data grid (figure 4-10):

Economic and Supplier-based data	value
Energy cost	
Growth rate of energy cost	
Mark-up on acquisition price	
Resale value	
Transport cost	
Installation cost	
Maintenance contract	
Maintenance labour cost	
Growth rate of labour cost	
Rent cost	
Growth rate of rent cost	

Figure 4-10: Economic and supplier-based parameters

No interaction with the user has been then implemented in this form, except for the presence of the button “Calculate LCC”, through which, after its pushing, the third form containing the results can be open and displayed. The complete representation of the second form is hereunder illustrated (figure 4-11):

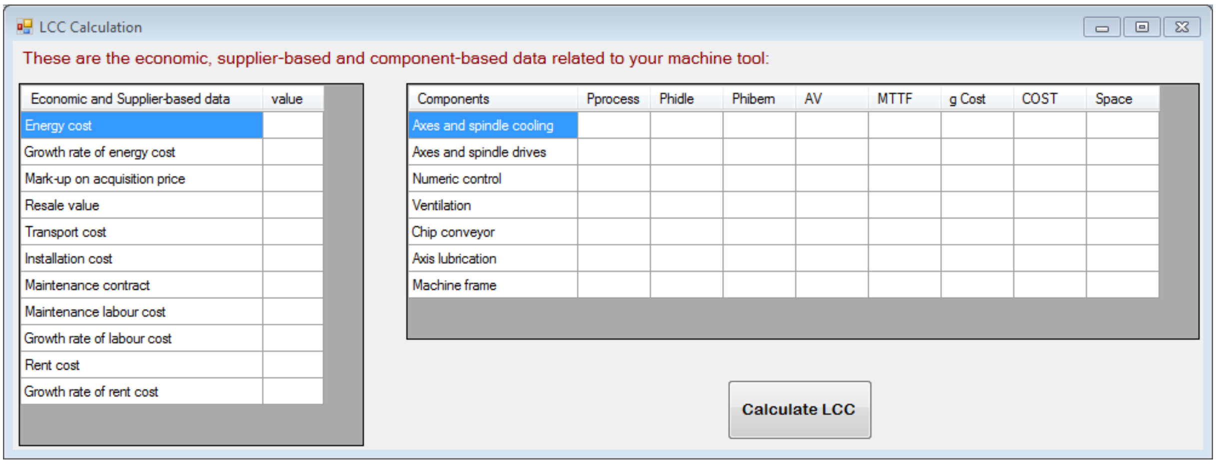


Figure 4-11: Second form

Finally, the output data required are resumed and grouped in the third form. In particular, the results concern:

- the machine tool lifecycle costs;
- the machine tool annual cost;
- the cost per part;
- the component energy states.

In regards to the machine tool lifecycle costs and annual cost, the algorithm is set in order to place the results in the left side of the form and highlight the total sum and the annual share (figure 4-12).

Acquisition costs: 78.545 €

Transport costs: 5.000 €

Installation costs: 3.000 €

Resale value: +0 €

Electrical energy costs: 8.128.590 €

Maintenance service costs: 162.218 €

Corrective maintenance costs: 2.098.609 €

Preventive maintenance costs: 72.775 €

Rent costs: 103.560 €

TOTAL: 10.652.300 €

Then the ANNUAL COSTS for the machine tool are :

1.065.230 €

Figure 4-12: Example of LCC results presentation

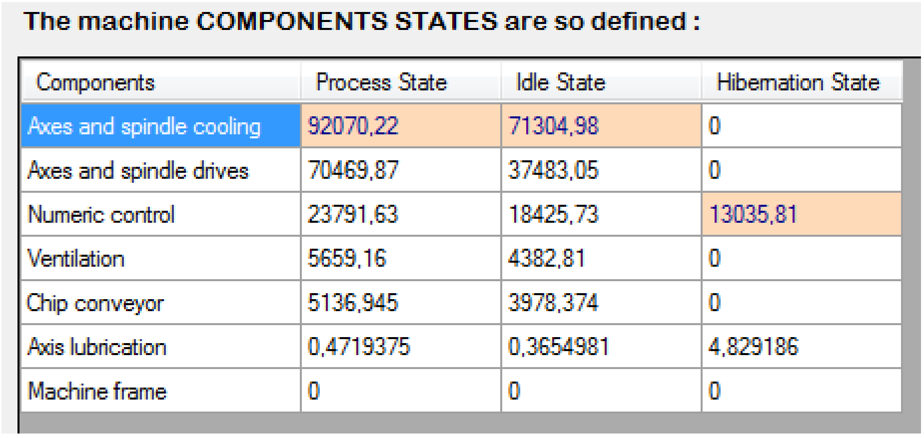
The cost per part and the component states are instead positioned in the right side of the form and their content is displayed in two data grid: the first one includes the number of produced pieces per batch, then the theoretical cost per part, the number of faulty pieces and the actual cost per part (figure 4-13).

The COST PER PART are :

Batch	1	2	3
N° Pieces per Batch	273	234	371
Cost per piece (€)	1.014,1	1.352,1	1.267,6
Percentage of faulty pieces	20 %	23 %	19 %
Actual cost per piece (€)	1.267,6	1.756	1.564,9

Figure 4-13: Example of Cost per Part grid

The second grid, instead, shows only the different energy states (Process, Idle and Hibernation state) for all the machine components. The purpose of displaying their energetic conditions is to highlight the machine tool parts that are more demanding in terms of time and power requirement, and then in terms of costs. This is useful in order to put the basis for a further research with the aim of evaluating how the energetic impact of certain components on the whole machine can be reduced by the improvement of their technical characteristics and performance (figure 4-14).

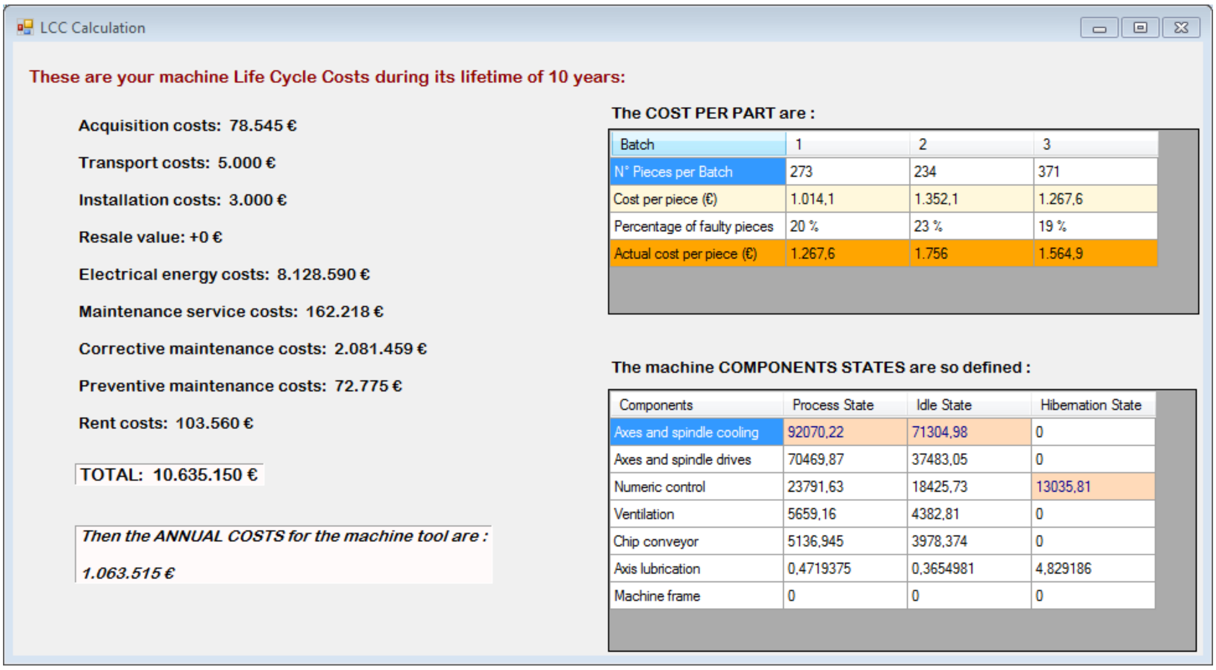


The machine COMPONENTS STATES are so defined :

Components	Process State	Idle State	Hibernation State
Axes and spindle cooling	92070,22	71304,98	0
Axes and spindle drives	70469,87	37483,05	0
Numeric control	23791,63	18425,73	13035,81
Ventilation	5659,16	4382,81	0
Chip conveyor	5136,945	3978,374	0
Axis lubrication	0,4719375	0,3654981	4,829186
Machine frame	0	0	0

Figure 4-14: Example of component states grid

Finally, the complete representation of the third form is shown in the picture below (figure 4-15):



LCC Calculation

These are your machine Life Cycle Costs during its lifetime of 10 years:

Acquisition costs: 78.545 €

Transport costs: 5.000 €

Installation costs: 3.000 €

Resale value: +0 €

Electrical energy costs: 8.128.590 €

Maintenance service costs: 162.218 €

Corrective maintenance costs: 2.081.459 €

Preventive maintenance costs: 72.775 €

Rent costs: 103.560 €

TOTAL: 10.635.150 €

Then the ANNUAL COSTS for the machine tool are :

1.063.515 €

The COST PER PART are :

Batch	1	2	3
N° Pieces per Batch	273	234	371
Cost per piece (€)	1.014,1	1.352,1	1.267,6
Percentage of faulty pieces	20 %	23 %	19 %
Actual cost per piece (€)	1.267,6	1.756	1.564,9

The machine COMPONENTS STATES are so defined :

Components	Process State	Idle State	Hibernation State
Axes and spindle cooling	92070,22	71304,98	0
Axes and spindle drives	70469,87	37483,05	0
Numeric control	23791,63	18425,73	13035,81
Ventilation	5659,16	4382,81	0
Chip conveyor	5136,945	3978,374	0
Axis lubrication	0,4719375	0,3654981	4,829186
Machine frame	0	0	0

Figure 4-15: Third form

4.2 Summary

In this chapter, a brief and illustrative description of the algorithm “*LC€nergy*” for the calculation of the lifecycle costs related to the energy consumption of a machine tool has been presented. In particular, a general overview on the structure of the code and of the graphical interface has been proposed, enhancing the reading through the use of the pictures relating to the different forms described.

In the next chapter, a complete evaluation of the concept and of its algorithmic implementation will be provided, in order to test both the logical coherence of the model, and its computational compliance in terms of output efficiency.

5 Evaluation

As for every computational implementation of a concept for the resolution of a specific problem or for the achievement of a desired result, the review and analysis of the output obtained after the analytical and algorithmic calculations is absolutely essential and strongly required. This is necessary not only to assess the presence and then the elimination of eventual bugs in the code, but above all to test the compliance of the algorithm to the real scenario of application, evaluating in this way if the output provided is both mathematically correct, and, most of all, reliable and relevant for the context in which it has been used.

The aim of the present chapter is then to give evidence of the efficiency and capability of the algorithm "*LC€nergy*" and to verify the robustness of the results at the variation of some critical parameters.

5.1 Benefits of evaluation

The software evaluation, intended in its broad meaning (and then comprehending also the phases of review, verification and validation), is the last step in the activity of implementing an algorithm (step 3, figure 5-1). It is a very crucial and significant point, since it implies the eventuality to face the inadequacy and insufficiency of the algorithm in achieving the goals for which it has been developed.

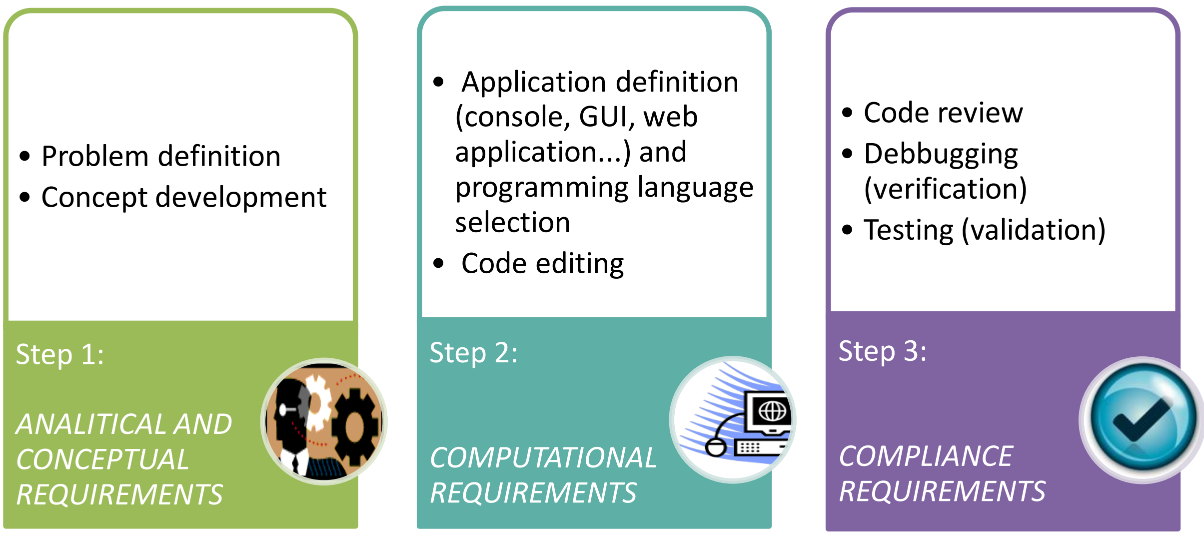


Figure 5-1: Algorithm implementation and evaluation procedure

It is then deducible that also all the preceding activities should be adequate, definitive and formalized, in order to assess the respect of the initial hypotheses and conditions by the algorithm: a bad appraisal of the conceptual and computational requirements (step 2 and 3, figure 5-1), is reflected in fact in the inability to produce the proper output, or the expected one.

The evaluation, therefore, is intended to test the whole research, in its theoretical definition and practical application, so to finally enclose the decisive judgement of how much worthy and deserving the work was.
The evaluation, then, allows the analyst to find an answer to these questions:

1) Has the initial problem or situation been properly and adequately identified and contextualized?
2) Has the problem been converted into a plausible and proactive solution?
3) Has the approach proposed been verified in the light of the initial conditions and of the expected final results?
4) Has a means for the implementation of the solution been found and adopted?
5) Has the implementation been produced the desired output?
6) Has the output been tested in order to assess its reliability?
7) Has the verification been sufficient to prove the implementation effectiveness?
8) Has a validation been carried out?
9) Have the results been proved acceptable and faithful to the relating scenario?
10) Has the research improved the actual level of knowledge and development in the context in which it has been applied?

From this partial list of all the potential questions to be taken into account during an activity of evaluation, it is anyway possible to individuate the major benefits connected to it, which can be briefly grouped in (figure 5-2):

- keeping the focus on the problem;
- testing the solution effectiveness;
- enhancing the solution robustness through the analysis of different scenarios;

– proving the usefulness and worthiness of the research, even in the eventuality of negative results.

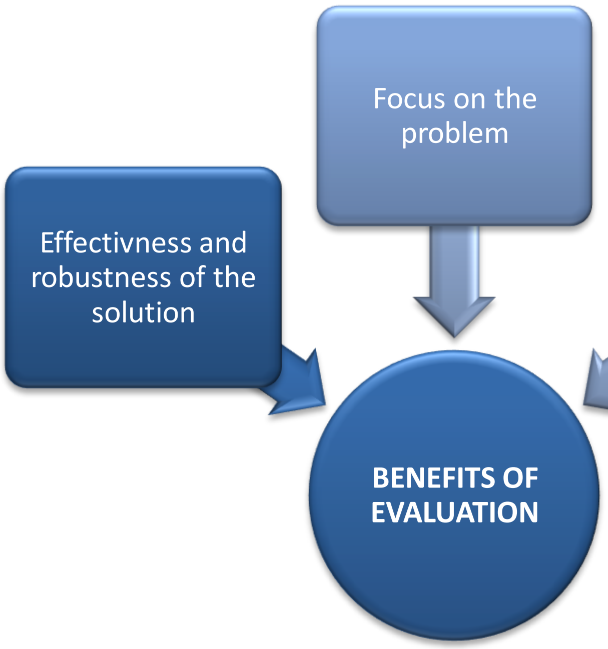


Figure 5-2: Benefits of evaluation

A correct and regular activity of evaluation, then, allows to gather and combine different sources of positive results, permitting the full respect of the initial conditions and hypotheses, and then the complete achievement of the desired outcome.

5.2 Evaluation procedure

In order to benefit of all the advantages related to the evaluation phase, it is important to define and formalize the procedure through which achieving them. What is required, then, is to zoom in on the third step described in figure 5-1 and define the flow of the activities to be carried out, which implies the need to analyze in details the phases of:

– Code review;
– Debugging;
– Testing.

Each of these elements of the evaluation procedure, indeed, is composed by a series of events and check points that, through their interaction, can easily lead the analyst to the achievement of the benefits previously listed, and therefore to the complete fulfillment of the project requirements.

The flow chart that has been derived to meet these requisites is depicted in the picture below (figure 5-3):

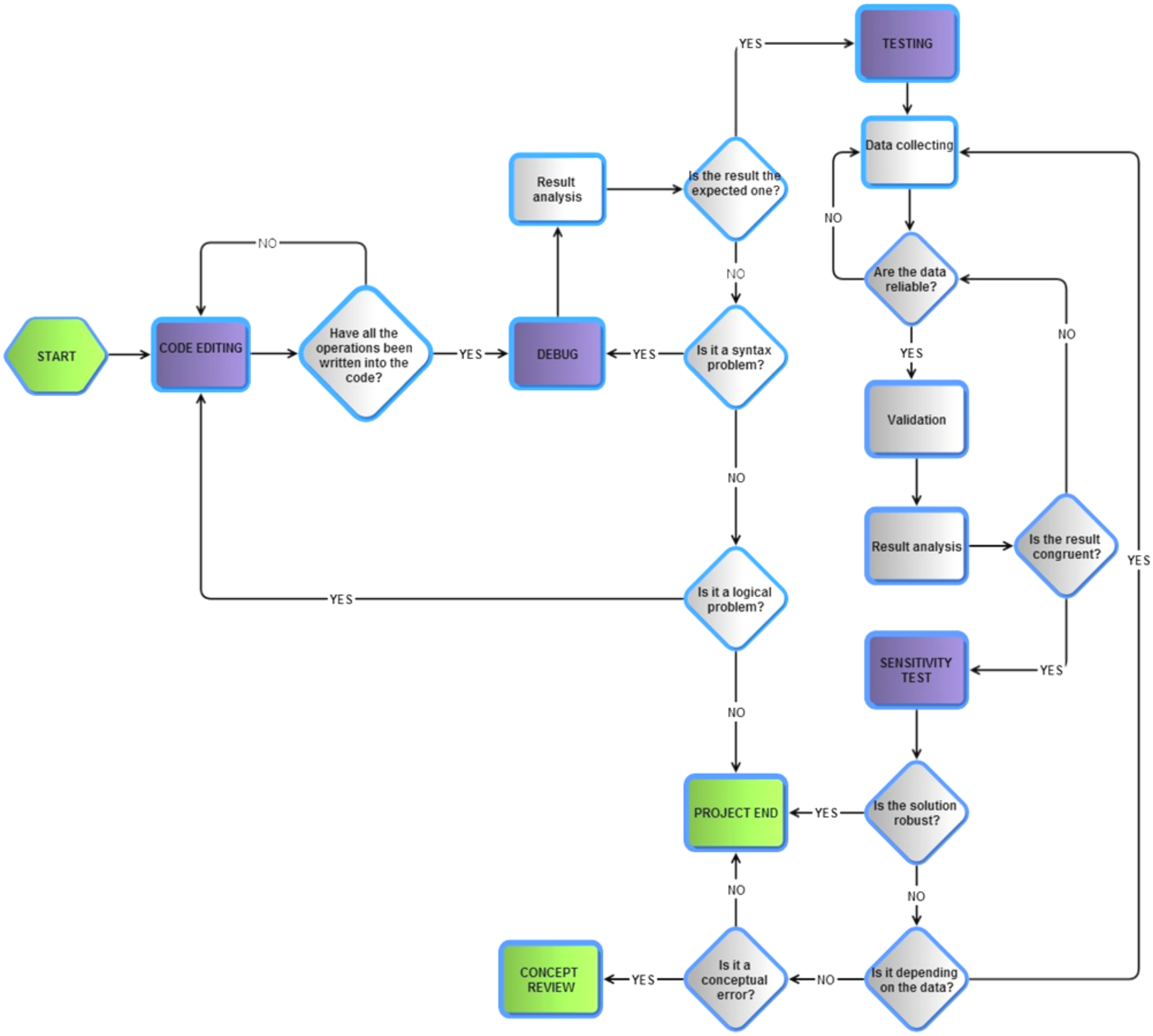


Figure 5-3: Evaluation flow chart

Starting from the code editing, the first verification consists in assessing the completeness of the algorithm operations: erroneously bypassing some logical and necessary functions would inevitably lead to the attainment of the wrong result. Once the code have been written in its entirety, the second phase is represented by debugging, and then by the verification of the result: if the outcome is plainly different by the one expected, a check both on the syntax and on the analytical operations is required. If the problem is simply a “grammatically” incorrect line of the code, indeed, it is sufficient to adjust the syntax; but if the computational operations are not faithful to the model requirements, then a review of the mathematical expressions of the concept has to be performed. In the case in which both the formulas prove to be effectual and the code is syntactically adequate, but the results differ from the real data, then some further analyses have to be carried out, ending the project and starting a new research on this phenomenon.

If the outcome is instead relevant and compliant to the expectations, the effective phase of testing can be started: after the collection of some real data and their examination in terms of reliability, the algorithm result is validated through its comparison with the data collected. Once the solution is proved to be dependable, a sensitivity analysis can be finally performed for evaluating its robustness: if the result is demonstrated to be stable, the project can end successfully; otherwise, a check on the data used or on the concept is recommended and required.

In the next paragraphs the most critical and sensitive aspects of the whole procedure will be presented and analyzed in details.

5.3 Verification

This phase consists essentially in providing the proof that the algorithm is at least computationally adequate, and then that it produces the expected result given a initial (even random) set of input data. The problems that can be faced in this step are substantially two:

1) Syntax errors;
2) Logic errors.

The first ones relate to an erroneous way of editing the code by the programmer, and can be represented, for example, by the lack of initialization of a variable or by the use of an undeclared variable. They can be identified by the compiler, and so are generally visible during the code compilation itself [FUNC13].

The logic errors, instead, are due to a bad comprehension or evaluation of the programming language tools, or to their bad application for the required operation. They can consist, for instance, in the choice of an inadequate loop control (for, while, do, etc), or in the general inability to transform the analytical requirements into the corresponding algorithmic command. For this reason, the logic errors are the most difficult to find: even if the syntax is correct, indeed, in order to be conscious of the potential fault and repair it, a good knowledge of the machine computational logic is needed [FUNC13].

In regards to "*LC€nergy*", both the algorithm syntax and the logic functions have been verified, supporting the analysis by the consultation of some tutorials and by the help provided by the Visual Studio debugger.

5.4 Validation

The validation phase is the one that guarantees the algorithm reliability, assessing its compliance to the requirements, and then proving if it can achieve the goals for which it has been developed. In order to ensure the completeness and congruence of this phase, it has been judged proper to carry on two different kinds of analysis:

- The evaluation of the result itself, given a set of real input data and their corresponding output, in order to appraise the eventual gap between this last one and the output provided by the algorithm;
- A sensitivity analysis, to estimate the robustness of the solution and identify the most crucial and decisive parameters, the ones which can sensibly affect the final result.

Both the activities will be presented in details in the next paragraphs.

5.4.1 Real data collection and result analysis

The data collection is always a key process, as pointed out in the second chapter of the present thesis, when analyzing the criticalities of the actual approaches in the quantification of lifecycle costs (Chapter 2, State of the Art, par 2.3). The congruence of the result (and then the worthiness of the whole project), indeed, is strongly dependent on the availability and reliability of the data themselves, and, in particular, also on their "coherence". What is suggested is that it is fundamental not only the amount of formalized information and its dependability, but also its being proper to the scope, its being adequate to the validation goals, that is identifying exactly which kind of data source could be the most suitable.

In regards to "*LC€nergy*", the aim is to obtain the machine tool lifecycle costs connected to its energy consumption: it is important, then, to decide which category of industry can be a valid reference for the data collection. Considering that the problem of precisely calculating the lifecycle costs and correlating them to the energy use can typically affect the job production systems (where the volumes are not so considerable to spread the fixed costs on a good amount of products and where the piece is characterized by a low rate of standardization and an high level of quality required), the context taken into account is represented by the aeronautical industry.

The data used then to test the concept and validate the algorithm have been collected by different enterprises database (not mentioned for privacy restrictions), and the final set is presented in the tables hereunder.

The data related to the enterprise parameters are the following:

Enterprise parameters	***Value***
Working days per year	220
Number of shifts per day	3
Shift duration (in hours)	8
Preventive maintenance time per year (in hours)	48
Operative efficiency (%)	68,84
Discount rate (%)	4

Table 5-1: Enterprise-based data

It is important to make a small observation in regards to the discount rate. Normally its appraisal requires a deep analysis of the enterprise capital structure, evaluating the ratio between equity and debt, in order to express it through the WACC (weighted average cost of capital) formula:

$$WACC = k_E \cdot \frac{E}{E+D} + k_D \cdot \frac{D}{D+E} \tag{5.1}$$

where:

- k_E is the cost of equity;
- k_D is the cost of debt;

– E is the amount of equity;
– D is the entity of debt.

The critical aspect of the WACC, anyway, consists in its difficult applicability, since it depends on the variation of the ratio between D and E: if the debt increases, both the cost of equity (k_E) and the cost of debt (k_D), at a certain point, will raise, determining a weighted cost of capital first decreasing, then increasing (figure 5-4) [PELL11].

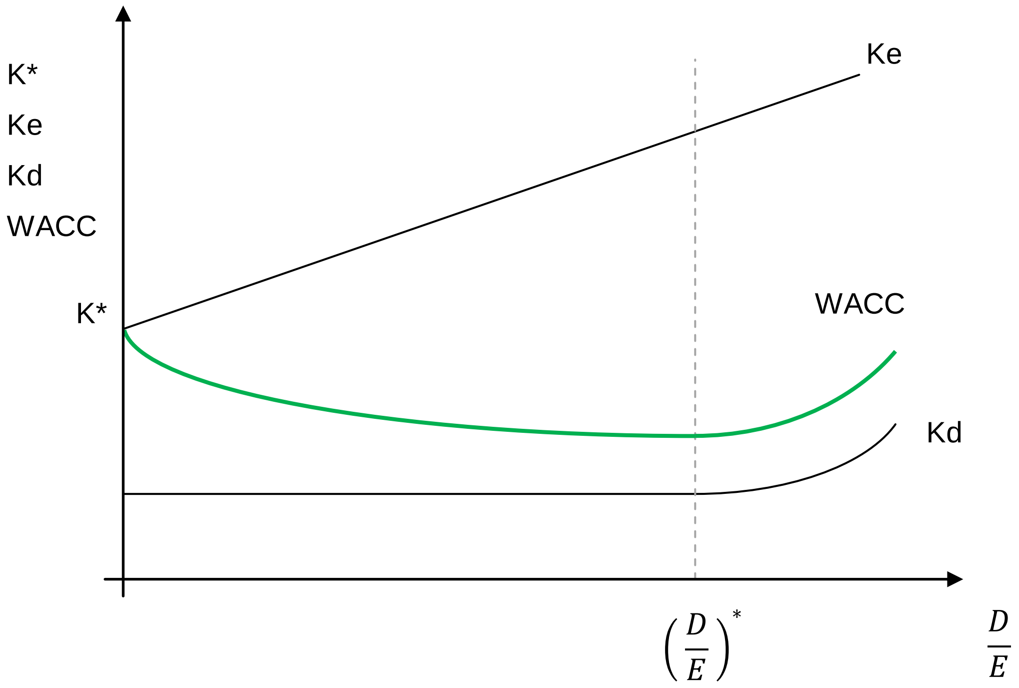


Figure 5-4: WACC variation in function of the ratio D/E [PELL11]

Where:

– K* is the cost of capital if the enterprise is unlevered (its financial structure is constituted only by the equity);
– Ke is the cost of equity;
– Kd is the cost of debt;
– WACC is the weighted average cost of capital;
– $\left(\frac{D}{E}\right)^*$ is the boundary ratio after that the WACC increases.

Even if some equations for expressing the WACC in functions of these parameters exist, the same results can be obtained by applying the method of separating the

NPV (Net present value) connected to the investment, from the NPV needed for remunerating the debt [PELL11].

In this way, making reference to the specific case of calculating the costs connected to a machine tool and making the assumption (as plausible) that these outflows are reasonably certain and at low risk (the machine will process a predetermined amount of pieces for a prefixed number of years – its lifecycle), the discount rate usually adopted is the one that the enterprise accepts to give the debt back.

Here the explanation of the little percentage used for the evaluation of the discount rate (4%).

In order now to linearly correlate the lifecycle costs with the energy consumption, some production scenarios have to be supposed. The case taken as an example regards the production of three different parts of the door of a plane, and these operations require each a specific configuration of the machine, and then they imply the necessity to plan the processing of three batches on the machine.

The process parameters are summarized in the table below:

Process Parameters	***Batch 1***	***Batch 2***	***Batch 3***
Number of produced pieces (year)	273	234	371
Process time per piece (in hours)	3	4	3,75
Changing time per piece (in hours)	0,1667	0,1667	0,1667
Number of set-up per batch per day	2	2	2
Set-up time per batch (in hours)	0,5	0,5	0,5
% of faulty pieces	20	23	19

Table 5-2: Process data

Then, other required input data relate to the machine components energy consumption (estimated for each of the three energetic states defined), together with some parameters regarding their technical performance, their cost and the space, or better their surface measured on the plane orthogonal to the machine height (table 5-3).

Components	Ppower	Pidle	Phibern	AV	MTTF	g Cost	COST	Space
Axes and spindle cooling	2926,348	2926,348	0	0,98	35040	0,08	22000	0
Axes and spindle drives	2239,805	1538,3	0	0,97	52560	0,04	34800	0
Numeric control	756,19	756,19	410,306	0,95	306600	0,03	1000	0
Ventilation	179,87	179,87	0	0,92	87600	0,09	3000	0
Chip conveyor	163,272	163,272	0	0,94	17520	0,06	6500	0
Axis lubrication	0,015	0,015	0,152	0,96	262800	0,05	1000	0
Machine frame	0	0	0	0	0	0	0	20

Table 5-3: Machine components parameters

In the end, the last data, and maybe the most important for the lifecycle cost appraisal, refer to the some economic parameters and to the supplier services and conditions (table 5-4).

Economic and Supplier-based data	*Value*
Energy cost	0,11
Growth rate of energy cost	0,18
Mark-up on acquisition price	0,15
Resale value	+ 0
Transport cost	5000
Installation cost	3000
Maintenance contract	2000
Maintenance labour cost	18,5
Growth rate of labour cost	0,002
Rent cost	5,32
Growth rate of rent cost	0

Table 5-4: Economic and supplier-based data

After having provided all these input data to the algorithm, the result returned is shown in the table below:

Lifecycle costs	**€**
Acquisition costs	78.545
Transport costs	5.000
Installation costs	3.000
Resale value	+ 0
Electrical energy costs	8.128.590
Maintenance service costs	162.218
Corrective maintenance costs	2.098.609
Preventive maintenance costs	72.775
Rent costs	103.560
TOTAL	10.652.300
ANNUAL COST	1.065.230

Table 5-5: Lifecycle costs in output

	Batch 1	***Batch 2***	***Batch 3***
N° pieces	273	234	371
Cost per part	1.014,1	1.352,1	1.267,6
Faulty pieces	20%	23%	19%
Actual cost per part	1.276,6	1.756	1.564,9

Table 5-6: Cost per part in output

In order to validate now the output efficiency, a comparison with some realistic values would be recommended. The issue, anyway, is that the concept implemented through "*LC€nergy*" is almost innovative, being the first in its category to estimate the machine tool LCC in function of its energy consumption. It is then evident the impossibility to compare the results, since no real data at the present are available for this specific purpose. Nevertheless, even if a concrete comparison is to be excluded for some practical and self-evident reasons, a way to appraise the validity of the concept has been found in the experts' consultation: a very knowledgeable and qualified person in the subject of LCC has been asked to evaluate the concept, obtaining finally his approval on the analytical method developed to estimate such costs. Then, since the algorithm has been verified and the specialist's opinion has been positive and confident, it can be confirmed the computational and conceptual compliance of "*LC€nergy*" to the requirements.

It has to be underlined, anyway, that the lack of data is a limit, and for this reason a real application of the concept to the industrial context is strongly required: only through the real and continuative experience, the results could be completely verified, and then totally validated for the future.

5.4.2 Sensitivity test

Once assessed the algorithm validity in terms of output reliability, it could be also important to evaluate its robustness, so to delineate, by the way, where action can be taken in order to improve the results.

The parameters whose values have been modified to appraise the impact on the final output are the following:

- Energy cost;
- Growth rate of energy cost;
- Process time;
- Components availability;
- Enterprise operative efficiency.

For each of them, only the lifecycle costs directly affected by their variations have been considered (together with their effect on the cost per part), and the result is commented and depicted in the pictures hereunder.

In regards to the energy cost, it has been considered a variation in the range of 0.03-0.27 €/kWh, and, as deducible, the impact on the LCC is significant. The increase, not only for the energy costs, but also in regards to the whole machine LCC, is almost linear: considering an increase by 800% of the energy cost (from 0.03 to 0.27 €/kWh), the registered increase in the machine LCC is by the 400% (from 4,787,783.673 € to 23,037,597.05 €).

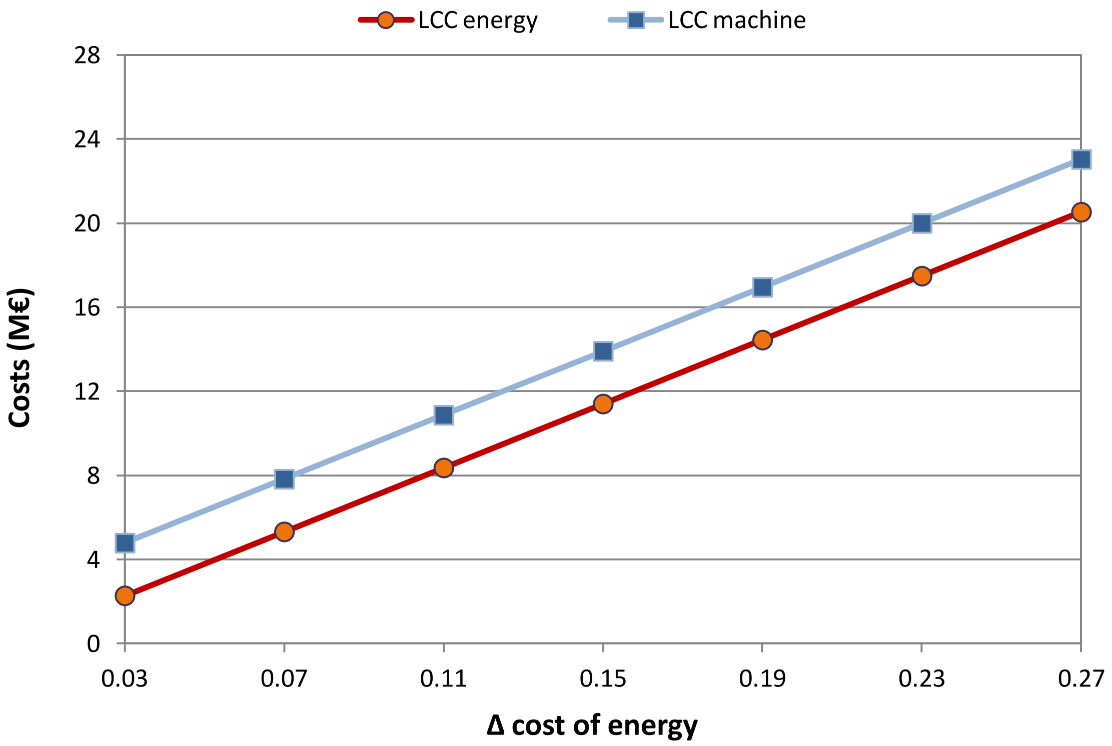


Figure 5-5: Effect of the variation of energy cost on the machine LCC

Also in regards to the cost per part, the increase produced by the variation of the energy cost is reflected in a linear rise of the product cost, characterized by different slopes, because of the different incidence of the process time and the number of produced pieces for each batch on the total time of production.

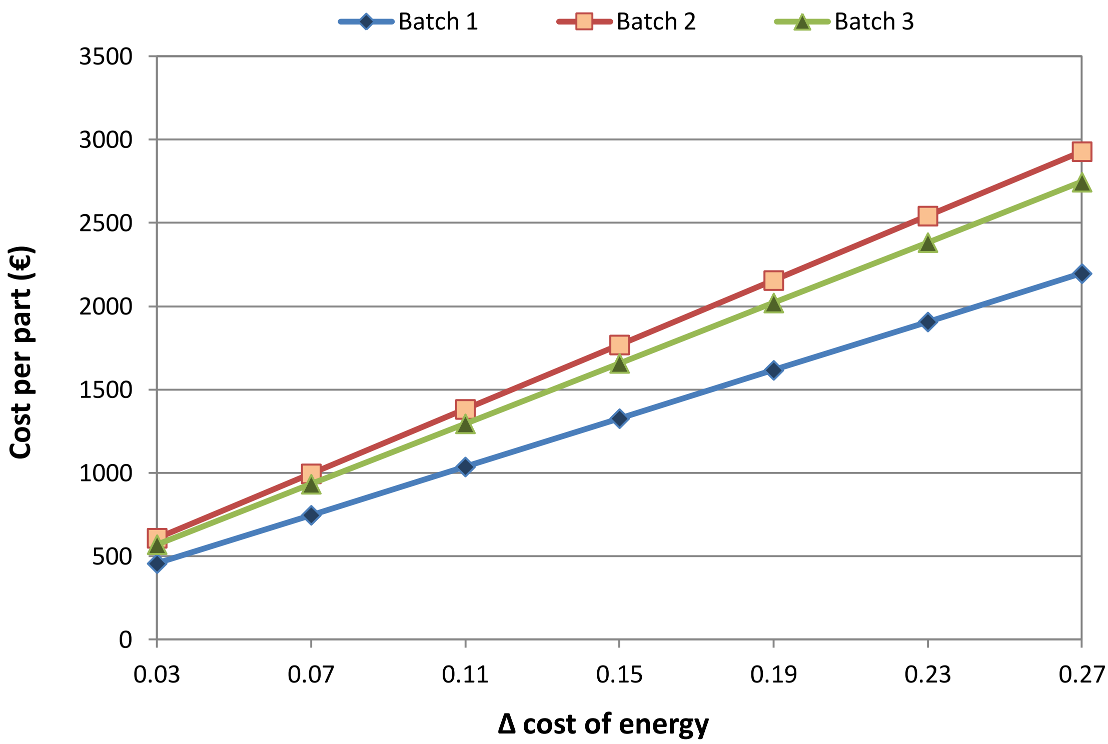


Figure 5-6: Effect of the variation of energy cost on the cost per part for each batch

As concerns the energy growth rate, the trend is exponential (figure 5-7), as deducible by the fact that in the LCC calculation it is always elevated, year by year, to the annual corresponding index (see formula 3.17, p. 61). Also the cost per part follows the same law, being proportionally dependent on the annual share of the LCC, and so, for not overloading the reading, it will not be illustrated.

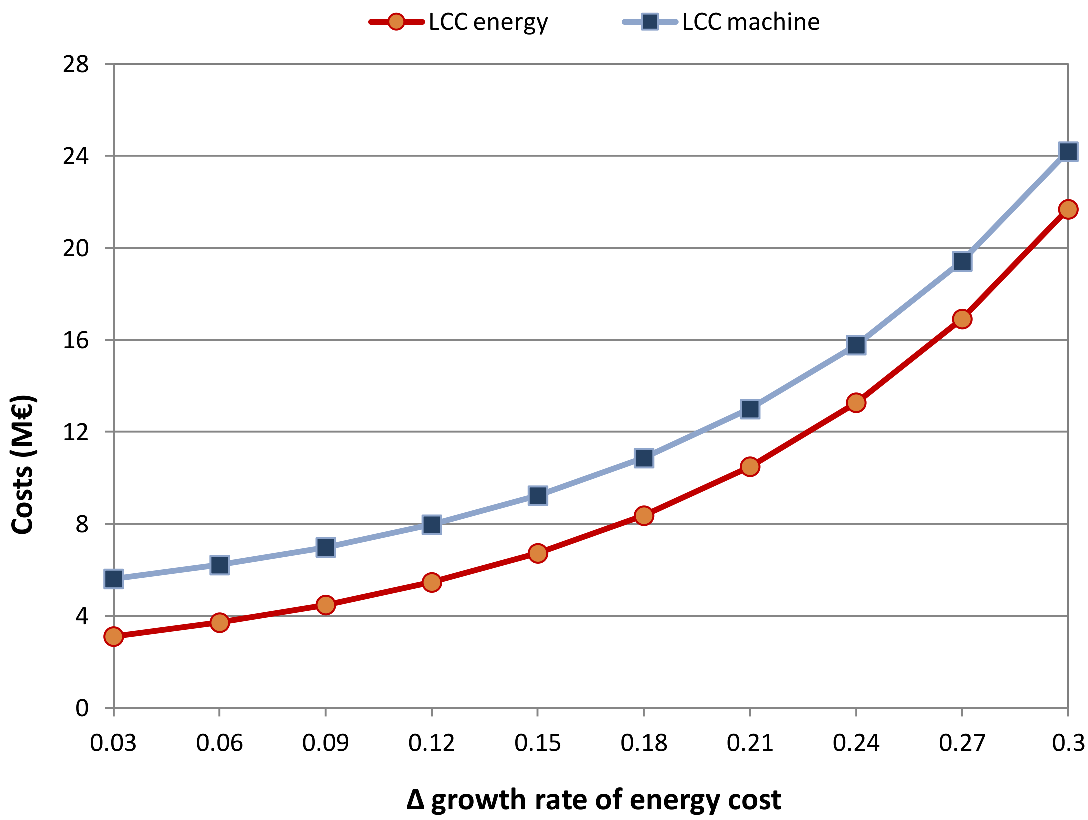


Figure 5-7: Effect of the variation of the growth rate of energy cost on the machine LCC

Directly connected to the energetic expenditure of a machine tool, besides the energy cost and its growth rate, there is also the process time required to satisfy the production needs. For this reason, the variation of the process time for the batch with the biggest number of produced parts and also for the batch with the highest value of this parameter has been studied and the result illustrated in the graphs below.

In regards to the batch with the biggest number of pieces, the impact on the LCC due to the process time decreasing is linear, but the slope is not really significant (figure 5-8). The effect on the cost per part is also linear, but here the slope is a little bit more accentuated, with an evident significant decreasing of the cost per part of the batch whose process time has been reduced, and the corresponding increasing of the other two batches costs, under the influence of the third batch (figure 5-9).

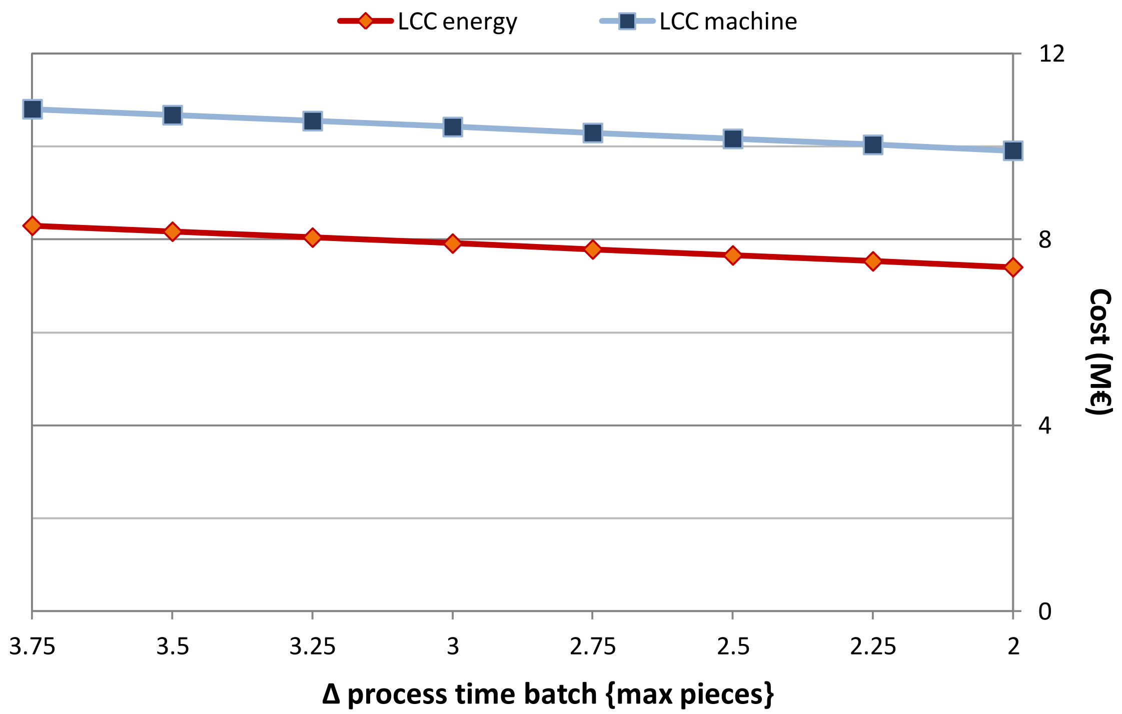


Figure 5-8: Effect of the variation of the process time of the biggest batch on the machine LCC

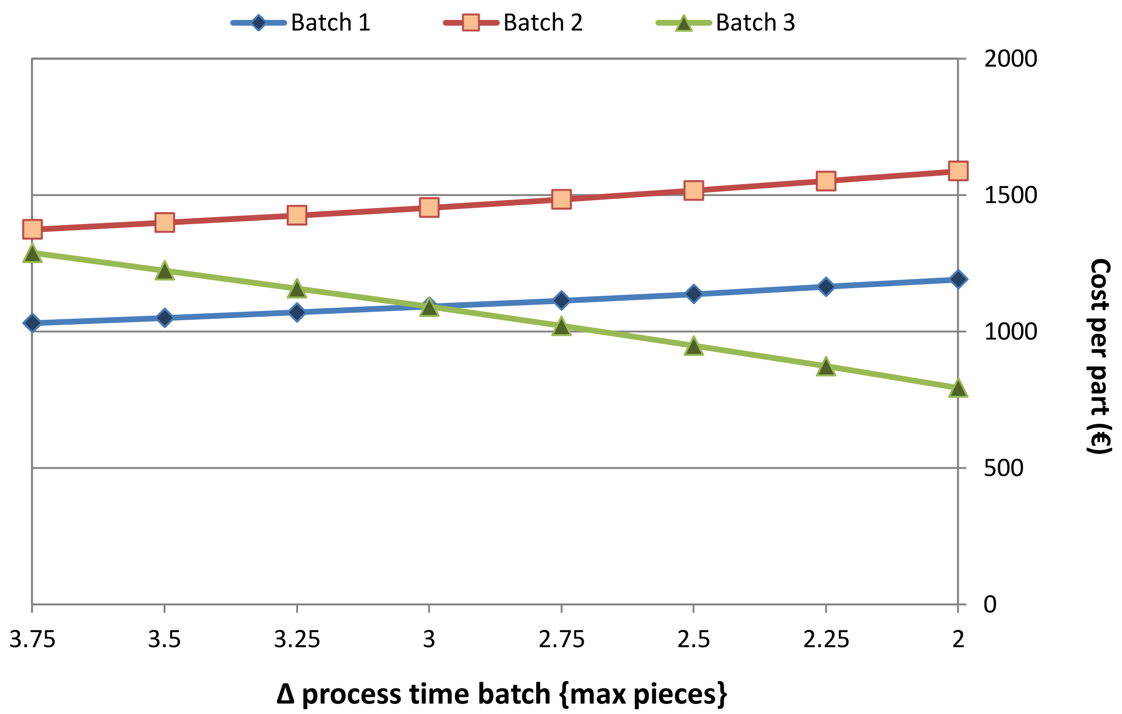


Figure 5-9: Effect of the variation of the process time of the biggest batch on the cost per part

As concerns the batch with the highest process time, instead, both the reduction of LCC (figure 5-10) and the impact on the cost per part (figure 5-11) is less significant than the previous case: this is a confirmation of the fact that the numerousness is the most important factor for costs decrease.

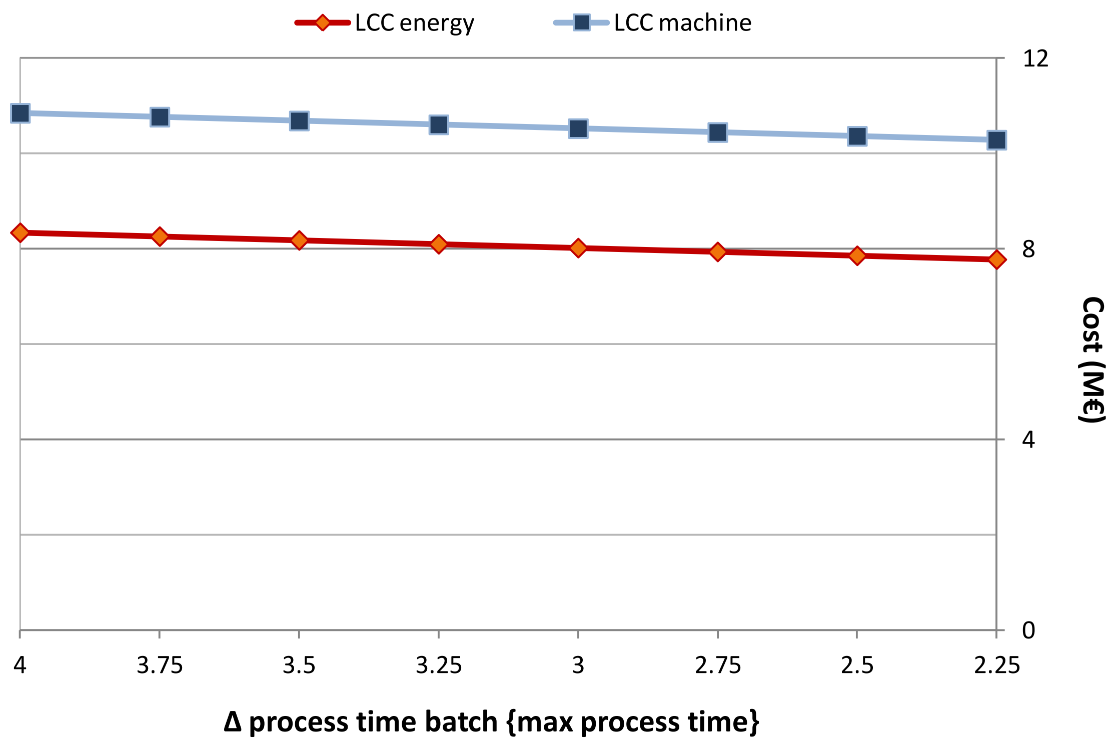


Figure 5-10: Effect of the variation of the process time of the batch with the highest process time on the machine LCC

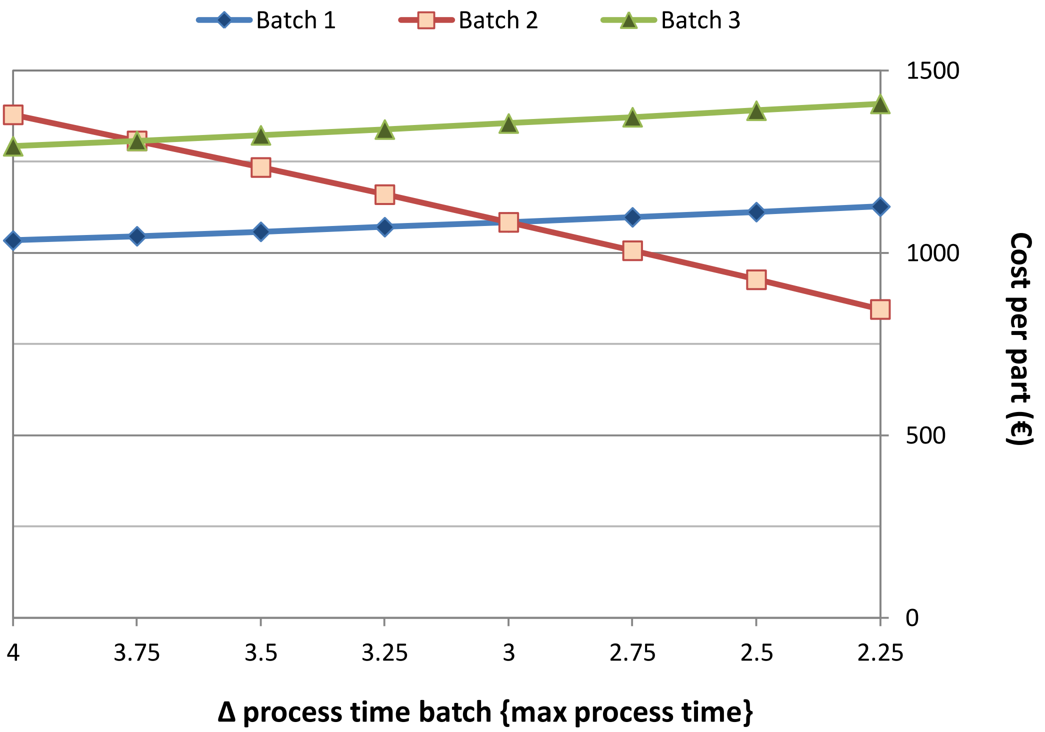


Figure 5-11: Effect of the variation of the process time of the batch with the highest process time on the cost per part

Considering now the components availability, the first thing to say is that the costs relating to corrective maintenance are those influenced the most by its variation: it is in fact deducible how increasing the component reliability, the time spent in inspections and reparations automatically decreases. It is important to highlight, moreover, that what changes is only the time spent in fixing all the eventual problems related to the machine components, and not the number of spare parts: the assumption, for now, is that the increase of availability is obtained by a decrease of the MTBF, being equal the MTTF (see formula 3.22, p. 64).

So, the components whose availability has been evaluated are:

- Axes and Spindle cooling and drives, that are the most important components for the process, and with the lowest value of expected life (MTTF);
- Ventilation, the component with the lowest availability in the simulation model.

The results are presented in the picture below, and it is noticeable how the impact of the corrective maintenance on the machine LCC is not really significant compared to the effect of the energy cost, previously analyzed: anyway, the reduction caused by the enhancement of the most important components (figure 5-12 and 5-13) is more consistent than the variation due to the ventilation improvement, whose trend is almost flat (figure 5-14), confirming the logical hypothesis that only the most energy-consuming components are those worthy to be constantly developed in more technically efficient versions.

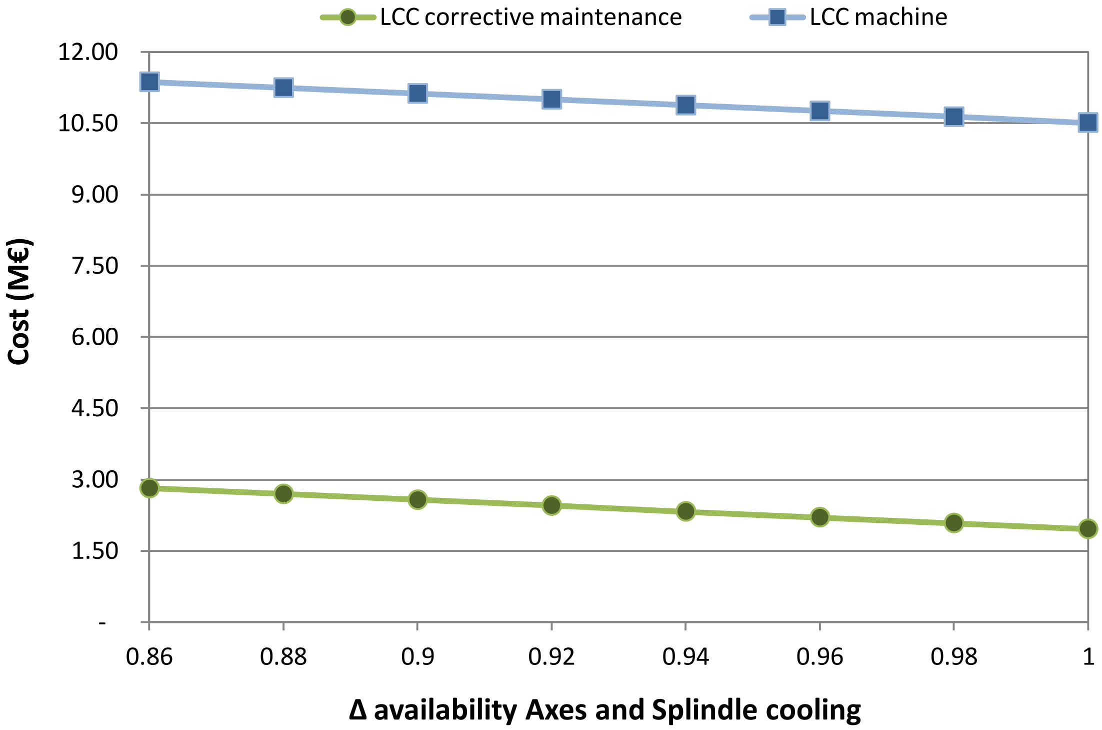


Figure 5-12: Effect of the variation of the axes and spindle cooling availability on the machine LCC

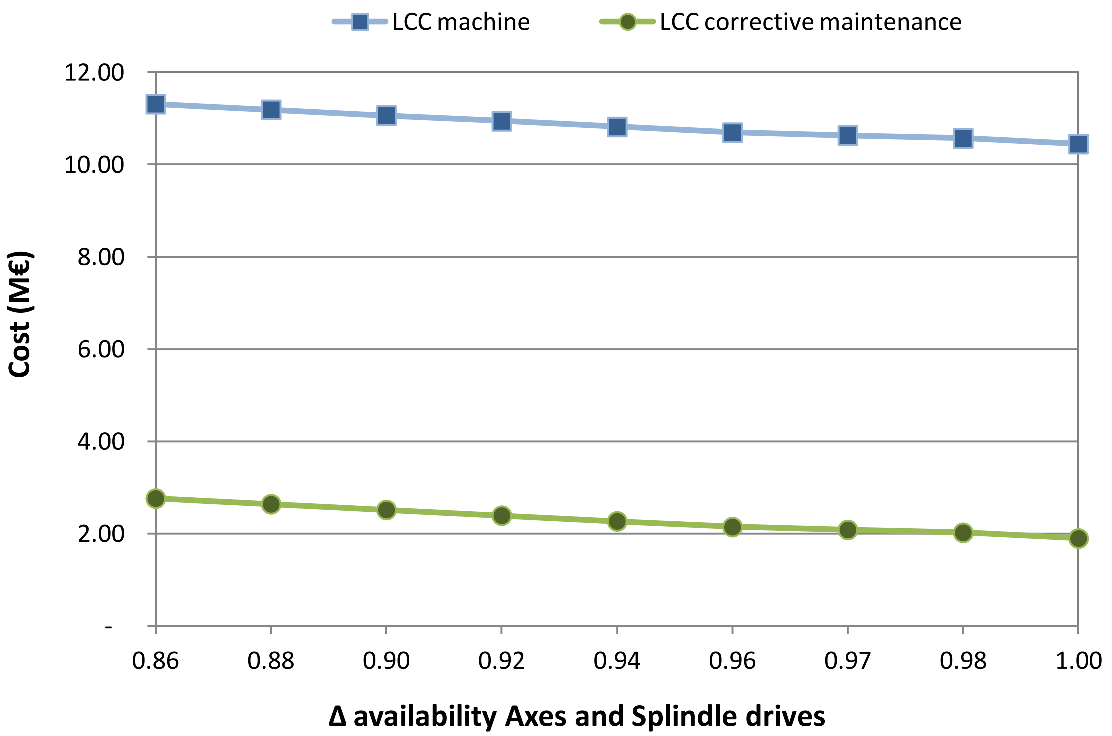


Figure 5-13: Effect of the variation of the axes and spindle drives availability on the machine LCC

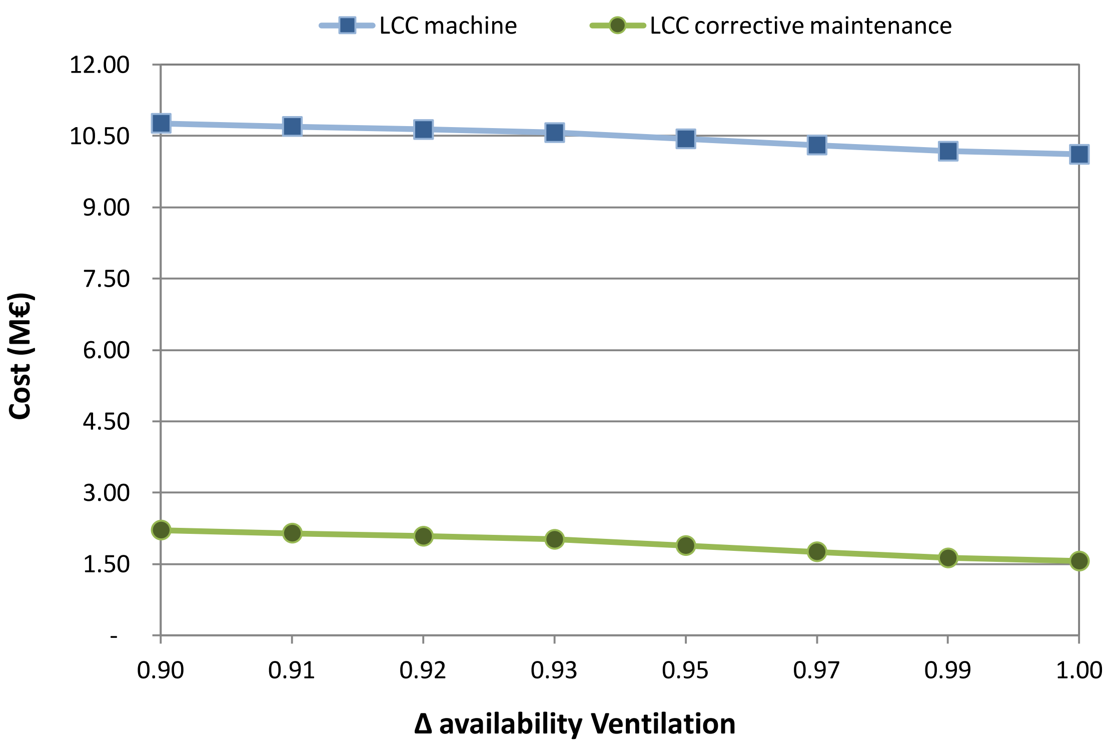


Figure 5-14: Effect of the variation of the ventilation availability on the machine LCC

Finally, the last parameter to consider is the operative efficiency. It has a direct impact on the Hitch time (see formula 3.4 and 3.5, p. 55), or better it is the factor through which it is possible to deduce how much efficient is the enterprise in the management of all the processes that do not directly impact on the final product. It means that, through the enhancement of the operative efficiency, the machine Idle state would be consequentially reduced (see formula 3.8, p. 56), and then also the LCC (both related to energy and to the machine tool in general) would be positively influenced (figure 5-15).

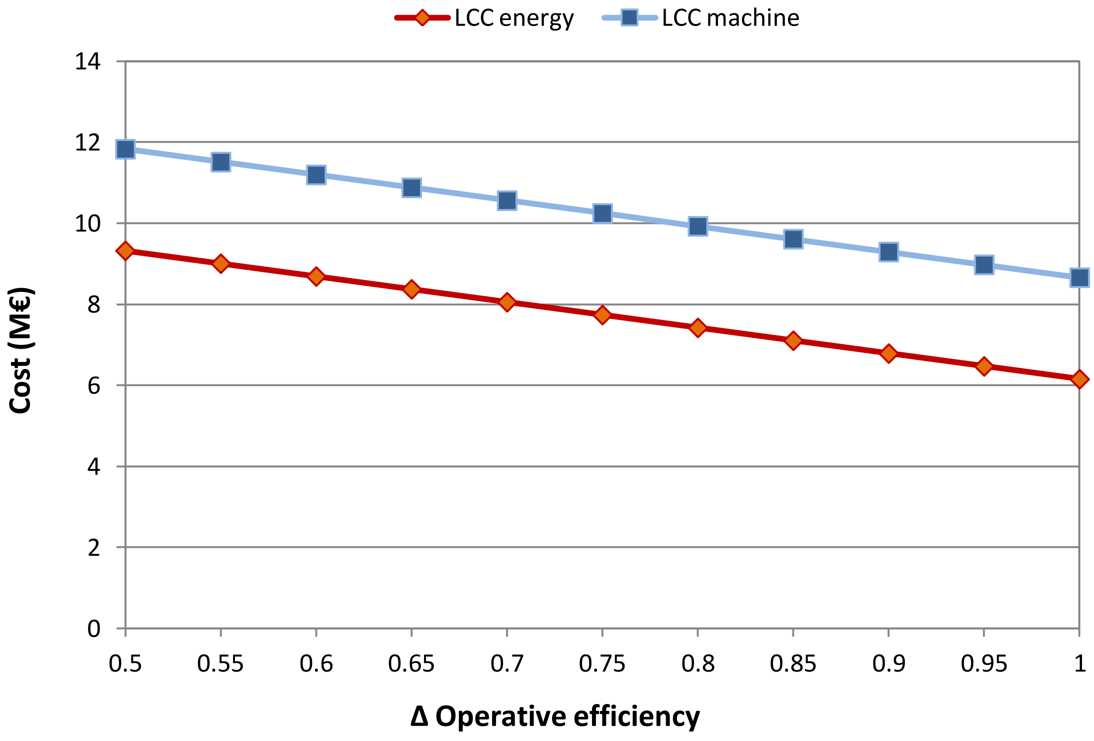


Figure 5-15: Effect of the variation of the operative efficiency on the machine LCC

Once assessed the impact of all these parameters on the lifecycle costs, another interesting evaluation is to consider how the acquisition costs can vary reducing the machine power requirement, being equal all the other costs. As highlighted in the state of the art (chapter 2, par. 2.2.2), indeed, customers are really sensitive in regards to purchase price, but if it can be proved positive the impact of energy savings on the initial capital expenditure, this could represent a valid means for persuading organizations in buying higher-priced machines, but also with an higher efficiency in terms of energy consumption, and then of energy costs.

Then, the validation test conducted relates to the assessment of the potential purchase price in function of the machine energy requirements variation, without modifying the current lifecycle costs structure (the value of all the other costs has been kept unaltered). The result is shown in the pictures below:

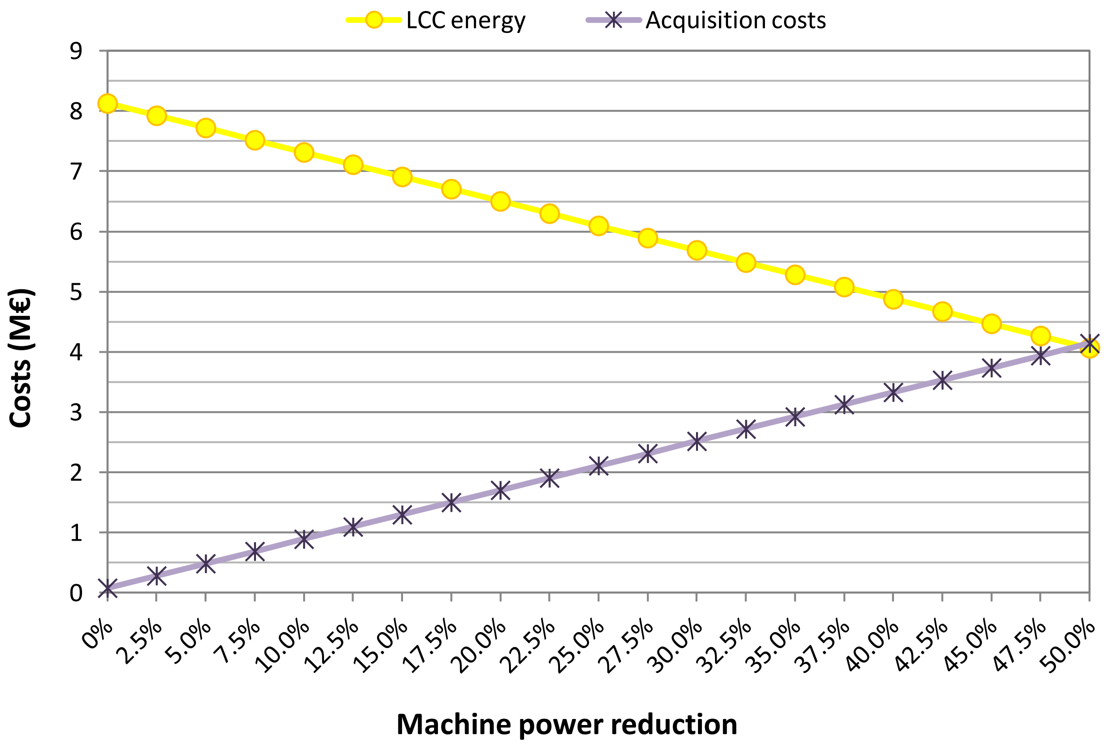


Figure 5-16: Variation of acquisition and energy costs in function of machine power reduction

As immediately noticeable, the trend is linear and perfectly symmetrical: the progressive reduction of machine power requirement leads to a negative slope of the energy lifecycle costs, which implies the contextual potential rise in acquisition costs (figure 5-16). It implies that, if the machine tool is able to save, for instance, just the 15% of its energy consumption, the corresponding purchase price that the customer could accept is even bigger by almost 1600% than the present value (78.545 €), without compromising the already estimated lifecycle costs (figure 5-17).

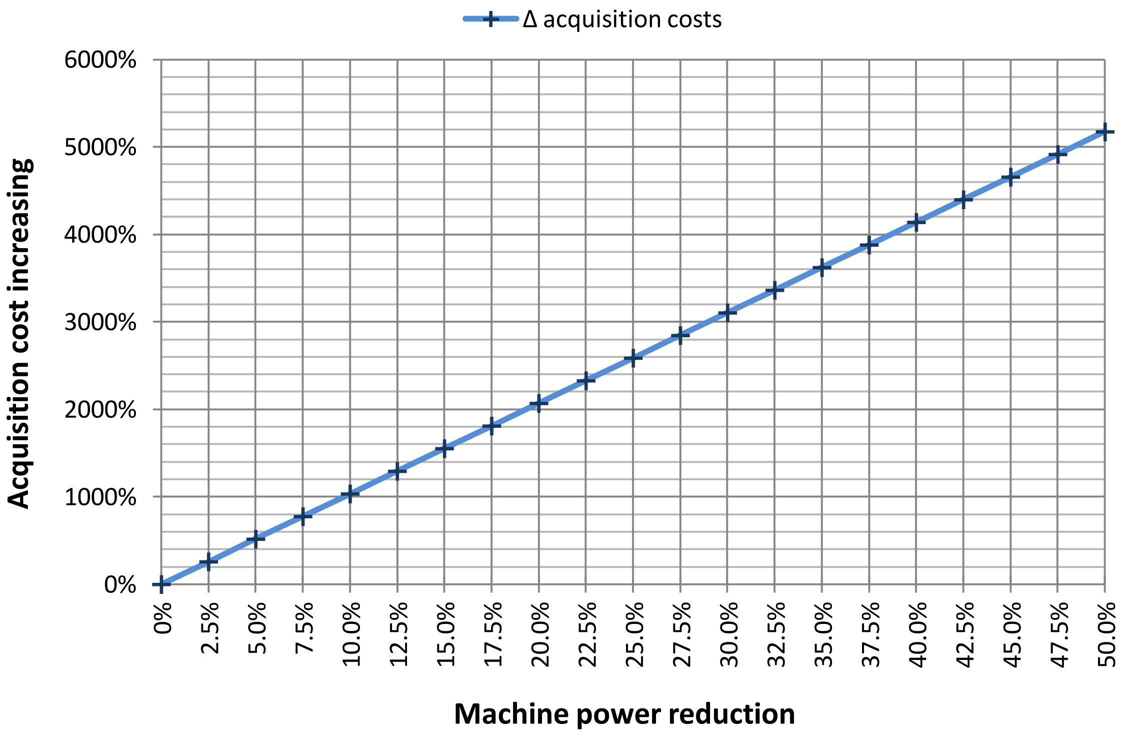


Figure 5-17: Percentage of acquisition costs increasing in function of machine power reduction

5.5 Summary

In this chapter the method through which the algorithm has been verified and validated has been described. First, a brief introduction on the importance of subjecting the results to a phase of control has been proposed, emphasizing also the benefits related to the evaluation process, generally identifiable in guaranteeing the focus on the problem and proving the effectiveness of the results and of the project in general. Then, the flow chart of the whole procedure has been presented, analyzing specifically the phases of verification and of validation.

The verification has been described only in the meaning of assessing the computational effectiveness of the algorithm, evaluating the mathematical correspondence between the input and the output. For the validation phase, instead, the proof of the conceptual effectiveness of the algorithm was required. For that reason, some real and/or plausible data have been collected and used as input for the algorithm; anyway, because of the lack of empirical results, the output could not be traditionally validated, but it will constitute the basis for future assessments, once the algorithm will be really adopted by the enterprises in their accounting processes.

At the end, a sensitivity analysis has been carried out, in order to understand the most critical parameters of the concept (the input data whose impact on the final output is the most considerable) and also to assess the effect of energy savings on the initial capital expenditure, so to delineate in both cases where intervening to improve the results.

In the next chapter, the critical aspects of the implemented concept, relating both to the analytical and conceptual deficiencies and to the insufficiency of the economic parameters considered, will be presented and discussed.

6 Critical aspects

In the current industrial context, the always harder requirement of achieving both technical efficiency and cost effectiveness implies the need to keep constantly the focus on market exigencies, economic factors and manufacturing restrictions for the entire lifetime of a product, especially at the beginning of its design phase [DENK13]. And dealing with some economical and technical aspects (and also with their future trends and expectations) could be often very complex and challenging: if the industrial requirements can be somewhat objective and their trend can be reasonably estimated through the study of the new technologies evolution, the economic parameters depend on a huge set of conditions and hypothesis, and then their evaluation must be subjected to a certain degree of tolerance, in order to consider the eventual deviations from the original (or expected) scenario.

The aim of the present chapter is then to put in evidence the criticalities emerged from the concept implementation, distinguishing between the technical issues and the economic matters.

6.1 Technical criticalities

The most significant technical insufficiency of the algorithm is related to the calculation of the spare parts number. The solution proposed (see formula 3.24, p. 65) is based only on the consideration of the MTTF (the expected life of the component), but it does not take into account the probability distribution for the components breakdown. Moreover, since the machine tool components are heterogeneous and various, the first observation that has to be done is to make a distinction between the electronic parts and the mechanical ones: the mathematical models that describe the two probability distributions, indeed, are very different.

The electronic components are not subjected to wear out, so they do not degrade over time: in more analytical terms, if the component is still working at time t, the distribution of its residual life (that is the probability that the component keeps on working at time s, with $s > t$) is independent from the time t elapsed. The cumulative probability distribution that best describes this behaviour is the exponential one:

$$F(t) = 1 - e^{-\lambda t} \qquad (6.1)$$

Where:

- $\mathrm{F(t)}$ is the *cumulative probability distribution* relating the breakdown of an electronic component at time t;
- λ is the *failure rate*, the frequency of a component breakdown, and then its MTTF;
- t is the instant of breakdown in which the probability is calculated.

As noticeable, the failure rate λ is constant, it does not vary over time, and then it represents exactly the characteristic of time-independency of the electronic components.

As concerns the mechanical components, instead, they cannot be modeled through an exponential distribution, since they are subjected to wear, and so their expected life (measured at a certain time s, with $s > t$) is strongly conditioned by the time t gone by. The most suitable cumulative probability distribution, then, is the Weibull one:

$$F(t) = 1 - e^{-\left(\frac{t-\gamma}{\eta}\right)^{\beta}} \tag{6.2}$$

Where:

- $\mathrm{F(t)}$ is the *cumulative probability distribution* relating the breakdown of a mechanical component at time t;
- γ is the *location parameter* and determines the shift of the distribution;
- β is the *shape parameter*, the one that defines the trend of the function;
- η is the *scale parameter*, that determines the statistical dispersion of $\mathrm{F(t)}$.

Therefore, in order to assess the proper number of spare parts for each typology of components, it would be recommended to simulate their breakdown behaviour through the described probability distributions, identifying the most likely instants of failure: for each of them, then, a spare part should be provided [GERI10].

Another criticality consists in the lack of a technical database in which the information relating to components and process parameters are stored. The present solution, in fact, does not consider the possibility to choose from a set of processes and materials (for instance, titan cutting, rather than iron drilling) and a set of machine tools (with different performance and technical characteristics), in order to determine the best configuration for energy (and then cost) savings, but it is only addressed to the evaluation of the efficiency of the production system at analysis. Moreover, the user is obliged to specify and insert manually in the program a considerable amount of technical data (such as the energy consumption of each machine component), whose knowledge is subordinated to the application of other software, and this makes "*LC€*nergy" not an immediate solution. Then, an integration between the LCC algorithm and all the other algorithms for the estimation of technical aspects should be required.

6.2 Economic deficiencies

The first economic criticality connected to the problem of the spare parts number calculation lies in the missed consideration of the effects of a stock-out situation, that is when no spare parts are in storage. This has a direct impact not only on the time spent for reparation (and then on the costs for corrective maintenance), but also in terms of failure to meet the production requirements. If no spare parts are available, in fact, it should be considered as a loss not only the time needed for fixing the machine, but also the one for managing the supply process, and in particular the lead time. It is also important to underline that the situation of stock-out has to be compared with the storage costs: depending on the machine component and on the supply contract conditions, sometimes it could be more convenient not to buy in advance the spare part (bearing in this way its storage cost), but to take the risk of a premature and unexpected breakdown.

Keeping the focus on criticalities, another negative aspect is related once again to the lack of a database for economic data. The need for the customer to provide to the algorithm a table with all the market parameters required for the computations (and relating, for instance, to the energy cost, or to the rent cost and its growth rate, or to the spare part costs) could be reasonably avoided by implementing a market database or by connecting the algorithm to some already existing web database, each dealing with the information requested.

The last critical point concerns the discount rate. It has been supposed a constant rate for the entire machine lifetime, even if it is not unlikely that it could vary in harmony with the financial and economic trends. For that reason, it could be proper to consider also the discount rate variation in the process of costs actualization (formula 6.3), even if this implies once again the need to dispose of constantly updated economic information [LUIC13].

$$LCC_x = \sum_{t=1}^{T} \frac{X_t}{\prod_{j=1}^{T}(1 + r_j)} \qquad (6.3)$$

Where:

- LCC_x are the Lifecycle costs relating to the variable x;
- X_t is the cash flow relating to the variable x at time t;
- r_j is the annual discount rate at time j.

7 Conclusion and future development

The continuously increasing competition characterizing the actual dynamic and global market leads organizations to be always more and more efficient in meeting the customers' expectation, together with the strong and compulsory requirement of achieving the goals in terms of sustainable development. The constant dwindling of resources, indeed, obliges European and world institutions to periodically elaborate strict regulations for protecting the environment and the mankind health, but without compromising, at the same time, the continual enhancement of the level of science, progress and technology.

Together with some ethical and political reasons, the other aspect connected to the obligatory limitation in the usage of resources relates to some economic motivations: to fulfill the actual production needs, a huge amount of energy is required, and this implies that also the costs to be borne are considerable. Then, what is strongly recommended in the evaluation of investment, especially in the manufacturing industry, is to estimate the operative costs associated with the production, in particular the cost relating to energy consumption.

The scope of the present work, therefore, was to develop a new approach to evaluate the lifecycle costs of a machine tool in function of its energy consumption. As a first step, a classification of all the costs directly associated with the machine has been carried out, identifying in this way the different categories of costs that had to be included in the definition of LCC. After that, a concept for the estimation of all of them has been developed, paying particularly attention to the quantification of the energy costs: as the core step in the development of the model, it implied the study of the enterprise production time management, and the classification of the machine operating modes. For that purpose, three energetic states have been identified, which correspond to the machine operations of processing, waiting for the process and stand-by, and they have been respectively named Process, Idle and Hibernation state. For each of these states, the related energy consumption has been estimated, and then through the data describing the energy cost, its growth rate and the enterprise cost of capital (discount rate), the calculation of the energy LCC for the whole machine lifetime has been deduced. The same procedure has been applied for the quantification of the other lifecycle costs (such as the corrective maintenance costs, the preventive maintenance ones or the room rent costs), and at the end an algorithm has been developed to implement the whole concept. The IDE chosen was Visual Studio 2010 and the programming language C#.

In order to assess the concept and the algorithm efficiency, some real data were collected and used as input for the software, calculating in this way some plausible results and estimating also the unitary production costs (cost per part). Anyway, because of the innovation characterizing the described approach, no real output data were available, and then a traditional validation phase, based on the results comparison, could not be carried out; but some sensitivity tests were performed in order to define the most critical parameters, and then to individuate where to take action for improving the solution.

In the end, some criticalities of the method proposed have been identified, defining in this way the topics to be analyzed in depth in the next projects. A good outlook could be, for instance, not to evaluate only the lifecycle costs relating to a machine tool, but also its positive cash flows, estimating in which period during the machine lifetime the investment could be totally recovered.

Another interesting opportunity, moreover, is that one to consider how the results would change if the investment were postponed over the years, that leads to the application of the contemporary approach of the so called “Real options” [DULM11].

More technical future developments concern the possibility of introducing into the concept also the costs relating to material supply: it could be a valid analysis, indeed, to study the cost variation at the swarf reduction, in order to determine its impact on the machine LCC. Moreover, also a more detailed study of the machine tool components, especially in regards of their failure probability, would be proper, so to improve the calculation of their spare parts, and then enhance the evaluation of the corrective maintenance costs.

It would be remarkable also to implement a component database to estimate which is the best machine configuration for satisfying the manufacturing requirements and calculate its relating energy consumption, finding the optimal trade-off between high performance and cost-effectiveness.

Finally, a deeper study on the possibility to identify more than three operating states for the machine would be appreciated: even if the distinction between Process state, Idle State and Hibernation one is the most likely and the most suitable for the present thesis, it is not to be excluded the eventuality to define another state, especially if other types of energy consumption, besides the electrical one (such as the heat consumption), are intended to be examined.

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