POLITECNICO DI MILANO

Facoltà di Ingegneria dell'Informazione

Master of Science in Automation and Control Engineering

Modeling and Minimization of Energy Consumption
in Machine Tools

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"La esperanza es el sueño del hombre despierto."

Aristóteles

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A Dios, mis padres y mi hermana pues sin su apoyo incondicional este proyecto no hubiera podido llegar a feliz término. -Diego

A Dios, mi roca y mi fortaleza. A mis Padres y mi hermana, quienes a pesar de la distancia estuvieron presentes en cada paso de este camino y sin quienes este proyecto no se hubiera convertido en una realidad. A mi familia, su apoyo constante es parte fundamental de lo que soy y de lo que logro. A Diego por su apoyo y compañía. -Catalina

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Contents

List of Figures

List of Tables

Abstract

Industrial sector activities, as almost every activity developed in the actual world, have an environmental impact related not only with the effects of the production process itself, but also with energy consumption and the consequent greenhouse gas emissions for its generation.

Strategies to reduce the energy consumption within the industrial sector, especially in the manufacturing processes, are gaining relevance due to the necessity of becoming sustainable economically and environmentally, creating cost savings and competitive advantages.

This work focuses on energy saving strategies for machine tools during its use phase by minimizing the energy consumption during non-value adding task.

Initially a motivation for energy saving within the industrial sector and particularly in machine tools is presented, focusing on the different production states of the machines. On the second part a classification of the machine tools and its main components is presented in order to allocate precisely the concepts need for future developments. Afterward a literature review regarding energy consumption in machine tools and the actual strategies for gaining energy efficient is presented.

On a later stage a methodology to describe the energy consumption of machine tools based on the energy consumption of its individual components is presented using a modular approach and automata theory.

Finally different control problems regarding energy minimization of machine tools during non-value adding tasks are described; for some of these problems, a control policy is analytically developed and diverse numerical results are presented. As a last contributions some of the control policies developed in this work are compared with similar approaches presented in the literature review.

Sommario

Le attività del settore industriale, come gran parte delle attività del mondo attuale, hanno un impatto ambientale legato non solo al processo produttivo stesso ma anche all'energia consumata e all'effetto serra che ne consegue.

Strategie per ridurre il consumo di energia nel settore industriale, specialmente nei processi produttivi, stanno guadagnando importanza a causa della necessità di diventare sostenibili sia dal punto di vista economico che ambientale, creando risparmi e vantaggi competitivi.

Questo lavoro si concentra sulle strategie di risparmio energetico nelle macchine utensili durante il loro impiego, riducendo al minimo il consumo di energia durante le fasi a non-valore aggiunto.

Inizialmente vengono introdotte le motivazione per il risparmio energetico nel settore industriale e in particolare nelle macchine utensili, concentrandosi sui diversi stati produttivi delle stesse. Nella seconda parte si presenta una classificazione delle macchine utensili e dei suoi componenti principali in modo da individuare gli sviluppi futuri. Successivamente una revisione della letteratura per quanto riguarda il consumo di energia nelle macchine utensili e le strategie effettive per ottenere efficienza energetica è presentato.

In una fase successiva si propone una metodologia per descrivere il consumo energetico nelle macchine utensili, basata sul consumo energetico dei suoi singoli componenti, attraverso un approccio modulare utilizzando gli automi.

Infine, si descrivono diversi problemi di controllo riguardanti la minimizzazione di energia nelle macchine utensili durante le fasi a non valore aggiunto; per alcuni di questi, si sviluppano analiticamente politiche di controllo e si valutano alcuni risultati numerici. Infine, come ultimo contributo, alcuni resultati ottenuti per le politiche di controllo sviluppate in questo lavoro sono confrontate con approcci simili presentati in letteratura.

Chapter 1

Introduction

This chapter presents the motivations that lead to a study of the energy consumption and the subsequent interest in energy savings, particularly at manufacturing level including elements such as machine tools.

In the first part, an outline of the energy consumption characterization and distribution around the world is made, making emphasis in the adverse consequences that brings uncontrolled energy consumption. Afterwards, a brief description of the importance of bringing sustainability into manufactory is presented, including the potential benefits that this practice carries to the industry. Finally an explanation of the energy usage, particularly in machine tools, is done highlighting the relevance of the energy consumption in the standby mode and the potentials for gaining energy efficiency in this field.

1.1 Energy Consumption

Energy is something that affects the lives of human beings in every moment of their existence even if they notice it or not. It facilitates things in a great manner from the simplest to the most complex activity, and is always latent in humans daily live. Energy is involved in all kind of activities such as heating homes, washing clothes and some other normal activities that for the contemporaneous mankind are considered as granted, but without energy are impossible to fulfill. Of course, energy benefits are beyond the use at home, some essential activities such as agriculture, computing, manufacturing, construction and health depends greatly on the access to energy.

Because of this dependence, energy has become an important factor in our days and has increased its importance as can be seen in figure 1.1, where historic data of the world energy consumption is shown. It is evident to notice that in the last years an increase of energy consumption is presented.

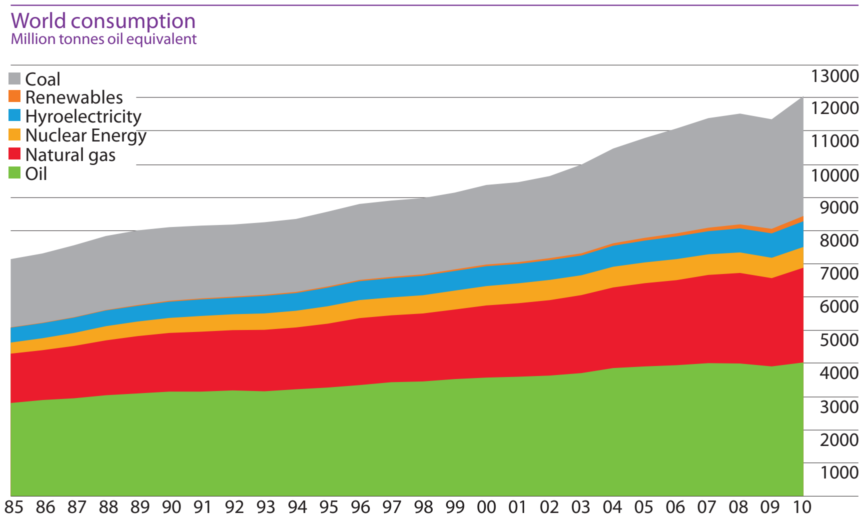


FIGURE 1.1: World energy consumption by source (1985-2010) (1toe $\approx$ 42 GJ)[Plc11]

For a long time economies worldwide have grown significantly without taking into consideration the role of energy in their processes, since energy was considered as an unlimited good with low costs. However, energy has become an issue of greater importance based on different factors such as:

- A possible energy crisis related with the increase of the energy demand and the utilized primary sources
- New aspects that have entered into consideration like the widespread conscience of a “greener” and sustainable world
- Other factors (like constant increase on the cost of energy or initiatives for promotion the long term social health of the world) that influence the desire of using the energy in an efficient manner

Manufacturing plays an important role in the worldwide energy consumption, and as a consequence, has a measurable impact on the environment; this circumstance enhance the necessity of achieving a sustainable world by reducing energy consumption in this sector.

1.1.1 Energy generation and distribution

It is known that the production of energy uses resources that can be classified as renewable and non renewable. These resources can be converted into secondary energy sources like electricity or hydrogen, and can be used in different ways such as heating homes, move cars and manufacture all kinds of products.

The problem with the use of these primary resources arises when it is noticed that 85% of the energy used in the world is produced employing non renewable energy sources. As an example of this behavior, on figure 1.2 it can be appreciated the energy consumption by source of United States of America (the second largest energy consumer worldwide), where only a 9.3% of renewable resources are used in order to produce energy.

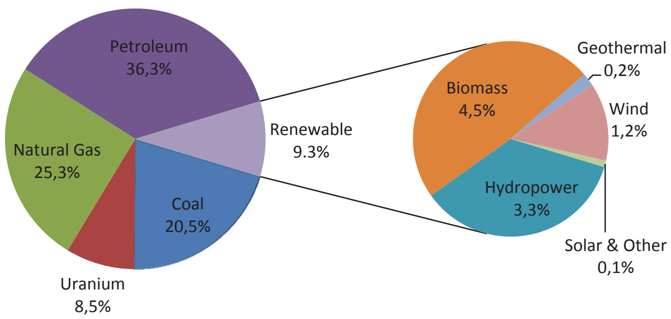


FIGURE 1.2: U.S. Energy consumption by source, 2011 [Adm12e]

In order to understand where all this energy consumption is directed, it is required to take into consideration the amount of energy that each sector consumes, and to realize that the industrial sector has an important impact on the overall energy consumption.

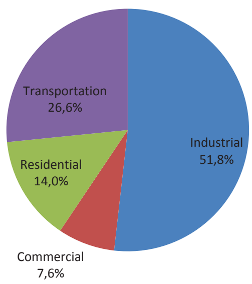


FIGURE 1.3: Total world delivered energy consumption by end-use sector, 2008 [Adm12b]

It is evident from the figure that the industrial sector has a great prevalence in the total energy consumption. With the purpose of deepen the understanding within the industrial sector, figure 1.4 is introduced; here historic data of energy consumption on different industrial sector from 1971 to 2007 is presented.

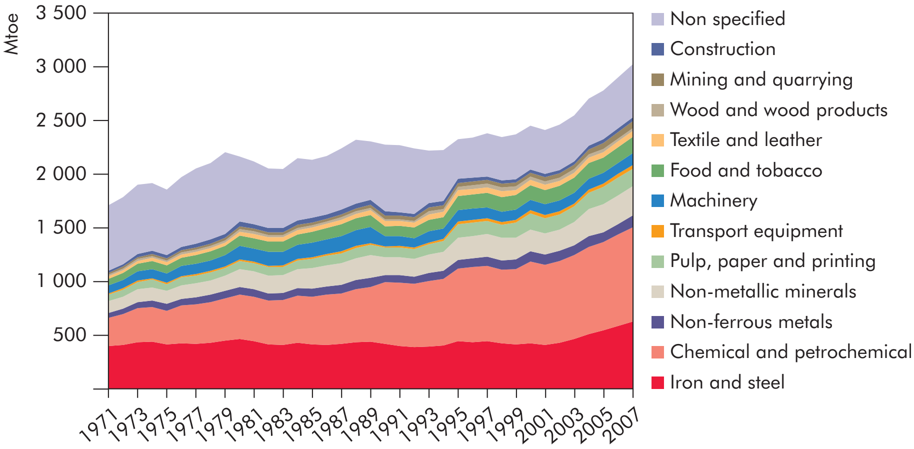
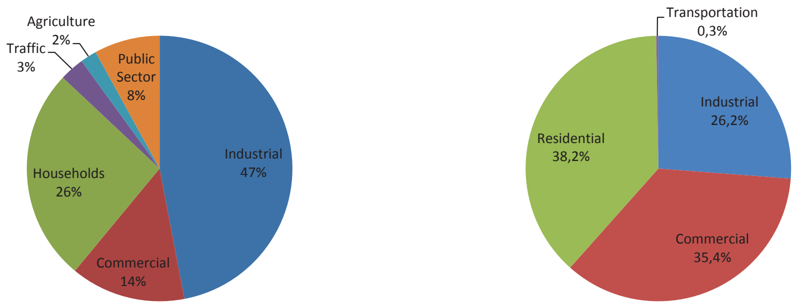


FIGURE 1.4: World industrial energy use by sector (Mtoe: Million tonnes of oil equivalent)[Age10]

It can be appreciated, that the five most energy-intensive sectors are iron and steel, cement, chemical and petrochemical, pulp and paper, and aluminum, but it is also noticeable an important contribution of the machinery process in which the scope of this thesis can be located.

In countries with a conventional focus on industrial production, the energy intensity perseveres. For example in Germany, industrial production is responsible for 27% of the primary energy consumption and 47% of the electrical energy turnover [Her09].

Even though in the United States of America the electric energy consumed by the industry is not quite as large as in Germany, it is possible to appreciate, from the data of the U. S. Energy Information Administration, that the industrial sector is a representative electric energy consumer.



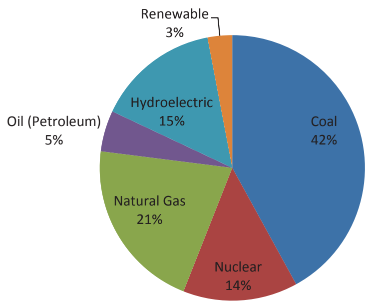
a) Electricity consumption in Germany by sector [Her09]

b) U.S Energy Consumption by Energy-Use Sector 2011 [Adm12f]

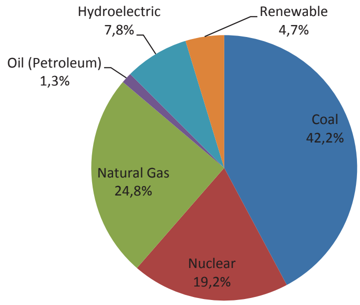
FIGURE 1.5: Electric energy consumption by sectors

1.1.2 Environmental aspects

Focusing now on electrical energy, a worldwide analysis upon the sources required for producing this kind of energy is presented, with the caveat that the amount of resources employed can fluctuate depending on the country producing energy, as can be seen in figure 1.6.



a) World electricity production sources [Dyn10]



b) U.S. Source of electricity generation 2011 [Adm12a]

FIGURE 1.6: Electricity production sources

From figure 1.6 can be infered that the most outstanding source for obtaining electrical energy is the coal, followed by natural gas and hydroelectric, leaving in the last places nuclear, oil and other renewable sources. Nevertheless, for the Unites States of America the scenery changes a little with a displacement from the first places of the hydroelectric power generation replaced by nuclear energy.

In order to give a complete spotlight of the consequences of energy generation and consumption in the environment, it can be remarked that depending on the different energy sources employed, a greater or lesser impact is perceived. A brief register of the environmental impact, focusing on the most relevant sources for producing electrical energy, is listed as follows [Ene12]:

- Coal: The mining of coal can affect air, water and land together if it is managed without precautions. The contaminated water can get filtered from mines underground contaminating water and land and affecting the air. It is known that the coal burning can cause dangerous emissions such as carbon dioxide (CO_2), sulfur dioxide (SO_2) and mercury.
- Hydropower: Although the hydroelectric power plants do not generate a great amount of water or air pollution, they can damage the environment by harming fish populations, changing water temperatures or forcing people or animals to move from its natural environments.

- Nuclear: The nuclear waste and spent fuels are of a great consideration since they are very dangerous to life itself, and its treatment has to follow specific and strict regulations.

- Oil and Gas: Oil spills are one of the most dangerous events that can affect the environment, even though they do not occur very often, its contaminating potential is something to be very aware of. The production can damage the land where drilling operations are being carried out and as it is known, the petroleum products being burned emit carbon dioxide (CO_2), carbon monoxide (CO) and other air contaminants which have vast effect on the environment.

It can be concluded that all the energy sources produce different effects on the environment that include emissions, waste, and land or water use, among others. From all of these effects, emissions are being considered of utmost importance since they are responsible for the greenhouse gases which play a major role in the warming of the planet.

Considering all the greenhouse gases, the energy related CO_2 emissions, that result primarily from the combustion of fossil fuels, are the most relevant, even though some other gases are involved this effect; this is the main reason that the energy consumption is placed in the heart of the debate of climate change. An example of the distribution of greenhouse emissions can be seen on figure 1.7.

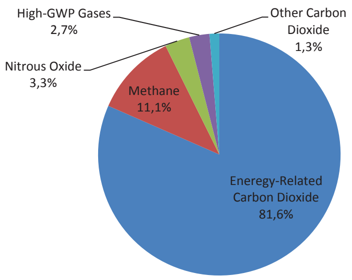
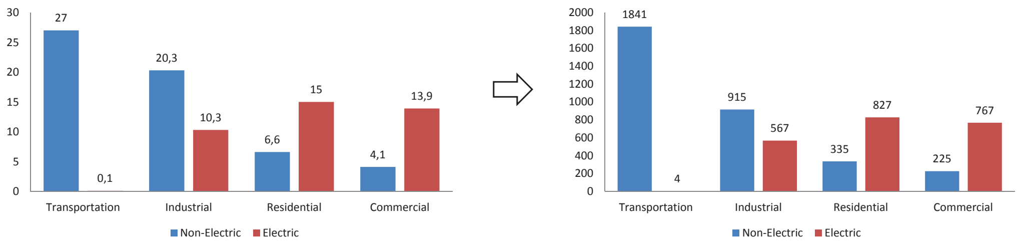


FIGURE 1.7: U.S. Greenhouse gas emissions by gas, 2009 [Adm12f]

The concern about the emissions of CO_2 and greenhouse gases has risen due to their quickly increment. In only 15 years, from 1990 to 2005, the global emissions of CO_2 derivated from the energy consumption have increased in a 25% [Age10], and are expected to increase by 1% annually between 2008 and 2035 [Adm12c].

Being coal and natural gas the most used primary sources (in the case of the United States of America) for producing electrical energy, it is not a surprise that 67% of energy-related carbon dioxide emissions were originated from the use of coal and petroleum fuels in 2011, and about 24% from natural gas [Adm12f]. It has to be pointed out that the transportation sector emits more CO_2 (for the non-electrical use of energy), since it is almost completely dependent on petroleum fuels, but the industrial sector contribute with a non-depreciable quantity of CO_2 emissions to the environment as seen in figure 1.8.



a) U.S. Energy consumption by energy-use sector 2011

b) Resulting CO_2 emissions by energy-use sector 2011

FIGURE 1.8: Energy related CO_2 emmisions by sector

1.1.3 Addtional factors

The large energy demand in manufacturing makes the process vulnerable to additional factors like the variability and growing of energy prices, making this factor (energy prices) worthy of consideration.

The increase of energy prices can be affected by many factors such as the cost for building, financing, maintaining, managing and operating power plants and also transmission and distribution lines. It also has to be considered that the price can vary depending on the consumer, being industrial, residential or commercial; this circumstance is based on the fact that industrial consumers use more electricity and can raise the voltage to higher rates making this price comparable to the one of selling.

A comparison of this situation is shown below for the year 2011, that considers the average prices by type of utility customer in USA [Adm12d]:

- Residential: 11.8¢/kWh
- Transportation: 10.6¢/kWh
- Commercial: 10.3¢/kWh
- Industrial: 6.9¢/kWh

Within this analysis, it is possible to understand the importance of saving energy-based on the tendency through years of increasing its consumption, becoming this a reason (not only for companies but also for households and commercial sectors) of making a more efficient use of the energy with the aim of saving money.

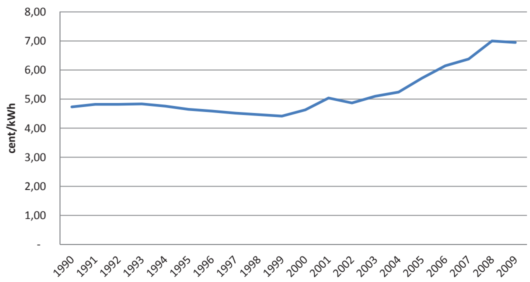


FIGURE 1.9: U.S. Electricity prices evolution from 1990 to 2009 [Adm09]

1.2 Energy and Sustainable Industrial Development

The industrial sector, as explained in the previous sections, has one of the largest energetic demands, and the continuous growth of this sector generates an increase of the energy and therefore the necessity of new supply sources. If this tendency of growing in the industry followed by an increasing on the energy consumption (which is a normal consequence) continues, at some point the world where mankind inhabits will not be able to respond to the industrial energetic requirements. In order to avoid this potential crisis, a sustainable industrial energetic policy has risen.

The challenge of achieving sustainability implies breaking the relationship between economical growth and energy consumption by the generation of productive and efficient processes, but at the same time aims to diminish the relationship between energy consumption and contamination, by the use of renewable energy sources and the efficient use of fossil fuels [Com04].

Since the manufacturing sector utilizes around 33% of the primary energy and generates around 38% of the CO_2 emissions, simple actions could be considered to reduce up to a 25% the used energy until 2020. All these actions are aligned with the improvement of energy efficiency like the use of more efficient electrical motors, lighting systems and other simple activities [Age10].

In order to support initiatives for "greener" companies, governments, aware of the importance of energy efficiency and sustainable development, have created incentives directed to companies in order to reward the use of renewable energy and energy efficienct practices in the industrial sector. Example of these incentive programs can be found in [Dat12] where a database of state incentives in the United States of America for companies can be found.

Companies can earn not only incentives given in form of grants but also, by incorporating energy efficiency management, they can gain [Loz04]:

- More efficient production by maintaining the level of production with less cost or less energy consumption
- Use energy performance indicators in the decision making process
- Protection in their production costs from the possible fluctuation of the prices of electricity and fuel market.

1.3 Energy Distribution on Machine Tools

Energy used in manufacturing has to be reduced in order to cut down carbon emissions derived from energy generation. In literature is showed that the energy consumed for non-cutting operations dominates the total energy consumption in machining processes [Dah04].

In a work from Devoldere et al. [Dev07], an experiment was carried out to determine the energy distribution of a 5-axis milling machine. In this experiment, some measurements of the idle or standby mode were acquired, and the results of the time and the power requirements are recapitulated in figure 1.10. Figure 1.11 complements the display of the results, and shows that the nonproductive mode (calculated by summing up the contributions of idle: when the machine is ready for production and runtime mode: when the machine positions and loads the tools) evidence a total share in energy consumption of 47%.

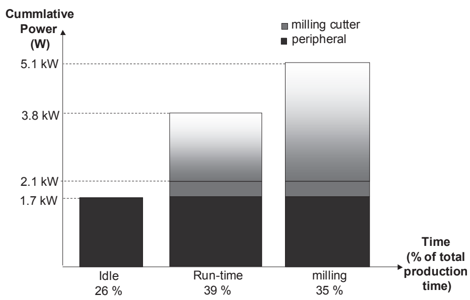


FIGURE 1.10: Relative energy consumption per production mode [Dev07]

Another analysis, presented by a partnership composed of four of the major European machine and equipment manufacturers [Sig10], showed that from measurements in the automotive industry, the electrical energy requirement during non-productive times represents 60% of the demand used in a normal production stage.

An accurate characterization of these non-productive modes requires differentiating the amount of energy consumed by the actual cutting requirements. It is exposed

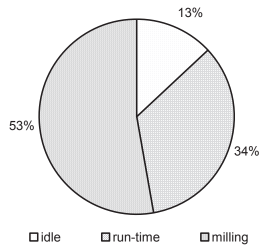


FIGURE 1.11: Total energy use of the milling cutter [Dev07]

by Dahmus et al. [Dah04] that the auxiliary equipment energy requirements, can easily exceed the cutting energy requirements.

Figure 1.12 characterize the energy use of a large Toyota production machining center installed in an automated transfer line, and with auxiliary components such as lubrication systems, chip recovery, etc. It can be appreciated that the energy consumed when removing material, represents at most the 15% of the total energy required in the manufacturing process. The rest of the energy (85%), corresponds to the constant energy consumption and is independent if a piece is being machined or not.

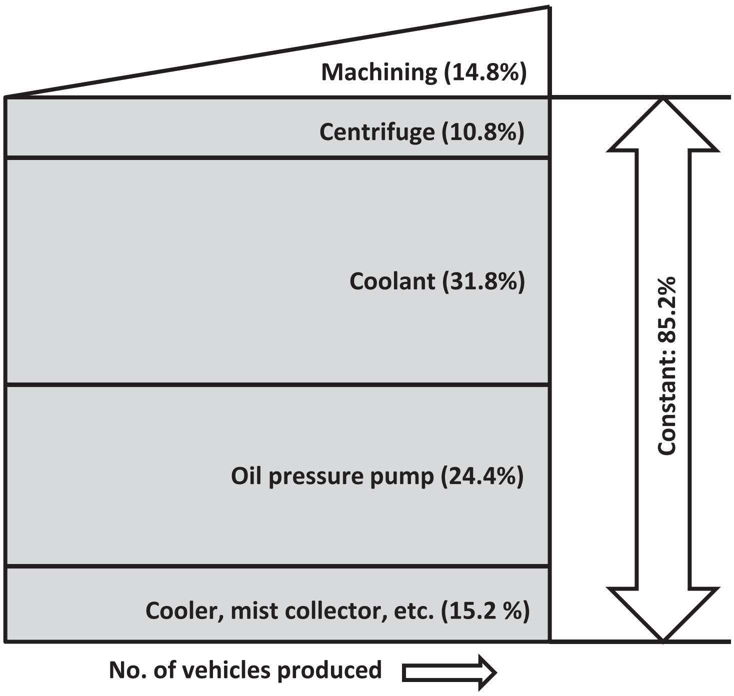


FIGURE 1.12: Machining energy use breakdown by type from Toyota [Dah04]

These analyses and the results obtained, showed that a great amount of the energy consumed by machine tools belong to non-value adding task (machine in standby mode) and hence there exist a large potential of reduction in this area.

1.4 Thesis Objectives

This thesis is located within a context for energy savings in the industrial sector, particularly in machine tools, with the aim of increase their energetic efficiency. An important objective is to develop control policies for minimizing energy consumption during non-value adding task of machine tools based on the concept of reducing the idle time which has high power demand.

The initial develop of this work is a support for achieving the main objective, and consists in the construction of the energetic model of a machine tool using a modular approach. The energetic model of the complete machine is obtained based on simple energetic models of its components, and allows to know the different discrete states in which the machine can be located during a production process and the energy consumption related to each one of this states.

The knowledge about the energetic states and its possible evolution is an important asset for the energy minimization strategies; since the energetic model is modular, the minimization strategies can be applied to control the complete machine (scope of this thesis) or to control individual components.

Using as pillar the previous model, the main objective of this research is the use of the energetic states of the machine tool to develop control strategies that allow to determine the optimal time to switch *off* or switch *on* a machine in order to minimize energy, maintaining an equilibrium with production performance; these strategies can be used as a tool to support decisions regarding energy sustainability.

Chapter 2

Machine Tool Description

Machine tools are involved in a great amount of processes; these processes generate items that people can see in their daily life. From simple objects to the most complex ones, in order to build them, there should be a machine tool involved on its elaboration.

Machine tools are crucial in the actual world and surely on the world of tomorrow in order to provide aid to the solution of future problems [CEC12b].

In order to allocate, with a more precise focus this work, it is necessary to settle some important concepts regarding machine tools, for the understanding of future developments.

Within this chapter, there will be exposed some definitions regarding machine tool and machining centers, classifications, elements, boundaries that this thesis will embrace and the working cycle of the modeled machine.

2.1 Definitions

2.1.1 Machine tool

A definition of machine tool based on engineering considerations, economic classifications, standards on process technologies and existing legal framework can be found on a report from the Fraunhofer Institute for Reliability and Microintegration [Sch10a] and is expressed with the following words:

"A machine tool is a stationary or transportable, but not portable by hand or mobile assembly, dependent on energy input (such as electricity from the grid or stand-alone / back-up power sources, hydraulic or pneumatic power supply, but not solely

manually operated) when in operation, consisting of linked parts or components, at least one of which moves, and which are joined together for a specific application, which is the geometric shaping of work pieces made of arbitrary materials using appropriate tools and forming, cutting, physic-chemical processing or joining technologies, resulting in a product of defined reproducible geometry, and intended for professional use"

A common denominator of these machines is that they are meant to build products or parts, reason for which a machine tool can be called *"the mother machine"*, since they allow the creation of all other different machines, including machine tools themselves [CEC12c].

2.1.2 Machining center

A machining center can be considered as an advanced numerical control (NC) machine; this machine can perform different operations on a part, by changing automatically the cutting tools [Wan96].

Almost every part that is produced nowadays requires several different machining processes (milling, drilling, facing, etc). These activities will be performed on the different surfaces of the part, in order to obtain certain surface finishing and dimensional tolerances. Since every machine, independently of the level of automation it has, is not designed to perform individually all the required operations, the introduction of machining centers, which are able to execute different cutting operations on different sufaces of the piece and on different direction, is a great asset.

Some advantages arise by avoiding the limitation on the use of a single machine tool: [Kal01]:

- Machining centers can handle a variety of forms and sizes on work pieces, with high efficiency, cost-effectively and with high repetitive dimensional precision.
- These machining centers can change quickly from one type of product to another, generating a reduction on the amount of machine tools needed and in consequence, an optimization of the surface of the floor on the production facility.
- The time for loading or unloading pieces, changing tools, measuring and locating failures is reduced, so the workhand is reduced and the production costs are minimized.
- One operator can handle two or more machines at the same time because of the high level of automation of the machining centers.

2.2 Classification

With the purpose of clustering machining tools and relating it to the definition of machine centers, it is possible to discriminate them based on the level of automation as shown in figure 2.1.

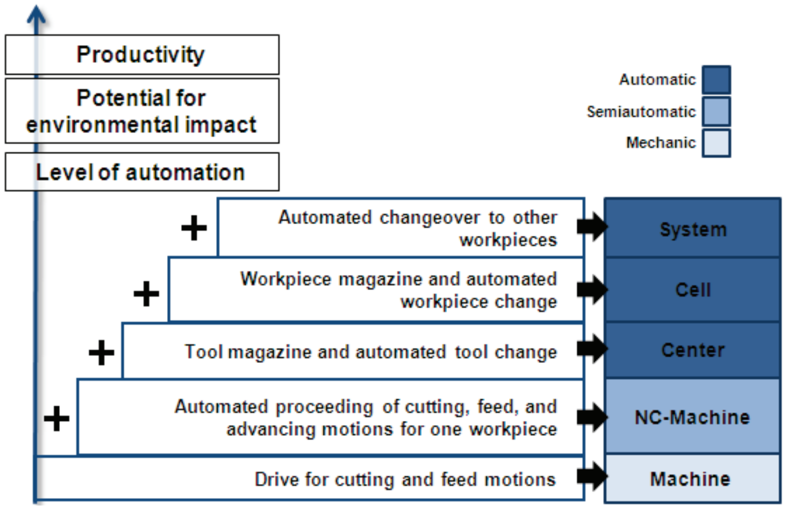


FIGURE 2.1: Distinction of machine tools according to level of automation [Sch10a]

By analyzing this figure, it is possible to infer that a "Machine" is categorized by the presence of cutting and feed drives. The "NC-machine" has a numerical control added, to automatically run the machining. The "Center" is classified according to the capability of perform an entire process on an individual work piece, where several tools can be changed automatically and a tool magazine is inserted. For a "Cell", the unconnected serial production of related work pieces is considered. Finally, the most automated level is the "System", in which the whole manufacturing process is automated and controlled by a master control, and can include more than few machines with work piece change, tool change systems and waste disposal.

More specifically, the most common classification for a machining center, according to Kalpakjian and Schmid [Kal01], shows that they can be clustered into two main categories that relate the orientation of the spindle as its defining characteristic.

- Vertical machining centers: The machining centers clustered into this category are suitable for different machining operations in plane surfaces with deep cavities, as for the fabrication of dice. These centers usually produce pieces with good dimensional precision.

- Horizontal machining centers: These machines generally favor production of big and tall pieces that are required to be machined on their different surfaces.

An additional category, created for specific purposes, that combines vertical and horizontal orientation, can be taken into account and will combine the benefits of the two scenarios presented above.

Additional classifications can be done for machine tools and machining centers, based on the size of the working envelope (area in which the work piece is machined), number of axis, type of axis, number of spindles, torque on the spindle, technical characteristics, among others. These classifications are only mentioned here, since a deep explanation will be out of the scope of this work.

2.3 Elements of a Machining Tool Center

As a first approach, it is necessary to separate the machine tool (or machining center) as an assembly of components, in order to understand the work that will be presented in following chapters, relating the decomposition of the machine tool center into several components, the analysis of energy of this component and its clustering in a model using automata language.

According to ISO [ISO12], machine tools components (and for the concern of this work also machining centers) can be classified based on its physical characteristics as mechanical, electrical, hydraulic, pneumatic or a combination of them. A possible segmentation can be done as follows [Sch10a]:

- Mechanical
  - Frame: Element that supports the machine carrying all the passive and active components; usually made of welded steel or cast iron.

FIGURE 2.2: Frame of a machine tool [Sod12]

- Guides and bearings: Reduce the specific motions of the machine to a determinate set of degrees of freedom. These elemnts are of special importance to several components of machine tools such as main and feed spindles, or work piece table. The guides elements can be linear and circulars, while the bearings, hydrostatic and electrical.

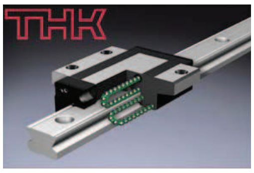


FIGURE 2.3: Linear motion guideways [Sod12]

- Piece Holder: Elements that come in different size and shape depending on the piece to be processed and the process itself. Can be entirely mechanic (like the one presented in 2.4) or have combined acting (like pneumatic, magnetic or electromechanic), depending on the level of automation of the machining center.

FIGURE 2.4: Piece holder [MMS10]

- Electrical
  - Control device: Include the elements required for the CNC applications.

FIGURE 2.5: Numerical control [She11]

  - Power supply: Involves the transformation of electric power for the various modules of the machine tool.

- Hydraulic
  - Hydraulic unit: Made of continuously variable linear drives; this unit is usually involved on the part and tool clamping process.

Figure 2.6: Hydraulic unit [Dir11]

- Pneumatic
  - Pneumatic Unit: Can be found in the form of sealing air, for maintaining clean optical sensors and for work piece holding or tool unloading.
- Combination
  - Main and feed drives: Usually machine tools are driven by electric motors that are often used in compressors, pumps, and spindles.

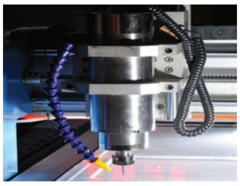


Figure 2.7: Spindle of a milling machine [Sto10]

  - Cooling/Lubricant Unit: Used for cooling the tool and work piece. There are also included systems for cooling the moving elements such as spindle or feed drives.

Figure 2.8: Cooling unit [Mas10]

– Chip conveyor: Machine tool chip conveyors are used to carry away the metal chips produced by machining process to prevent curled chips from adhering to the piece or the tool which will result in quality losses.
– Auxiliary elements: Elements created for supporting the machining process and introduced depending on the level of automation of the machining center or special conditions on the work, like the automatic pallet changer or the automatic piece loader.

a) Automatic pallet changer

b) Automatic piece loader

Figure 2.9: Some auxiliary elements [Mac10]

This classification can also be linked with the functions performed by the component into the machine, creating and interconnection of components between its physical characteristics and its functions, as can be seen in figure 2.10.

Regarding the functional classification, the aggrupation can be made as follows:

- Control function: CNC.
- Assisting function: Process lubrication, cooling, chip removal, mist removal and cooling of devices.
- Set up functions: Part handling/part clamping, tool handling/tool clamping and process media supply (related with specific process such as welding and laser cutting systems).
- Shape of part transformation functions: Manufacturing process integration, part / tool relative motion, transforming energy supply.

In a subsequent chapter, a classification that includes all the components mentioned above, but that is more directly related with the scope of this work, will be presented. This classification is based on the energy consumption of the components, necessary for the afterwards work on this thesis.

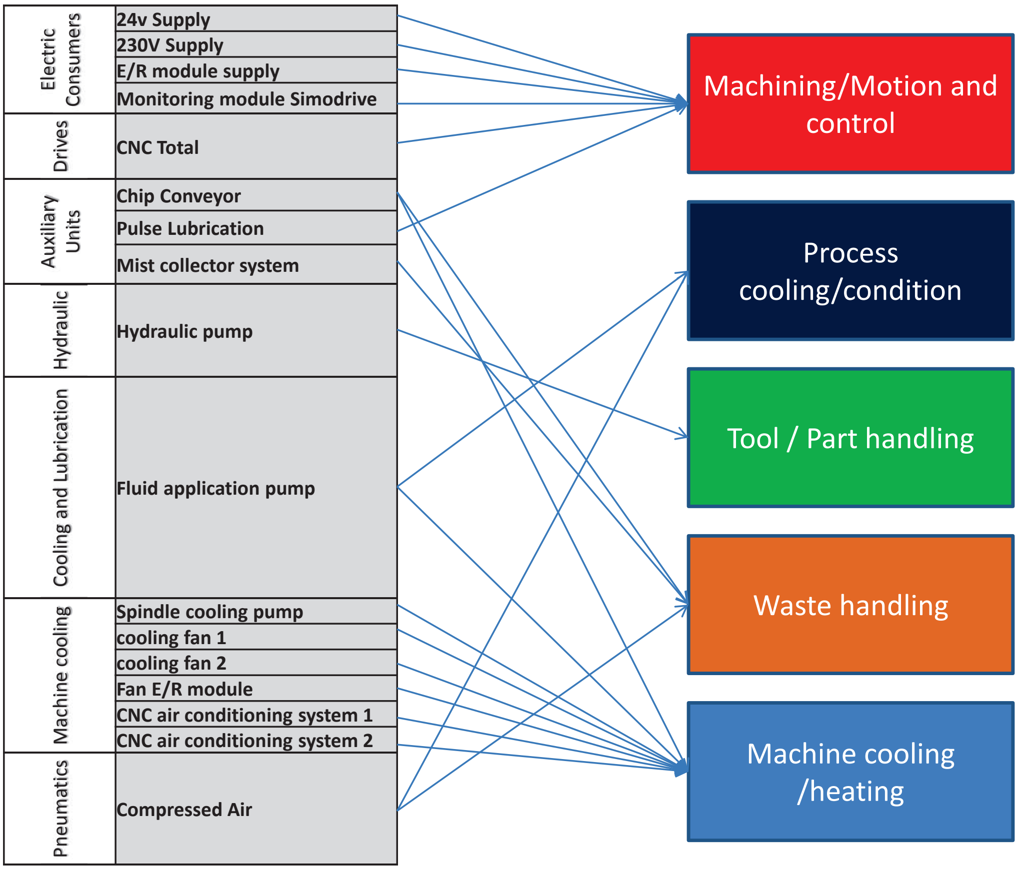


Figure 2.10: Machine components-Machine functions

2.4 Boundaries

First of all, it will be essential to notice that from now on, a reference made to a machine tool, in this work, will be directly related with a machining center and all the implications, descriptions and constrains that this correspondence implies will be taken into account.

Having broadly described a machining center (from now on a machine tool), with its respectively and most important components, it is now necessary to locate the scope of the machining process made by a machine tool into the conglomeration of several activities such as tool preparation, material production, material removal and cleaning, among others [Dah04] being a general machining scenario more clearly represented by the figure 2.11.

In the considerations presented here, the shaded part of the figure 2.11 represents the limit of the process to which this study will aim, by analyzing the operational

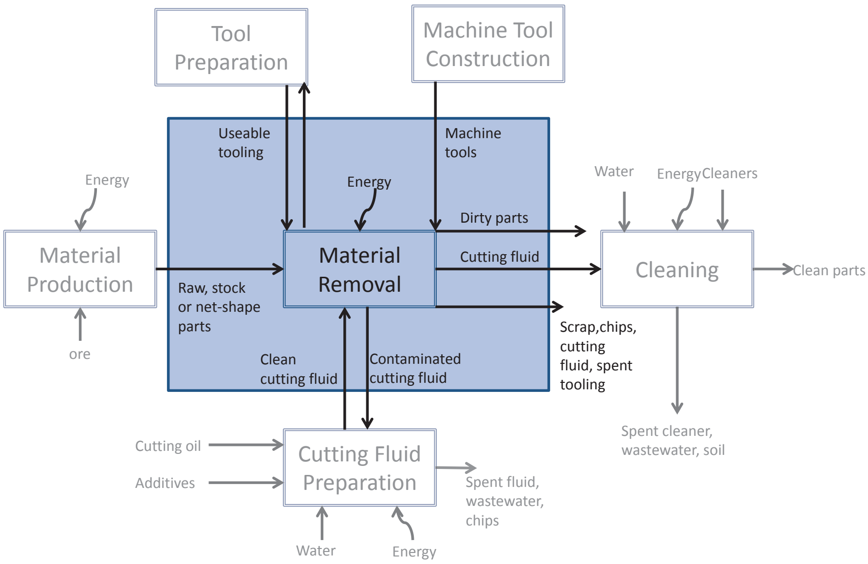


FIGURE 2.11: System diagram of machining [Dah04]

states of the machine on the material removal process. This limit includes startup, shutdown, idle and in cycle states [Vij10], and of course the energy located only on the machine and not in the additional process surrounding it.

For the machine that will be taken into consideration in this work, some specific assumptions are considered along the following lines:

- The input buffer is considered as of infinite capacity. Thus, the machine could have a constant and unlimited number of pieces, but of course the consideration of a void buffer is also possible in this remark. This supposition is made in the case that the model of this machine is put in a production line; the capacity on the entrance will be dependent only on the output buffer of the previous machine.
- The machine tool is able to operate one pallet (or pieces on a single pallet) for a cutting process.
- An automatic tool changer is considered, but not a tool magazine with the aim of simplifying the model.
- Only one spindle is considered (no matter its orientation: vertical or horizontal).
- The number of axes is not relevant for the model. The machine can have as many axes as it is wanted, since the modeling of the consumption of one individual axis can be multiplied for the number of axis.

- Each one of the axes and the spindle has a cooler system.
- The output buffer is made of a specific capacity (K) that can be assigned for future and specific models.
- The pneumatic unit is not taken into account on this model, since the consumption of the compressor is considered as being part of the production system, and is not of exclusive use for the machine.
- The hydraulic consume is divided into two: Normal and clamping services.
- The pallet clamp is automatic. Even though is done using hydraulic pressure, its energy consumption is considered like a different and specific element. This assumption is made, so that it is possible to model the loading or unloading of the piece without a direct dependence on the hydraulic unit.
- A chip conveyor is considered; it can be removed in the case that a machine does not have this mechanism, by assuming its energy consumption equal to zero, and without significant problems for the model
- A cutting coolant system is considered, but in the case of a machine designed for fiber removal, the cutting coolant can usually be replaced by an aspiration system.

2.5 Machine Tool Cycle

As presented in previous lines, the model that is developed in a forthcoming chapter is being based in a numerical controlled automated machine tool. In this kind of devices, in order to process a piece, the first step to follow is to set up the process for the machining operation [Wan96].

The "set up" process is performed when appropriate fixture is secured on a pallet and calibrated, and also the tools required for machining the part are loaded into the magazine. This "set up" process is made every time the machining conditions (such as different geometries or materials among pieces) are changed.

Since this process migth change drastically based on the selected machine and the machining conditions, it is not included in the energetic model of the machine.

- Initialization process

  The first condition that has to be fulfilled for starting a machining process is to provide the required services to the machine, such as electrical power, compressed air, cooling lubricant fluid and fluid for the cooler devices. At the absence of any of these consumables, the process may present different failures or will not start.

Depending on the specific needs of the process and on the machine, a "warm up" phase, (where some of the parts of the machine will move in order to acquire thermal specifications) is executed, but if this phase is note required, the machine can avoid it, and go directly to a waiting state.

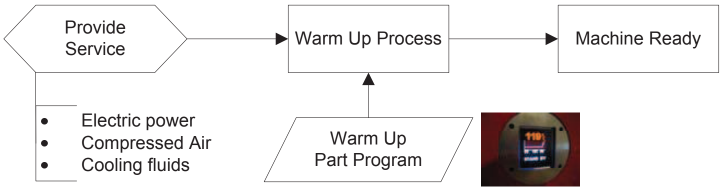


FIGURE 2.12: Machine tool cycle diagram: Inizialization

- Raw material placement

  The machining process itself starts when a piece or a pallet arrives to the input buffer and the operator loads the proper part program into the CNC control, regarding that the set up process mentioned before has already been performed.

  Once the piece or pallet is located in the buffer, and the machine is empty, the automatic loader/unloader component will transfer the element to be processed into the machine working area, based on the specifications described in the "set up" process.

  When the loader arrives to the desired position, this component will discharge the element and leave the working space in order to avoid interfering with the movements of the machine drives, and also to be ready for the next time it is needed. Once the piece or pallet is placed, it will be fixed with respect to the moving elements in the environment with the hydraulic pallet clamp action (dictated by the part program).

  The pallet clamp that is taken into consideration in this work, behaves in a very similar way to the loader/unloader element according to its behavior on the clamping and unclamping stages of the process. This behavior is associated with the fact that the consumption of energy is considered when the process requires energy for activating the clamping devices. Once the piece or pallet is clamped, it will be mechanically locked (on behalf of safety reasons) for maintaining it secured during the material removal process, avoiding the consumption of energy during the cutting process.

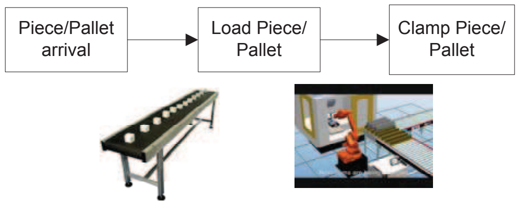


FIGURE 2.13: Machine tool cycle diagram: Placement of the piece

- Material removal process

  From this point on, until the material removal procedure is finished, the process, with exceptions of failures or external actions, will depend on the part program loaded into the numerical control. Within the lines of the part program, developed using "G-Code" language, there can be found instructions that direct actions such as a tool change, change of velocities and ways to move the axes, change velocities on the spindle, impose pause times, among others.

  Different auxiliary elements of the machine are controlled during the cutting process, and its control actions can be strictly bounded to the part program or might have some degrees of freedom for the user to configure.

  The cutting coolant element, which is in charge of providing refrigerant in the working area to dissipate heat produced by the tool-piece interaction, is commanded entirely by the part program with a special "G-Code" command.

  Another example of elements, whose control strategy depends on the part program, is the automatic programmable tool changer. The action perfomed by this element is executed at the beginning of the cutting process if no tool is loaded on the spindle, or once an operation with the loaded tool is finished, and a new tool, for continuing the process of machining is required.

  The auxiliar chip conveyor element operations can be driven by the part program, or it might be controlled by external actions.

  Some of the most important ancillary elements are the cooler devices. Its importance resides in that the work they perform, keeps the temperature of the moving elements below a prescribed level to ensure the process quality.

  The regular working cycle of a cooler device is parameterized by the constant circulation of refrigerating fluid through the element to cool down, as long as it is *on*, and the activation of a heat exchanger to cool the circulating fluid when the drive is actually making movements. The control of the heat exchanger depends not only on the part program, but also, on the desired temperature for the moving drive, given as a set point by an external subject.

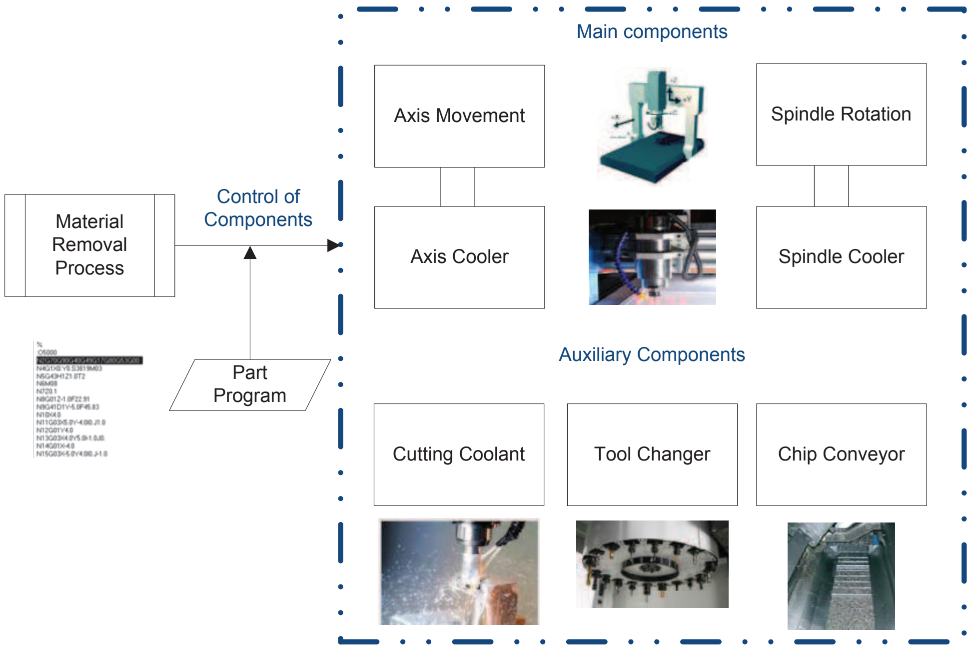


FIGURE 2.14: Machine tool cycle diagram: Material removal process

- Machined piece dischrage

  After the machining operations are finished, the time for automatically unloading the piece or pallet has come. The pallet clamp draws energy on this specific instant, since the piece or pallet needs to be released automatically. After the piece is released, and considering a machine with an output buffer, the loader/unloader component will only execute this action, if there is still capacity in the mentioned buffer. If the process requires, a new raw piece will be put into the machine and will start the process again.

- Additional accessories

  Depending on the requirements of the final user, a machine tool can have different elements and behaviors associated to these elements, which even though are not considered in this work, are worthy to mention, since in future analysis can be taken into consideration and can be replaced or added to the elements that are already being taken into account here.

  An aspiration element, apart from the mentioned in previous paragraphs (considered instead of the cutting coolant element on a fiber removal process), can intervene in a process of mist aspiration on the working area, and can work in parallel with the cutting coolant element.

  Also there can be found elements, as the ones intervening on the process of cleaning the piece or the working area, which can be added or not, depending on very specific user requirements.

Furthermore, some behaviors can be also differing from the ones that are presented in this analysis, only by changing the activities of the elements already present on the machine. One example of this is the behavior of the lighting system, which can be controlled by an energy saving policy. This policy can dictate that after some inactivity time on the machine, the lighting system is switched *off*. This policy will lead to place the lighting system away from the fixed power elements (as it is considered here) and put it into the variable power demand.

Chapter 3

State of the Art

At the present time, issues regarding energy saving guidelines are becoming of great importance, not only for common people, that are gaining conscience about energy significance, but also for companies, that are becoming more aware of the depletion of the resources (in which they play a major role as stated in previous chapters) and how this fact affects the sustainability of the business.

The depletion of nonrenewable resources employed to produce energy generates a tendency of increasing the cost of the energy; and as a consequence, the optimization of the energy used by machinery plays a foremost role on industrial production.

This chapter follows a sequential order. Initially it is explained how is distributed the energy consumption on a machine tool on its different life phases, making emphases in the use phase where energy consumption is more critical and can be characterized in different kinds, influencing the energetic classification of the components of the machine tool.

In the second part of the chapter it is described how the energetic efficiency in a machine tool can be achieved based on different approaches, and the third part delves in the control approach. Finally, different solutions available on the current market in order to optimize the production taking into account the energy efficiency of machine tools are presented.

3.1 Energy Consumption of a Machine Tool

3.1.1 Product life cycle

Every generated product undergoes different life phases. The basic approach consider three of them counting for the design and manufacturing of the product, its use and its end of life [Dia11]. A more extended approach contemplates an inclusion of an additional cycle, accounting for the transportation of the product [San11].

Taking into consideration these different phases, the environmental impact of any product (in this particular case a machine tool) can be expressed in base of its energy consumption and its CO_2 emissions during its whole life.

The manufacturing phase involves the energy consumed in order to fabricate each single component belonging to the product and the energy used for assembling all of these components. It is important to underline that for each component it is necessary to consider the materials and all possible processes that they can undergo before being assembled, like casting, extrusion rolling, grinding, heat treatments, etc.

For the transportation phase, the environmental impact considers the different CO_2 emissions produced by the specific means of transport employed. The trajectories considered in this phase are: the displacement of the product from the place where it was built to the place where it will spend its operational phase, and once the machine has finished its functional life, the route to the place where it will be disposed.

The use phase considers the energy consumed by the machine in the plant where it will be used to actually manufacture products; this energy varies depending on the environment in which the machine is configured and the type of use to which it will be subjected.

The boundaries of the end use phase are not clearly defined in the literature since machine tools are constantly resold in the used market, making difficult to understand the potential future use of a machine tool after the conclusion of its functional life with one user.

Several studies have been conducted to measure the environmental impact of each life phase of a machine tool. Diaz et al. performed one of these studies, with the aim of calculate the grams of CO_2 equivalent emitted by two different machines in order to produce a standard manufactured part.

The phases considered in this study were manufacturing, transportation and use of the machine tool. The use phase incorporated three different manufacturing environments: community shop, job shop and commercial facility, which allowed the analysis of different facility characteristics and production schedules.

The results of the analysis are shown in figure 3.1; it can be appreciated that the transportation phase has a relatively small contribution on the total CO_2 emissions while the use phase comprises the majority of the overall emissions on intervals from 70% to 90%, of the total emissions [Dia10a].

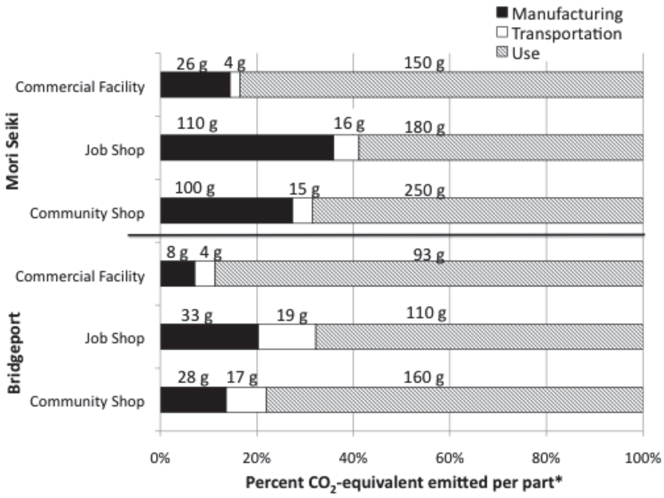


Figure 3.1: Result of the life cycle impact on two machines (Bridgeport Manual Mill Series I and Mori Seik Duravertical 5060). Values provided have units of grams of CO2 equivalent emitted per part [Dia10a]

The result of the previous analysis causes that focusing on quantifying the energy consumption of a machine tool during the use phase, becomes a factor of crucial importance. Since it is also known, that more of the 99% of the environmental impacts of machine tools used in discrete part manufacturing, are due to the consumption of electrical energy [Li11b], the analysis enclosed in this thesis will be focusing on this type of energy.

3.1.2 Use phase energy consumption characterization

Constraining the analysis to the use phase, it is identified that the energy consumption of a machine tool results from a temporal power demand; this demand is not static but rather dynamic, and can be classified into three categories: constant, variable and cutting power [Li11b] [Dia10b].

The definition of the different categories of power demand will be given based on the work done by Santos et al. [San11], Li et al. [Li11b] and Diaz et al. [Dia10b].

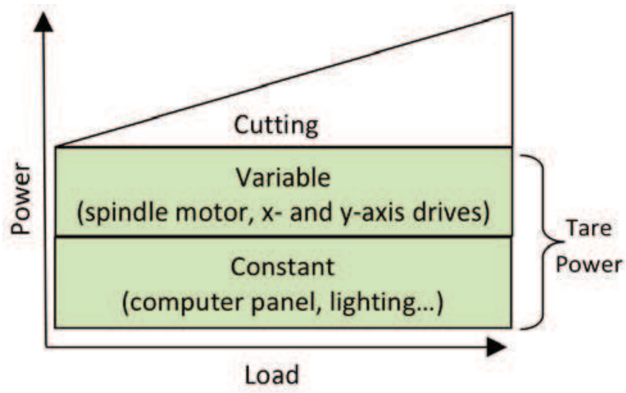


FIGURE 3.2: Power as a function of load from material removal [Dah04]

- The constant category considers the power demand even if the machine is not performing a manufacturing operation. This power ensures the functional mode of the machine (ready for operation) and includes the requirements of operating components like motors and spindle, which are energized to maintain a specific position.

- The variable power demand or operational power, contemplates the consumption of the components that will be involved in the cutting process, enabling the cutting as performed in air-cuts; meaning that the machine can perform all the movements required for producing a particular piece but without removing material. This power depends on the operator control and its magnitude varies with commands like move axis or operate the spindle.

  The previous two power demands (constant and variable) can be clustered as the tare power of the machine, being this the minimum power that will be demanded for a set of process parameters, regardless if there is removal of material or not.

- The cutting power demand is defined as the amount of energy that is required to produce a work piece; it takes into account the amount of material to be removed, the type of material to remove, the material removal rate (MRR) and the cutting tool, creating a strong correlation between the load from the material process and the power demand.

  It is important to notice that the maximum value of the cumulative variable part is limited by the machine characteristic.

This type of energy distribution can be seen in figure 3.3, which corresponds to a power profile of a turning process, and in which the Tool Tip Power corresponds to the cutting power and the Unproductive Power is defined, as the power converted to heat, mainly due to frictions during the material removal.

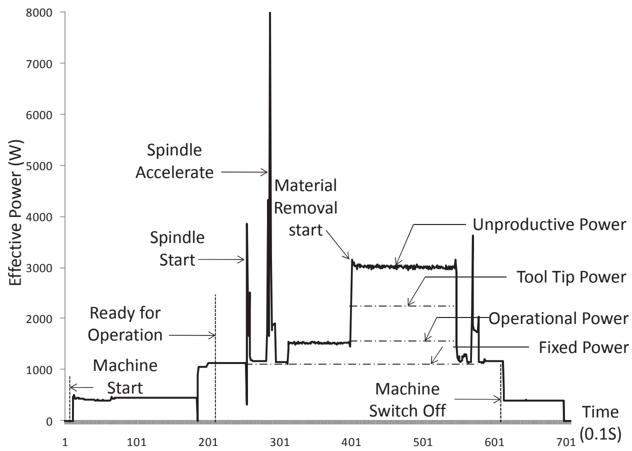


FIGURE 3.3: Power profile of a turning process [Li11b]

The overall energy consumption of a machine tool (including all power demands: constant, variable and cutting), depends on the contributions of individual energy request of all its components, as it can be seen in figure 3.4.

The consumption of each component depends on its individual operational states. The state of the component at a specific point usually depends in the part program execution, but some particular components might show an additional degree of freedom, depending on parameters fixed by the user of the machine.

There are many different classifications for consumers on machine tools, being one of the most common one a segmentation into drives, peripherals and auxiliaries devices. The drives category includes the feed axis, spindle, and its electronics. The peripheral devices are the hydraulic units, cooling and coolant components, and the auxiliary devices depend on the machine tool itself and include components such as the tool magazine, pallet changer or the chip transporter[Sch11].

During production time, the components that influence the energy consumption are the spindle and feed drives. The feed drives consume a small portion of energy, nevertheless the spindle can considerably impact the energy consumption on this state, and if it is operated below its nominal power, a proportional amount of losses will be presented [Hei11].

On the other hand, a major share of the energy consumption belonging to the constant category is attributed to auxiliary and peripheral equipment [Sch10b]. These devices can have different behavior depending on their energetic state evolution [Li11b].

- Components that regardless the states of the machine are activated (always *on*); in this category there are contained, the electronics in the control cabinet, the HMI, PLC, NCU, some fans or cooling devices. The consumption of these components constitutes the basic power load of the machine tool.
- Components that are either fully activated or not; these components are commanded to be switched *on* or switched *off* by the machine control based on the current program; some examples of this type of components are the chip conveyor, the hydraulic pump or the coolant pump.
- Components that are operated with a dynamically adjusting load; these components have a continuous state depending on the requirements of the process of the machine tool; generally spindle, servo drives and its control systems belong to this category.
- Components with an additional degree of freedom; these components besides being switched *on* or *off* by the machine, have an additional degree of freedom in their control; a possible example of these components are the cooling devices of the main drives which are switched based on a specific temperature.

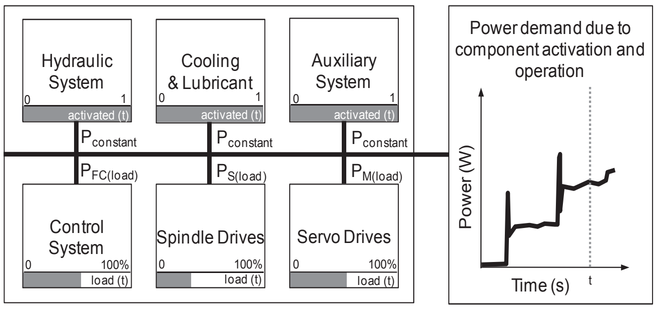


FIGURE 3.4: Power agglomeration of components to the power demand of a machine tool [Li11b]

3.2 Efficient Machine Tools

Despite the fact that the definition of energy efficiency is not very specified in literature, a good approximation to its meaning is the one relating efficiency to the ratio between benefit and cost. In this case, the benefit will be an output (for example pieces elaborated) and the cost will be the amount of energy required for obtaining this desired output [Irr08]. In this way the efficiency can be associated with the fact of using less energy to produce the same amount of service or output [Pat96].

Based on this definition, it is possible to define the energy efficiency of machine tools as the amount of electrical energy spent to perform a complete machining operation, where the procedures of start-up, set up, processing of a distinct amount of material and shut down are consuming different amounts of energy [Li11a].

According to the previous description, the improvement of energy efficiency in a machine tool can be achieved following two different approaches, maximizing the output for a given energy input or minimizing the energy required to provide an output. The strategies for upgrading a machine tool into a more efficient one are aligned with the minimization of the energy demand of its components and the reuse of invested energy and/or recovery of energy losses [Li11a].

3.2.1 Minimization of input energy

According to GE Fanuc [GE 05], the reduction of energy consumption can be achieved by applying technical or organizational measures. More accurately, the minimization of input energy can be segmented in three different levels: component, control and machining parameters. Regarding figure 3.5 the technical measurements correspond to the component level and the organizational measures enclose the control and machining parameters level.

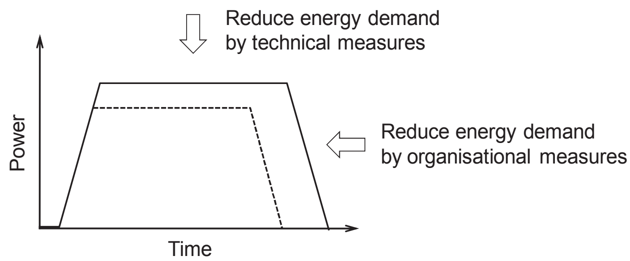


FIGURE 3.5: Strategies to reduce the energy demand of machine tool [GE 05]

- Component level:

  In order to minimize the energy consumption, some technical measures can be applied towards the reduction of the fixed power demand of components, by installing in the machine energy efficient devices [Li11b].

  The International Organization for Standardization (ISO) propose in [ISO12], different actions to be executed during the machine tool assembly and design with the purpose of reducing its energy consumption. To achieve this goal, ISO suggests a separation of the mechanical and electrical components of the machine into drive units, hydraulic system, cooling and lubrication system, power electronics, peripheral devices and control, and recommends for each one of them, diverse options, like the use of inverted controlled motors for auxiliary units, the minimization of the mass of moving parts, leakage monitoring, among others.

Fraunhofer technical report of task 5 [Sch10b] also describes different actions in order to achieve the minimization of energy by acting on the components, with technologies expected to be introduced in the market within the next two to three years. This work presents options such as, mass reduction of the moving parts, utilization of electrical clamping devices, use of hydraulic accumulators, and employment of optimized valves. These suggestions are closely related with the ones of ISO described in the previous paragraph.

Some of these proposals have already been implemented in different companies like Rexroth from the Bosch Group, by using synchronous motors with high efficiency, direct drive technology with linear and torque motors, speed control with jerk limitation, speed variable pumps, hydraulic accumulators, pneumatic valves with low power input, among others [Bos08].

- Machining parameters level:

  In studies performed by Diaz et al. it is stated that the energy per manufactured unit is determined by the power demand of the machine tool during machining and by the processing time [Dia09].

  The variable power demand and the processing time depend on the process parameter selection; for example for a milling process, the processing time per manufactured unit, is principally governed by the feed rate, which at the same time depends on the number of revolutions per unit of the spindle, the feed per tooth and the number of flutes of the tool. The interaction of the process parameters with the time and power demand, and thus energy is represented in figure 3.6.

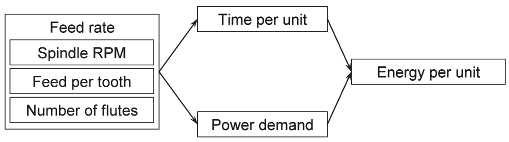


FIGURE 3.6: Influence of process parameters on the energy per unit manufactured [Dia09]

  Analyzing a cutting process, it can be inferred that as the feed rate increases the processing time reduces, and thus the energy per manufactured unit tends to decrease, but this same increase in the feed rate demands more power from the machine tool, generating an intensification of the power demand. This consideration results in a tradeoff between changes in the feed rate and the overall energy consumed, allowing finding an optimal region in which the energy is minimized.

  In an extension of the work cited above, Diaz et al studied the effect of the material removal rate (MRR) on energy consumption, using as motivation that a variation of the MRR affects the processing time, and as stated on the previous paragraph, a change in this variable (processing time) implies a modification on the energy consumption of machine tools [Dia11].

Considering again a milling process, the MRR on a 3-axis machining center can be varied by changing not only the feed rate, but also the width of cut and depth of cut. A proper selection of these parameters allows a maximization of the MRR and thus generates a decrease in the energy consumption; it is important to be aware that when increasing the MRR the resulting process condition and the work piece quality might be altered.

- Control level:

  This category contains the different strategies that can be used at the machine and process control level to minimize the input energy, by minimizing time of non-value adding tasks. Since the scope of this thesis is based on the control, an extended explanation of the current state of the art with this approach will be described in section 3.3.

3.2.2 Energy recovery

Nowadays different components, such as axis and spindle drives, are able to recover energy on the machine in order to use it on different processes. Also there can be found systems for heat recovery that use the heat losses in order to preheat or heat specific areas of the machine [CEC12a].

- Reuse energy:

  The recovery energy systems are supported on the fact that every acceleration process of a drive has as a consequence a breaking process, and the energy spent in this deceleration can be reconverted into useful energy instead of losing it as heat released to the environment. The recovered energy systems can be classified into regenerative or non-regenerative [Sch10b].

  The kinetic energy recovery systems (KERS) belong to the regenerative process category and are conceived to recover the energy used during the breaking of the spindle and posteriorly storage it into super capacitors. In a study performed by Diaz et al. different simulations were made in order to explore the viability of implementing these systems into machine tools. The results of this work showed that these systems were not yet commercial feasible because of the elevated cost of super capacitors, but it was left open the possibility of using this technique when the process has a significant amount of tool changes, or in a future, in which the recovered energy will be redirected to the electric network or in which the cost of super capacitors decreases [Dia09].

Regarding non-regenerative energy recovery clasiffication, the system transforms the kinetic energy from the breaking process into heat to be used in different applications. These systems are more efficient, and thus more used when there is a small number of the tool changes in the machining process [Sch10b].

- Recover energy losses:

  A part of the electrical energy used in the machine tool is transformed into heat; these energy losses can be recovered by heat recuperation techniques using thermal management [Li11a].

  These techniques are based on systems of heat exchangers installed in different parts of the machine. The heat exchangers use the heat dissipated by the machine to warm up water or other fluids, and transfer this heat to other components needing a preheating process, allowing the minimization of energy drawn from the main grid [Sch10b].

3.3 Control Strategies for Minimizing Energy Consumption

On a generic production process involving machine tools there can be found different reasons to let the machines, belonging to a system, remain on a state in which the consumption of energy is not null, even if they are not performing a proper machining operation.

A motivation to perform this practice is aligned with guaranteeing a thermal steady condition in order to obtain high accuracy on the elaboration of products. If the machine is switched *off*, its specific thermal strain can be affected and thus its precision [Sch10c].

One of the major consequences of the practice of leaving *on* the machines regards considerable energy loses, since the electrical power consumed during these periods reflects on great accumulated energy consumption [Ott12].

Focusing on minimizing the total energy consumption of a machine tool, an understandable approach consist on the implementation of standby strategies, which will permit the user to set default times for shutting down the machine, without compromising neither the production cycle nor the quality of the product.

The compromise between energy saving (by switching *off* the machine) and product quality can be consolidated with automatic wake up and warm up functions that will automatically restart the machine and lead it to a desired operational temperature at a time specified by the user [Sch10b].

The implementation of standby strategies can be used in non-continuous manufacturing process, such as turning and milling, where the standby time is unavoidable but viable to be minimized.

Summarizing, if the standby time is long enough the machine could be switched *off*, nevertheless, since the constant power is responsible for allowing the machine to be ready to operate, and this readiness take some time, the switch *off* strategy should not sacrifice the availability and thus, the production level of the machine tool [Li11b].

On the following paragraphs different control strategies available in the current state of the art for minimizing energy consumption will be exposed.

3.3.1 Energy efficient production planning [Mou11]

The production planning strategy is conceived in order to be used on a managerial sphere of a production plant involving machine tools, as an instrument to be employed by a production manager, with the aim of determining the most efficient schedule of jobs in a machine with a proper energy consumption level.

Due to the way this strategy is conceived, its application could be considered as an offline control of the machine, since the decision making, regarding the state of the machine during the idle periods, is executed before the production process starts.

Mouzon and Yildirim provide “a methodology to schedule tasks on a machine while considering minimization of energy consumption and total completion time objectives by intelligently turning *off* and *on* the machine between schedule tasks instead of keeping the machine idle”.

The studied scenario corresponds to a single machine scheduling problem with the aim of minimize the energy and total completion time, and as input data (belonging to the process) a deterministic job arrival and service time. Within the characteristic described, the problem is modeled as a multi objective mixed integer program.

Additional input data required to define the problem include specific characteristics of the machine such as the idle power, the processing power and the tip power (marginal power utilized to process a part). It is also necessary to define the setup as the operation of turn *off* and then turn *on* the machine, which consumes a fixed amount of energy and time.

A set of solutions to the problem is obtained by means of a genetic algorithm that provides information about the appropriate time to start each job and in which intervals turn *on/off* the machine.

Finally, the "best/most" appropriate solution is selected among the set provided by the algorithm by the plant manager, using a technique for organizing and analyzing complex decisions (Analytic Hierarchy Process).

3.3.2 Self-optimized machine [Sch11]

Unlike the previous strategy, the control of the machine based on a concept of self-optimization can be considered as a proper control action, not a scheduling problem.

"A self-optimized machine tool is an intelligent system that has the capability to react autonomously and flexibly to its surrounding environmental conditions, to the interference of external users/systems, or also to their own dynamic behavior, modifying their local objectives and adapting their parameters-structure in response to these dynamic factors. Regarding the specific problem of energy efficiency, such machine is able to adapt itself to the current production requirements, plan the power balance of energy consumers and reduce energy losses".

In order to define in a more accurate way the optimization problem, it is necessary to divide the machine consumers into machine components and common supply systems.

The supply systems are defined as systems that provide the services requested by the machine components, such as spindle, feed drives, tool magazine among others; different examples of these components are the hydraulic, cooling and electrical power supply systems.

It is worthy to focus on suppliers, since are elements that keep consuming energy (the power source is not shut *off*) even if they are not providing any service to the machine components, being unnecessary available at a specific time; this kind of behavior is characterized as supply excess as can be seen in figure 3.7.

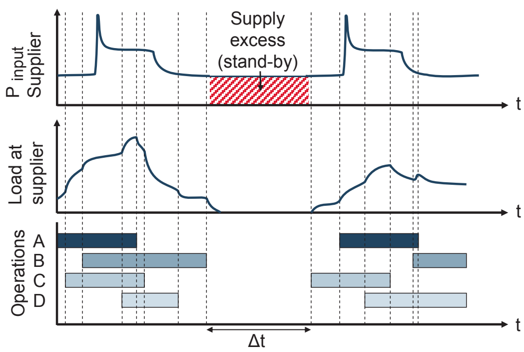


FIGURE 3.7: Typical supplier with load progress and supply excess [Sch11]

In order to pursue a reduction of the energy consumption of suppliers, some supply controllers, which are able to drive suppliers into different mode or states can be implemented.

With the aim of minimize the supply excess, a functional state machine for common suppliers is suggested. The main characteristics of this particular type of component modeling corresponds to adding not only cost but also energy to the transitions between states (providing essential information for further optimization). The states represent which operations are being supported by the supplier, and each performed operation demands time and energy. Finally, it is important to notice that each common supplier has to be represented with a functional state machine.

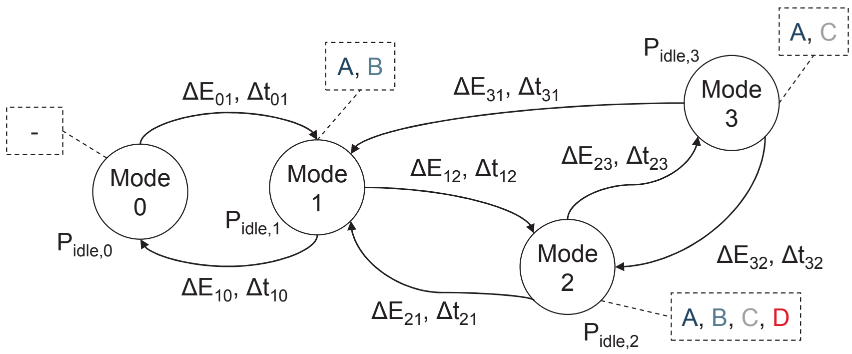


FIGURE 3.8: Example of functional state machine [Sch11]

In figure 3.8 an example of a functional state machine for a specific common supplier is presented; the supported operations are denoted with letters A, B, C and D, and the states are entitled by different "Modes". In the first state ("Mode 0") non operation is supported and its inclusion emulates a low power state, that could be employed to save energy when the machine tool does not demand services from the supplier.

With the use of a functional state machine for each supplier, it is possible to help with the decision and implementation of a switching strategy, in which the optimization problem will be subjected to find the best state/trajectory in order to reduce idle power and total energy consumption.

3.3.3 Production and energy control [Pra12a] [Pra12b]

The strategy proposed by Prabhu et al. [Pra12b] suggest the use of "a machine-level energy control policy in which a machine is switched *off* to a low power consumption state if the idle time exceeds a threshold", emulating policies already implemented in electronic devices such as laptops, cellphones and others.

The control policy (EC1) is designed in such a way that interacts with the production control to maintain equilibrium between energy savings, production losses and product quality related with the thermal effects due to extended *off* times.

The threshold time will be chosen based on the interaction of the energy control policy with the production system, and the possible solutions will be compared in terms of different key performance indicators like cycle time, utilization, availability, energy, among others.

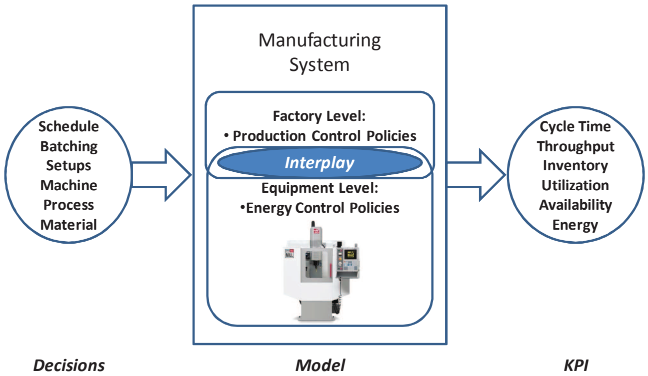


FIGURE 3.9: Proposed model focuses on linking decisions to KPI [Pra12a]

The power consumption of a machine is determined by its states that are physically controlled by the PLC or the CNC based on the part program execution (G-code, M-Code, S-Code). This fact contributes to have a machine-level energy dynamics as a combination of discrete and continues state variables, hence the interplay between the production control and the energy control will require a mapping of this states as can be seen in figure 3.10.

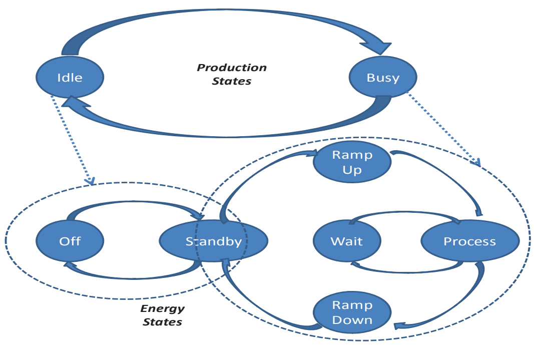


FIGURE 3.10: Mapping of discrete production states to energy states [Pra12b]

In a later work [Pra12a], EC1 is applied to existing analytically models based on queuing theory in order to control energy waste reduction and some experiment are performed to test the robustness of this analytical model using different probabilistic distributions.

A detailed explanation of the model and policy employed in this work is presented in section 6.2.1.

3.3.4 Multilevel control [Ver11]

The operation of a machine in an energetic optimal way requires information about the energy consumption characteristics of the components and the machine itself; it is also necessary to specify the desired behavior of the machine, identifying the parameters constrains that come with it (the desired behavior). Taking into account these constrains, the machine and its components can be controlled "to follow a state trajectory that minimize the total energy consumption".

A decentralized machine architecture is proposed, in which each component is equipped with the capability of learning models of its energy consumption, and an energy control loop is implemented to drive the component into an energetic optimal state. The optimal state will depend on the production program, for both the machining time and the standby time. The behavior of this type of architecture can be appreciated in figure 3.11.

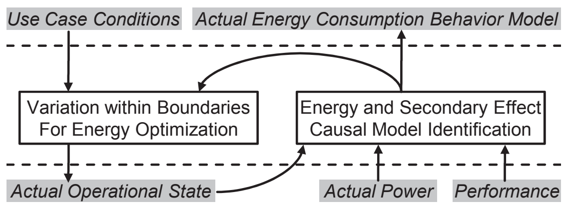


Figure 3.11: Local energy control loop closed within a control level [Ver11]

Once certain requirements are fulfilled, the energy control loops mentioned in the previous paragraph can be accomplished, by the implementation of reducing options solutions on all levels of control.

- Component level energy control: This approach is based on the different type of components, previously explained in section 3.1.2.

  Regarding the components that have only two operational states (*on/off*) and when they are *on* always operate in an optimal point, the optimization gives as a result a schedule of the situations in which the component is needed and when it can be switched *off*.

  In the case that the load of the component varies along the machining cycle, and thus, when it is *on*, it is not necessarily on its optimal operational point, the previous approach is not enough, and a way to improve it, is by implementing a machine control that will enforce the component into a specific energy state, based on the information of the machine and the process.

Finally, when the components of the machine are smart (can learn its energy consumption model) and are connected through a digital field bus that allows communication mechanisms for detailed model information, a different approach can be used. The methodology is based in providing information to the control of the component about the boundary conditions, for example a pause period, and let this control decides locally (by itself) a trajectory to follow, providing the most energetic efficient solution.

- Energy control function on the individual machine level: The application of this methodology requires a module that decides and sets the energetic optimal state of the machine.

  This module bases its decision in information gathered from the machine, like the interpretation of the NC code, the production line commands (idle periods) and PLC information.

  With the information gathered from the machine and the process, the machine and its components are set to energy optimal states after the last command of an operation is executed. Furthermore, if a component is not used for a defined period of time, the module will check if there is a more optimal energetic state, in order to decide if it is worthy to send the component to this condition and later wake it up at the proper time.

3.4 Industrial Developments

In the current market there have been developed different options in order to support machine users to optimize its production, without disregarding energy efficiency. These developments have been made by machine tool builders and by providers that support the final users and builders of machine tools [Ott12].

3.4.1 DMG EnergySave

According to the vendor, this device is able to reduce power consumption automatically and efficiently during unproductive machining times.

These energy saving technologies automatically drives the machine to different energetic modes, once the standby period exceeds a customer defined limit. The limit can be easily selected by means of a BCD code switch with preset time intervals.

After the selected time has passed, the device drives the machine into an energy stop condition, and additionally can switch *off* the lighting system. This action allows the operator to restart the machine without problems, since the emergency condition is completely known by the operator [DMG10].

FIGURE 3.12: DMG Energy Save Module [DMG10]

Adding some additional functionalities like the wake up and warm up, it is possible to set the machine in an operational status at a defined point, and automatically heat it up to operating temperature. This action is conceived in order to avoid time losses on the production system because of the non readiness of the machine [Sch10b].

3.4.2 SINUMERIK Ctrl-Energy

The approach made by Siemens AG in order to make its contribution to the problem of energy saving in machine tool centers, is characterized by the development of new technologically and powerful sophisticated functions that are included in the CNC control system [Sie12].

FIGURE 3.13: SINUMERIK Ctrl-Energy [Sie12]

Sinumerik Ctrl+E offers a solution that allows, with a combination of keys made on the operator screen, a rapid evaluation of the energy consumption of the machine, and of the management of the energy consumption during stand still times. With this approach, the machine user is able to analyze the energy consumption for each work piece and derive an optimal machining strategy [Ott12].

Chapter 4

Model of the Energetic States of a Machine Tool Using Automata

This chapter starts with an introduction about discrete event systems and *automata* theory with the aim of facilitating the comprehension of the reader in a commonly knowledge frame.

Subsequently, an energetic decomposition based on different components of a machine tool is bestowed; this decomposition is the prelude of an event characterization, necessary for modeling energetically the different components previously presented.

With the previous characteristics in mind, it is possible to present the different energetic models, in *automata* language, of each individual component of a machine tool. These individual models will lead to obtain a complete energetic model by the use of a particular operation of the *automata* language.

In the final part, the complete energetic machine tool model is clustered in states with analogous energy consumption, in order to allow a better comprehension of the energy distribution within the machine.

The energetic model of the machine is a joint work with Maria Luisa Calvanese [Cal12].

The complete energetic model of the machine, clustered model and the energetic model of the individual components (all presented in the following paragraphs of this chapter) were subjected to validation from three different experts on the field of machine tools from the following Italian companies: JOBS SpA , Comau SpA, and Pama SpA.

4.1 Discrete Event Systems and *Automata* Theory

4.1.1 Discrete event systems (DES)

A discrete-event system is a system whose behavior can be described by means of a set of time-consuming activities or particular conditions of the system (States) performed according to a prescribed order, and events that correspond to starting or ending some activity or condition [Coh85].

These are systems that at any time-instant occupy a unique state of being, out of the finite set of such states, which in correspondence represent a configuration or situation during which certain physical laws, policies and rules apply. This system performs transitions that are associated with the occurrence of events happening asynchronously at discrete points in time. In this way the behavior of the system is described as sequences of the occurring events (traces), and sequences of the states visited as a result of these traces [Fab06].

Some application and complex systems can be naturally and easily modeled as discrete event systems, such as [Cas08]:

- A production machine whose states can be selected from a set such as: {ON, OFF} or {BUSY, IDLE, DOWN}.
- A computer running a program may be viewed as being as in one of three states {WATCHING FOR INPUT, RUNNING, DOWN}.
- An inventory of discrete entities (e.g. Products, monetary units, people),which has a natural state space in the non-negative integer depending on its capacity.

4.1.2 *Automata*

A finite state *automaton* is a description of a discrete event system composed by states and events. The system is always located in one of the finite states of the *automaton* and moves between these states through the occurrence of the events connecting them [Fab06].

- *Automata* definition

  A finite state automaton P is described as a 4-tuple $(Q_P, \Sigma_P, i_P, \delta_P)$ where:

  - Q_P is the finite set of state (states names)
  - Σ_P is the finite set of events (event labels), also known as the *alphabet* of the *automata*

- $i_P \in Q_P$ is the initial state
- $\delta_P : Q_P \times \Sigma_P \rightarrow Q_P$ is the transition function that describes, for a specific state and event, the state in which the *automaton* will be located after the occurrence of the event

A state represents a configuration or situation under certain physical laws and policies apply and summarize all information necessary to determine future behavior.

An event represents an incident that causes the system to move from one state to another, perhaps the same state; events are set to be associated with their transitions, meaning that either the event is generated when the *automaton* performs the transition or the transition is triggered by the occurrence of the event. It is important to notice that an *automaton* can only execute events from its alphabet.

The transition function is generally a partial function not defined for all the combination of states and events.

- *Automata* representation

  The finite state *automata* can be represented graphically, by means of a directed graph or with a matrix expression that represents the transition function.

  In the graphical representation, the states are usually characterized by circles, the transition by arrows connecting the states (circles), and the events being the labels associated to the different arrows; finally, the initial state is represented with an arrow with no predecessor.

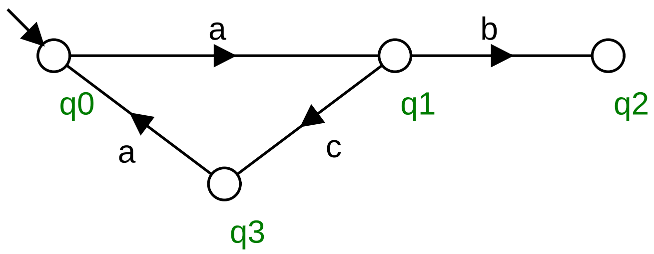


FIGURE 4.1: Graphic representation of *Automaton A*

The formal representation of the *automaton A* above is given by:

$$Q_A = \{q_0, q_1, q_2, q_3\} \tag{4.1}$$

$$\Sigma_A = \{a, b, c\} \tag{4.2}$$

$$i_A = q_0 \tag{4.3}$$

	q_0	q_1	q_2	q_3
q_0		a		
q_1			b	c
q_2				
q_3	a			

TABLE 4.1: Matrix representation of the transition function of *automata* A

$$\delta_A = \{((q_0, a), q_1), ((q_1, b), q_2), ((q_1, c), q_3), ((q_3, a), q_0)\} \tag{4.4}$$

The matrix representation is shown in table 4.1

- Synchronous composition

  Given two *automata* representing two different discrete event systems, the result of the synchronous composition is a third *automaton* which models the respective component behavior, under the constraint that shared events must be executed synchronously. Thus, each component restricts the behavior of the other component [Uni12].

  Assuming two *automata* $A = (Q_A, \Sigma_A, i_A, \delta_A)$ and $B = (Q_B, \Sigma_B, i_B, \delta_B)$ its synchronous composition $C = A||B = (Q_C, \Sigma_C, i_C, \delta_C)$ can be obtained using the following stages:

  – The set of the states is the cartesian product of the set of the states of the two *automata*.

  $$Q_C = Q_A \times Q_B \tag{4.5}$$

  – The alphabet is given by the union of the other alphabets

  $$\Sigma_C = \Sigma_A \bigcup \Sigma_B \tag{4.6}$$

  – The initial state corresponds to the initial states of the previous *automata*.

  $$i_C = (i_A, i_B) \tag{4.7}$$

  – And the transition function depends on whether the event is a common one or not

$$\delta_C((q_A, q_B), \sigma) = \begin{cases} \{\delta_A(q_A, \sigma)\} \times \{\delta_B(q_B, \sigma)\} & \text{if } \sigma \in \Sigma_A \bigcap \Sigma_B, \\ \{\delta_A(q_A, \sigma)\} \times \{q_B\} & \text{if } \sigma \in \Sigma_A - \Sigma_B, \\ \{q_A\} \times \{\delta_B(q_B, \sigma)\} & \text{if } \sigma \in \Sigma_B - \Sigma_A. \end{cases} \tag{4.8}$$

4.2 Energetic Decomposition of a Machine Tool

A machine tool can be decomposed as an assembly of several components that perform a specific function, allowing the entire system to execute a more complex task. Each of the components can be described with different states, each of one with different energy consumption.

According to Dietmair [Die09] and Li [Li11b], a machine tool can be divided taking into account the components that consume energy. In this work, the following classification is considered:

- Axis (A): In the axis component are considered the **servomotor**, which provides the linear motion for the cutting tool in a specific direction, and the **servo amplifier/frequency converter**, which is in charge of transferring the numerical control signals for the specific servo into an adjusted electrical signal.
- Axis Cooler (AC): Takes into consideration the **pump motor** with which the coolant is provided to the refrigeration circuit of the axis, and the necessary **heat exchanger** for cooling the circulating fluid.
- Chip Conveyor (ChC): Correspond to the **conveyor motor**, that generates the movement for the chip handling.
- Cutting Coolant (CC): Describes the **pump motor** that is in charge of delivering the coolant to the hydraulic circuit with the prescribed pressure. In the case of a machine designed for fiber removal, the cutting coolant is usually replaced by an aspiration system.
- Fixed power (FP): Takes into consideration all the components that have a constant power demand. In this element are considered the **computer** and the **display**, that allow the processing and visualization of the program, the elements that have as a function **lighting** the working area, the **fans** that generate air flow to cool the electrical components, the **electric cabinet** of the machine and the **CNC Control**.
- Loader/Unloader (L): Takes into account the devices that allow an automatic/semiautomatic loading of the piece like a **robotic arm** or a **pallet changer**.
- Pallet Clamp (PC): Represent the **motor** that supplies the clamping pressure to the piece.
- Spindle (SP): In the spindle component are considered the **spindle motor** which provides the rotary motion to the tool, and the **spindle amplifier/frequency converter** which is in charge of transferring the numerical control signals for the specific spindle motor into an adjusted electrical signal.

- Spindle Cooler (SC): Takes into consideration the **pump motor** with which the coolant is provided to the refrigeration circuit of the spindle.
- Tool Changer (TC): Consider the **motor** that is involved in the tool changing process.

The combination of the different states of each component, leads to the knowledge of the states where the machine can operate. The energy consumption of each state of the machine will be given by the sum of the energy consumption of each component, depending on which state the component is located.

4.3 Events Caracterization

Given the fact that the evolution of discrete event systems is driven by events, it is important to describe properly the set of events used to model the different components.

These events can be divided in three categories according to its dependence: system level, machine level and part program level.

4.3.1 System level events

The events classified in this category are related to the behavior of the external environment of the machine, considering in this environment, the different situations in which the machine can be configured (single machine or production line). The events belonging to this category are the following ones:

- Arrival: Represents the fact that a new raw piece has arrived to the machine for being worked, and that this piece will start the loading process once the transition is executed.
- Buffer not full (BNotFull): This event represents the fact that in the machine environment exists a buffer in which the pieces that finished the machine process are unloaded. The event is triggered if this buffer is not at its full capacity, thus, in the current cycle the unloading process can be executed.
- Switch *off* (SwitchOff): Counts for the action in which an external subject deliberately turn off the principal switch of the cabinet, taking off all the electrical supply to the machine.
- Switch *on* (SwitchOn): Represents the action in which an external subject moves the principal switch of the machine to the *on* position and executes the warm up routine of the machine.

4.3.2 Machine level events

The actions contained in the machine level are those that are related with the machine and its components characteristics, such as:

- Piece loaded (PLoaded): The process of loading the piece on the machine is finished.
- Piece unloaded (PUnloaded): This event is analogous to the previous one, regarding that the piece has left the machine instead of arriving to it.
- Recharge hydraulic services (Recharge): The machine tool have different systems in which a hydraulic pressure is used for its operation. The recharge event is triggered when one of this services requires a charge of hydraulic fluid because its pressure is getting lower than required for normal operation.
- Recharge completed (RechargeFinished): This event represents the fact that the action for recharging the hydraulic services of the machine, has come to an end.
- Spindle stopped (SVel0): Once an instruction given to the spindle to stop its movement is executed, the spindle reaches, after a period of time, its zero velocity, triggering this transition.
- Spindle steady state (SVelK): This event is generated once the spindle starts its movement, and reaches the desired speed in order to start the machining process.
- Spindle temperature reached (Temp): When the spindle movement has stopped (SVel0), the temperature of the spindle start to decrease (aided by the spindle cooler). Once the temperature of the spindle has decreased at a level, chosen by the machine designer, this transition is activated, deactivating in contrast the operation of the spindle cooler that is no more required until the spindle starts its operation again.
- Tool loaded (ToolLoaded): In order to trigger this transition the process of changing the tool has finished.
- Warm up finished (WupFinished): This event is triggered when the warm up routine of the machine has come to an end.

4.3.3 Part Program level events

The events belonging to this category are those related with the programing phase of the machine process, including the instructions given by the "G-Code" and its auxiliary codes corresponding to the executed part program.

- Approach: This is a "virtual" event that represents the first movement instruction given to an axis, and corresponds to the initial rapid movement with which the tool approaches to the piece to be machined. It is triggered by a rapid movement instruction (G00), but it has a different label since the use of this instruction (G00), generates an inconsistency once the synchronous composition process is performed.
- End of operation (EndOperation): This event characterizes the fact that the operations performed with a particular tool have ended.
- End of the part program (EndPartProgram): Represents the fact that the part program in execution has come to an end, and thus, the machining of that particular piece is finished.
- Feed movement (G01): Represents the action with which a command for an interpolation movement has been given to the axis and thus it has to move at feed velocity. This event counts for the different kinds of interpolations that can be programed in a machining cycle (Linear Interpolation (G01) or Circular Interpolation (G02 or G03)).
- No material removal (NoContact): In this event the system is ready to remove material (correct tool is loaded, axis moving at feed velocity and spindled with the steady state velocity reached), but the tool is not in contact with the piece.
- Rapid movement (G00): An event triggered by a part program command for creating a rapid movement of the axis.
- Removal of material: (Pcontact): The conditions for machining presented in a previous event (No material removal) are fulfilled, but in this occasion the tool is removing material.
- Spindle movement (S): Correspond to the instruction written on the part program in order to start the movement of the spindle at determined parameters in a previously established reference frame, using S code.
- Tool change (M06): Stands for the instruction given by the part program executed after an operation with a particular tool is finished and it is necessary to load a new tool in the machine for continuing the working process.

4.4 Energetic Model of the Components

The *automata* language was used to model each of the different components of a machine tool, because it allows representing easily the different energetic states of a particular device, and its evolution depending on programing commands or user-specified events.

Since this components share some events in their alphabets, the synchronous composition operation of the *automata* formalism, was used to obtain the complete model of the machine based on the states of the different components.

The individual components were modeled using an open software tool named Supremica[1], and then the software utilities for synchronization were employed to obtain the machine tool discrete energetic model.

Due to some restrictions of the language regarding an acceptance of logic operations of the events (OR, AND), the elaboration of the model was composed of two parts; initially it was built a logical model of the component disregarding the limitations previously mentioned, and then it was introduced an extended model by the use of additional "virtual" states, that emulates the logical model, and that allows the exploitation of the facilities of the language (Synchronization operation).

Regarding the representation of the logical model of the different components, the AND condition is symbolized as a transition with two or more events associated (one arrow with several names), and the OR condition as two transitions in parallel (two or more arrows going from one state to a common other one).

An additional consideration should be made for some particular components. For these components two different models will be developed, one extended model that resembles the usual behavior of the component, and another model that is a simplification of the previous one. It is important to remark, that for the subsequent operations performed with the *automata* (synchronous composition), the models employed will correspond to the basic ones with the aim of obtaining a simpler model of the machine, which is enough for the purposes considered in this study.

4.4.1 Axis

The axes of the machine can have different operative states each one representing a different action and thus having distinctive energy consumption. The states are listed as follows:

- Axis *off* (AOff): The axes of the machine are stopped and do not request any power.
- Axis warm up (AWUp): The machine is executing a warming up program that might or might not involve the axes; if this component is involved, the energy consumption depends on the configuration of the program, in the

[1] http://www.supremica.org/

other case, the energy consumption will be the same that in the state of the standby of the axis.

- Axis standby (ASBy): The axis are active, ready to start the movement and waiting for a command to follow.
- Axis rapid (AOn1): Axis performing the rapid movement operation (G00).
- Axis feed (AOn2): Axis moving with feed velocity and performing an interpolation operation, with the tool not being in contact with the piece (G01,G02,G03).
- Axis machining (AOn3): Axis moving with feed velocity and performing the required machining operation.

The axis starts in the *off* state (AOff) until a turning *on* command is executed leading it to the warming up. After the warm up is finished the axis goes to the standby state, where it can go back to the *off* state if the machine is switched *off*, or can perform any movement operations if the following conditions are fulfilled: there is a piece and the proper tool loaded on the machine as can be seen in figure 4.2.

Once the axis has left the standby state, it can move from AOn1 to AOn2 and vice versa, depending on the command proposed by the part program. When the component is located in the AOn2 state it can move to the AOn3 state if the tool gets in contact with the piece to be machined.

From the AOn1 state the component can go back to the waiting situation by the completion of the single operation or the total machining of the piece.

This model hypothesize that the tool always approach and retracts form and to the piece with a rapid movement instruction (G00), accounting with the correctness of the part program and its definition of the security planes.

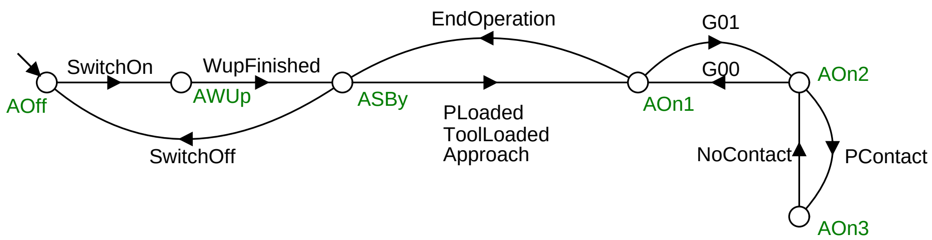


FIGURE 4.2: Axis logical model

As stated in the modeling considerations another representation including "virtual" states was introduced for each component. The axis component required the addition of 2 "virtual" states.

Ad1 is introduced with the same energy consumption as ASBy, and is a state representing the waiting period for a piece to arrive, reached by the ending of the warm up or by the conclusion of the operation performed. The Ad2 state is presented with the purpose of represent the waiting time for having the required tool loaded and ready to be used, and is reached only from the Ad1 state with its same energy requirement.

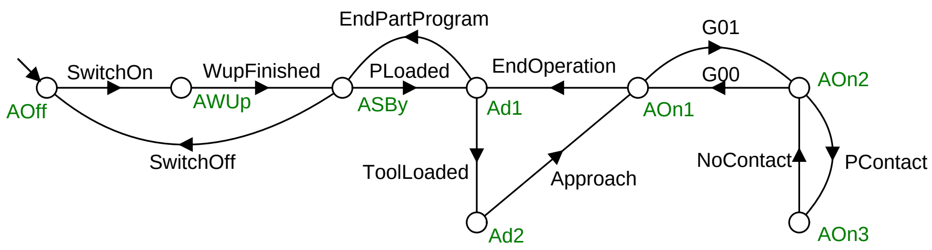


FIGURE 4.3: Axis complete model

4.4.2 Axis Cooler

- Extended Model

  The extended model of this component contains four different energetic states representing the *off*, a possible warm up, the standby state in which the pump is only circulating fluid and the high energy consuming state (ACOn).

  Its initial behavior is similar to the one of the axis, in which it moves from the *off* state to the warm up when the machine is switched *on* and to the standby state when the warm up is completed, and can return to the *off* state if the machine is switched *off*. To reach the high energy consuming state, three conditions should be fulfilled: The piece and the proper tool should already have been loaded and a move command (counting for the first movement of the axis) is executed.

  In the high energy consuming state, the cooler device is not only circulating fluid, but also making use of the heat exchangers to cool this fluid and be able to reach the desired temperature. To go back to the standby state, it is assumed that the axis has to stop (condition reached with the end of the operation) and also the set point of temperature should be reached (TempAxis).

- Basic Model

  This element has been modeled in a reduced manner, since its real behavior is out of the scope of this work, and increases dramatically the complexity of the final *automata* of the machine tool.

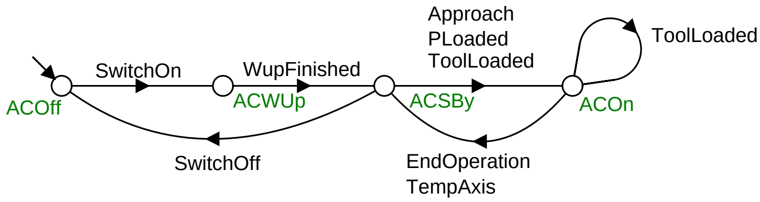


Figure 4.4: Axis Cooler extended model

This model has the same four energetic states explained before; but its operation is completely connected with the operation of the axis, leaving out of consideration the degree of freedom corresponding to the user selected set point for the desired axis temperature. This means, that the axis cooler will be fully active if and only if the axis are making any kind of movement, and it will be in a low consuming state (ACSby) if the axis are standing still and finally, it will be in a non-consuming state if the axis are *off*.

- Axis Cooler *off* (ACOff): The axis cooler of the machine is stopped and does not request any power.
- Axis Cooler warming up (ACWUp): The machine is executing a warming up program involving the coolant of the axis, the requested energy consumption depends on the configuration of the program.
- Axis Cooler in standby (ACSby): Axis cooler ready to start operation and waiting for the axis to move.
- Axis Cooler operational (ACOn): Axis cooler is working in order to maintain the axis in an optimal temperature.

The first state is the *off* state where no power is needed, then, once the machine is initialized with a warming up process the component will reach the warming up state and after the warming up is finished the component arrives to the standby state; from this state it can go to the *off* state if the machine have been switched *off* or to the operational state (ACOn), that will be reached once the axis are commanded to start the movement, and return to the standby state with the completion of the operation (EndOperation).

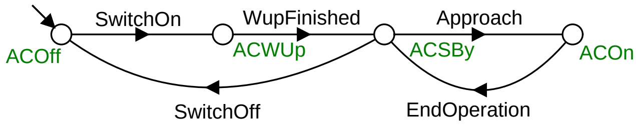


Figure 4.5: Axis Cooler model

This model is also the complete one since no "virtual" states were needed; a quote must be done regarding the "move" transition, which can only be fulfilled if some previous actions have taken place.

4.4.3 Chip Conveyor

- Extended Model

  The chip conveyor component is modeled with only two energetic states, one for its complete deactivation and the other state with the chip conveyor being operative.

  The extended model of this element as shown below, can be switched *on* by a manual action independent of the process of machining a piece or by the execution of an "M" command included in the part program; in this particular case the G-Code instruction corresponds to the M36, but it has to be said that this command for this auxiliary element depends on the builder of the machine tool.

  For turning *off* again the component, a manual action or an instruction within the lines of the part program (in this particular case M37) could be considered. The reaching of the *off* state can also be considered depending on the end of the operation, in order to emulate an automatic behavior that will leave the component on during an interval of time (Δt) after the operation is finished.

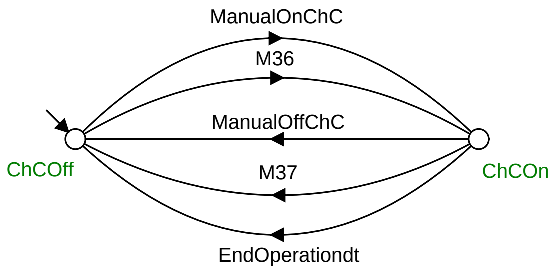


FIGURE 4.6: Chip Conveyor extended model

- Basic Model

  As it was explained before, the chip conveyor could be activated or deactivated at will of the user of the machine tool. In order to avoid a very complex model that depends on singular events, common events were used.

  To resemble the normal operation, and assuming a clean machine for the starting of the process, it can be said that the chip conveyor starts its movement some time before the spindle starts to move, so for this model the closest event to this condition is the piece being loaded (Ploaded).

  The deactivation of the component is triggered by the ceasing of the part program (EndPartProgram), taking into account that it will be deactivated sometime after the production of chip is finished. These assumptions were thought in order to consider the most energy demanding scenario in which the chip conveyor could be usually set.

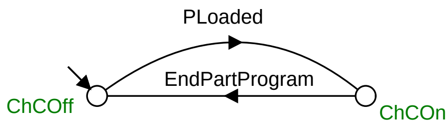


Figure 4.7: Chip Conveyor model

On the other hand, a scenario in which the chip conveyor is only activated once there is contact between the work piece and the tool, thus producing chip, can be considered as a saving energy scenario. This consideration could lead to a continuous switching (*off* and *on*) of the chip conveyor motor, causing damages on the element casued by high frequency behaviors.

4.4.4 Cutting Coolant

- Extended Model

  As in the previous model (Chip Conveyor), the cutting coolant has two states (*on* and *off*).

  The normal behavior of this component is to be controlled by the lines of the part program when the machining process is being performed. The two events M07 and M09 are used, in order to emulate the instructions required for activating and deactivating the component respectively in the G- code.

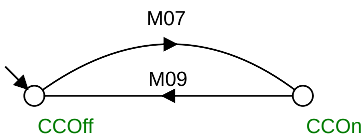


Figure 4.8: Cutting Coolant extended model

- Basic Model

  Also as the previous component, this element can be manipulated at will of the user in a way depending on the requirements of the process, but since it is needed an interrelation between events of the components, some events common to outer *automata* are used for explaining the behavior of this element.

  The activation of this component is produced by the event that assumes a start of movement of the spindle (S). This statement is made since usually the M code command for starting the cutting coolant (M07 or M08) are close to the command for starting the spindle movement, so it is not a very wicked approximation for the purpose of this model.

For deactivating the component, an event of end of operation is required, since the end of the operation will need a change of tool and a spindle stopped, so the cutting coolant will be wasted during this process.

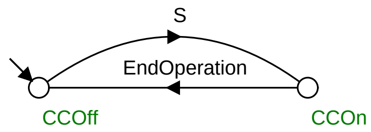


Figure 4.9: Cutting Coolant model

4.4.5 Fixed Power

This component includes all the elements that do not depend on the machine operation but on the activation of the whole machine, that is why it has only two states (*on* and *off*) connected between them with the switching *on* and *off* of the principal electric cabinet.

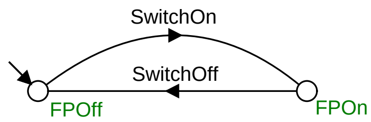


Figure 4.10: Fixed Power model

4.4.6 Hydraulic System

This component is in a consuming state during the whole machine process, since one of its principal functions is providing pressure for the hydraulic circuit that allows the clamping of the tool. It is not included in the fixed power because under some special circumstances, its consumption can increase and so, its energetic state should change.

The logical model, thus, is composed by 3 energetic states counting for the non-consuming one (HOff), the normal operation of the component (HOn1) that is reached once the machine has been switched *on*, and finally, a third state that represents that the component is consuming a different amount of energy (HOn2) that is greater than the one of the normal operation. In this final state (HOn2), the hydraulic system has to increases its pressure to provide special charge to different services of the machine, which request this operation by the activation of the recharge event; it is important to take into account, that this state can only be reached, if the machine is in a non-working state without the piece or pallet loaded.

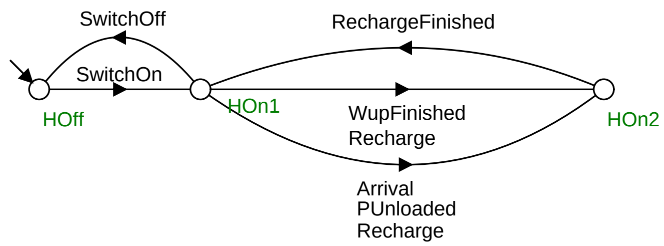


FIGURE 4.11: Hydarulic System logical model

The complete model of the hydraulic system is obtained by the addition of two "virtual" states with equivalent energy consumption of the HOn1 state, and are introduced with the aim of representing the AND conditions required for reaching the most demanding state (Hon2).

The first "virtual" state (HOnd1), represents the condition in which the warm up process of the machine is finished, and thus, if required (by the triggering of the event recharge), since is just the beginning of the operation and no piece has been loaded on the machine, the component can start providing the additional pressure to the hydraulic circuit, to fulfill the demanded fluid.

The "virtual" state "HOnd2" is introduced with the objective of blocking the execution of the recharging action if the machine has already started a machining process. This requirement is modeled by driving the *automaton* to HOnd2 when an arrival happens, and not allowing it (the *automaton*), to execute the recharge operation, until the piece has been unloaded from the machine.

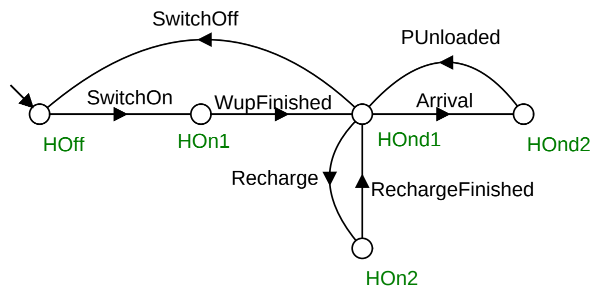


FIGURE 4.12: Hydarulic System complete model

4.4.7 Loader/Unloader

This component illustrates the operation of loading a piece from the entry queue into the machine, or unloading the same piece after being machined to the system buffer.

As some of the previous parts this component is modeled by means of two states that represent the activation and deactivation of the element itself, taking into account that the amount of energy consuming for the operation of load and unload can be considered as equal.

The conditions for going from the initial state to the active one are: there has been an arrival if the piece has to be loaded, or the part program is completed and the buffer is not full if the required operation is to unload the piece. The returning to the initial state is given by events that happen as a consequence of the component completing its operations (Ploaded or PUnloaded).

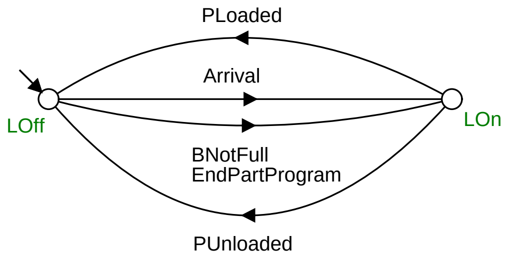


FIGURE 4.13: Loader/Unloader logical model

The complete model of the Loader/Unloader is obtained by the addition of four "virtual" states. The first two states (Ld1 and Ld2) are conceived in order to relate the switching *on* and warming up phase of the machine with all the components, and prevent that there are some unfeasible states in which for example, the fixed power is *off* and some of the components of the machine are *on*.

The "virtual" state Ld3 allows to represent that no piece can be unloaded if it has not been previously loaded, and the next one (Ld4) is a consequence of the two events that make it able to unload, taking into account that the piece has completed the machining process, but also the buffer must have some capacity to receive the new part. For this four "virtual" state the energy consumption equals the one of the off state.

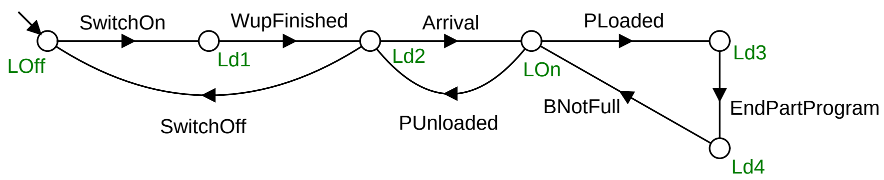


FIGURE 4.14: Loader/Unloader complete model

4.4.8 Pallet Clamp

- Extended model

  The pallet clamp is a simple component composed of two states: *on* and *off*. The *on* state that represents the consumption of the pallet clamp clamping the piece and also unclamping it; since the energy consumption for the two actions is assumed to be the same, even though the results on the piece will be opposite.

  This pallet clamp is only an auxiliary device that helps to fix properly the piece onto the machine, but during the machining process, the main clamping action is executed by a mechanical device for safety reasons.

  A typical pallet clamp device, start its clamping operation when the piece or pallet is loaded in the machine and stays *on* during a period of time until the piece or pallet is properly clamped (PClamped) when it returns to the *off* state.

  The unclamping behavior is quite similar to the clamping, reaching an *on* state when is the end of the part program and the subsequent buffer is not full, and returning to *off* when the time for unclamping has passed (PUnclamped).

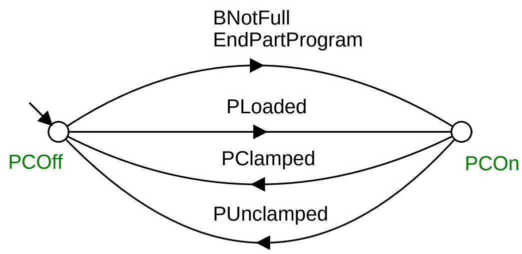


FIGURE 4.15: Pallet Clamp extended model

- Basic Model

  As for all the previous components with basic models, this one is introduced to avoid an unnecessary complexity of the final model regarding the scope of this work. To avoid the introduction to the PClamped or PUnclamped events, the behavior of this component is model as the Loader/Unloader element.

  The complete model, also based on the Loader/Unloader behavior, does not take into account the warm Up phase since the pallet clamp does not require this procedure; in the Loader/Unloader this phase was introduced with the purpose of avoid non feasible states, but since with this type of approach the two elements are completely correlated, there is no need to include the warm up phase twice.

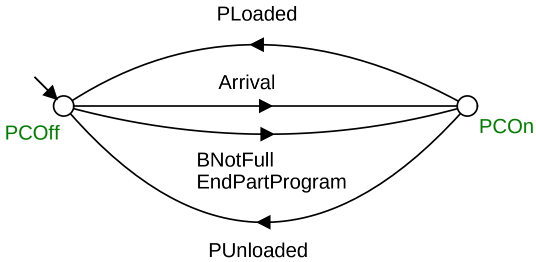


FIGURE 4.16: Pallet Clamp logical model

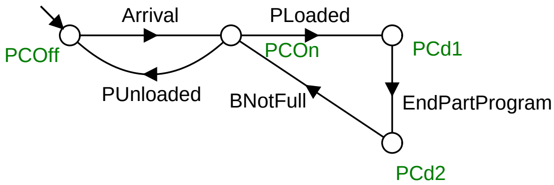


FIGURE 4.17: Pallet Clamp complete model

4.4.9 Spindle

For this model it is convenient to initially make a list of the state as follows:

- Spindle *off* (SOff): The spindle is stopped and does not request any power.
- Spindle warming up (SpWUp): The machine is executing a warming up program involving the spindle, requesting energy consumption depending on the configuration of the program.
- Spindle in standby (SSBy): spindle ready to start the movement and waiting for a command to follow.
- Spindle ramping up (SpRUp): spindle on acceleration profile in order to reach a desired working velocity.
- Spindle in steady state (SpSS): spindle is already on its working velocity but is not machining any piece.
- Spindle machining (SpOn1): The spindle is on its working velocity and is machining the piece and the tool is in contact with the piece, thus the actual cutting process is performed.
- Spindle ramping down (SpRDw): spindle is decreasing its velocity because the operation is completed. The process can continue with a new part program or a tool change.

The initialization of the spindle is similar to the one of the axis component, starting with the spindle switched *off* and going through the warm up process until reaching the standby state where is ready to move or to switch it *off*.

Following a command to start the movement, with prerequisites such as the correct tool loaded and the piece ready to be machined, the spindle will start the movement by accelerating (Ramp up state) with the objective to find the desired constant velocity (spindle steady state), and reach the machining state depending if the tool is in contact with the piece or not.

From the desired velocity state, given the condition that the operation was finished, the spindle will decelerate (Ramp Down) until it is completely stopped arriving to the standby state.

The component will stay in the standby state if the part program is finished waiting for a new piece to arrive.

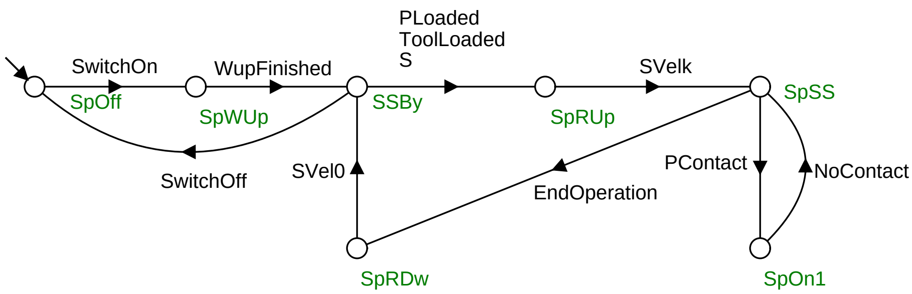


FIGURE 4.18: Spindle logical model

Two "virtual" states (Spd1 and Spd2) were added to obtain the complete model and each of them has the energy consumption alike the one of the standby state.

These states where conceived with the purpose of splitting the AND condition regarding the necessity of having a piece loaded to be machined and the correct tool to do it. They also allow a tool changing in the process when the operation is completed.

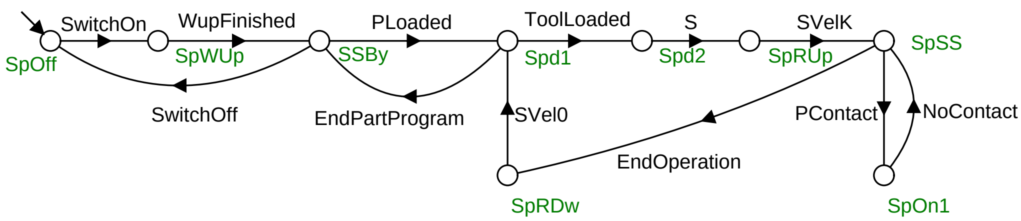


FIGURE 4.19: Spindle complete model

4.4.10 Spindle Cooler

A record with an explanation of states for this component can be seen below.

- Spindle Cooler *off* (SCOff): spindle cooler stopped and does not require any power.
- Spindle Cooler in warming up (SCWUp): The machine is executing a warming up program involving the spindle cooler.
- Spindle Cooler in standby (SCSBy): spindle cooler ready to start the movement and waiting for a command to follow.
- Spindle Cooler operational (SCOn): The spindle cooler is activated in order to keep the spindle in a desired temperature level.

The spindle cooler is a component that depends on the spindle making their operations directly correlated. The spindle cooler has a warm up stage as usual and besides this phase is composed by a standby and *on* state in which it transits depending on the spindle commands.

Its operation behavior is triggered by the activation of the spindle movement (and all the necessaries prerequisites fulfilled); once the spindle has stopped its temperature starts to decrease until it reaches the optimal temperature that will place the spindle cooler into the standby state; but if the spindle is activated again and it has not reached the desired temperature, the spindle cooler will continue its normal operation.

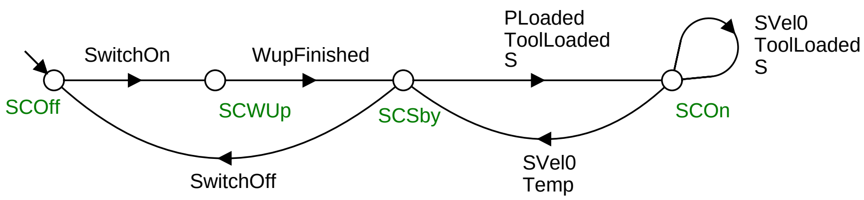


FIGURE 4.20: Spindle Cooler logical model

For modeling the necessary AND conditions that involved the spindle cooler action, there were required five "virtual" states. The first two states (Scd1 and SCd2) are related with the energy consumption of the standby state.

The first one (SCd1) is introduced with the aim of show the state in which a piece is loaded into the machine and is waiting for a correct tool to be loaded; once the action is fulfilled there is a change of state directing the *automaton* to SCd2, in which the component awaits for the spindle to start its movement and activate the spindle cooler.

The three remaining "virtual" states (SCOnd1, SCOnd2 and SCOnd3) share the same energy consumption as the SCOn state where the spindle cooler is working at its full capacity.

The first state contemplates the action when the spindle has stopped in which case can happen three different things: If the required temperature for the spindle has been reached, the *automata* will lead the spindle cooler to the standby state, if there is a requirement for a new tool to be loaded, the *automaton* will go to SCOnd2 and wait for the spindle to start moving again not reaching the standby state and continuing on during the process, and finally if the spindle has been turned *off* because it is the end of the part program the *automaton* will get to the SCOnd3 state.

From the SCOnd3 state the *automaton* can have again two ways to go, the first one consists in reaching the temperature and thus arriving to the standby state, and the second one contemplates the possibility where a new machining process is started in a time shorter than the required for the temperature transition to be activated, directing the component to the SCOnd1 state, where it can take one of the paths explained on the last paragraph.

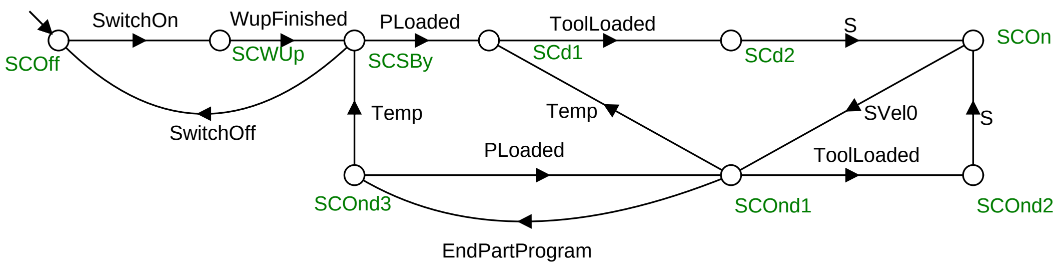


FIGURE 4.21: Spindle Cooler complete model

4.4.11 Tool Changer

The last component was developed with two states *on* and *off*. The starting state, as habitual, shows the complete absence of energy consumption in the *off* state. The possibility of going out from this state is made by the presence of a piece loaded and thus the necessity to change the tool, or if the piece is already loaded in the machine, just the necessity to change the tool with the condition that the spindle is motionless. Once the tool is loaded the component returns to the *off* state.

Three "virtual" states are present on this complete model associated to the energy consumption of the *off* state. The first one (TCd1) represents the moment of the arrival of the piece and the possibility that the required tool is already loaded, or in the other hand the necessity to load a different tool.

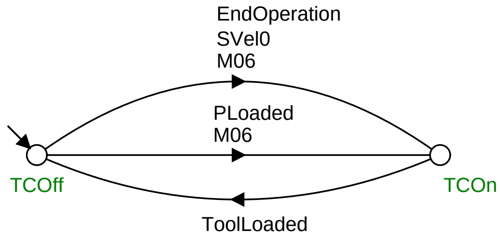


FIGURE 4.22: Tool Changer logical model

The second one (TCd2) is used when the piece is already loaded on the machine and the event of the end of an operation occurs, allowing the system to wait for the complete stop of the spindle therefore arriving to TCd3; a new tool change is executed if its required by the program, or the current tool is kept loaded if it is the end of the part program.

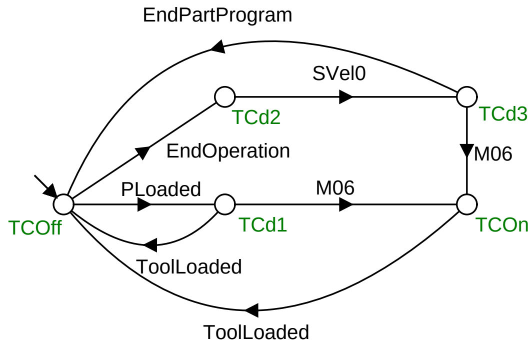


FIGURE 4.23: Tool Changer complete model

4.5 Synchronization and Complete *Automaton* Of The Machine

In order to create the complete *automaton* of the machine tool, the synchronous composition operation was used.

Since the machine model required the synchronization of eleven different *automata*, in the previous models the introduction of some "virtual" states was directed to relate the events of the different components and avoid the presence of unfeasible states. By exploding the properties of the synchronous composition (commutative and associative), it was possible to do this operation in one phase to obtain the final machine *automata*.

The model of the machine is composed of 28 states (ST), 20 events (E) and 51 transitions that will be presented using the state diagram shown afterwards.

The initial state is the machine *off* (ST0) where all the components of the machine are switched *off*; the first step for going out of this state is when the switch *on* (E18) transition is triggered, activating the fixed power and starting the machine warm up process (ST1). After this action is ended, the activation of the warm up finished (E21) will lead the machine to the initial starvation state (ST2).

From here (ST2) different actions can be done: The first one is going back to *off* (ST0) by switching *off* the machine (E17), the second one goes to recharge the hydraulic services (ST4) if the recharge event (E12) occurs, and finally after an arrival (E0) occurs, it can move to the loading state (ST7) and consequently after the loading process is finished (E10) progress to an idle state (ST10).

When the machine is located is located in the recharge hydraulic system state (ST4), it can go back to the previously explained Starvation state (ST2) when the recharge is completed (E13).

From the first idle state it is necessary to check if the required tool is ready; if this condition is satisfied (E20), the machine will move to the next idle state (ST13), in the other case, it will activate the tool changer (ST14) with the M06 instruction (E6) and once the process is completed (E20), will get to the same idle (ST13) reached by the execution of the first situation.

Arriving to this point, the machine is ready to start the standard operational condition, where the state of the main components will change: for the axis from standby (ST17 and ST25) to rapid movement (ST19, ST20, ST26) or to interpolation (ST22, ST23, ST28), and for the spindle will evolve from standby (ST19, ST22) to ramp up (ST17, ST20, ST23) and then to the steady state condition (ST25, ST26, ST28). All of the combination of the states of these two components (axis and spindle), can be reached depending on the order of execution of the events Move (E7), G00 (E4), G01 (E5), S (E14), and SVelK (E16). For these possible states the spindle and spindle cooler will be operative if the component to which they provide refrigeration has received a moving command.

Only when the process has reached a state in which the axes are moving at the desired feed velocity and the spindle is rotating at steady state (ST28), the machine can reach the material removal state (ST29) triggered by the event of the tool being in contact with the piece to be labored (E9). If there is no contact between the piece and the tool, the machine will return to the previous steady state condition (ST28).

From the state where the axes are moving at rapid velocity together with the spindle at steady state (S26), and after recognizing the end of the operation (E2), the machine can start the ramp down (ST27) of the spindle until it is completely stopped (ST16). At this point the process can continue with a new tool change and the subsequent operations, or if it is the end of the part program (E3), it can get to one of the blocking states (ST8 or ST9) in case that the buffer is full, or keep going to the unloading phase (ST6 or ST7) and wait for another arrival (ST2 or ST3) to start a new machining.

Since the standby situation for the spindle cooler depends on the set point given to the spindle temperature in its final part, (after the spindle is stopped), the *automaton* duplicates some of the previous states, to account for the fact that this temperature has not been reached and thus the spindle cooler is still *on* (States 3,5,6,9,11,12,15,18,21,24) but allows either to change a tool and start a new operation or unload the piece and start a new machining, without having the obligation to wait that this component (spindle cooler) reaches the standby state.

In table 4.3 the record of the states is shown in order to help with the interpretation of the *automaton*. This table relates the number assigned to each state with its name and also with the status of each component.

Table 4.2 shows the events; in table 4.4 is represented the state-event matrix with the state and events symbolized by the numbers assigned in table 4.3 and 4.2 respectively.

With these tables it is possible to represent all the information to describe mathematically a labeled *automaton*, being the table 4.3 the set of the states and thus the first element of the mathematical model of the *automaton*, table 4.2 the alphabet of the *automaton* (set of events), the initial state corresponding to the machine off (indicated in figure 4.24 with an arrow without predecessor and in table 4.3 with the state number 0) and finally the transition function presented in table 4.4.

ID	***Event***	***Label***
0	Arrival	Arrival
1	Buffer not full	BNotFull
2	End of operation	EndOperation
3	End of the part program	EndPartProgram
4	Rapid movement	G00
5	Feed Movement	G01
6	Tool Chande	M06
7	Move	Move
8	No material removal	NoContact
9	Removal of material	PContact
10	Piece loaded	PLoaded
11	Piece unloaded	PUnloaded
12	Recharge hydraulic services	Recharge
13	Recharge completed	RechargedFinished
14	Spindle movement	S
15	Spindle stoped	SVel0
16	Spindle steady state	SVelK
17	Switch off	SwitchOff
18	Switch on	SwitchOn
19	Spindle temperature reached	Temp
20	Tool loaded	ToolLoaded
21	Warm up finished	WupFinished

TABLE 4.2: Set of events

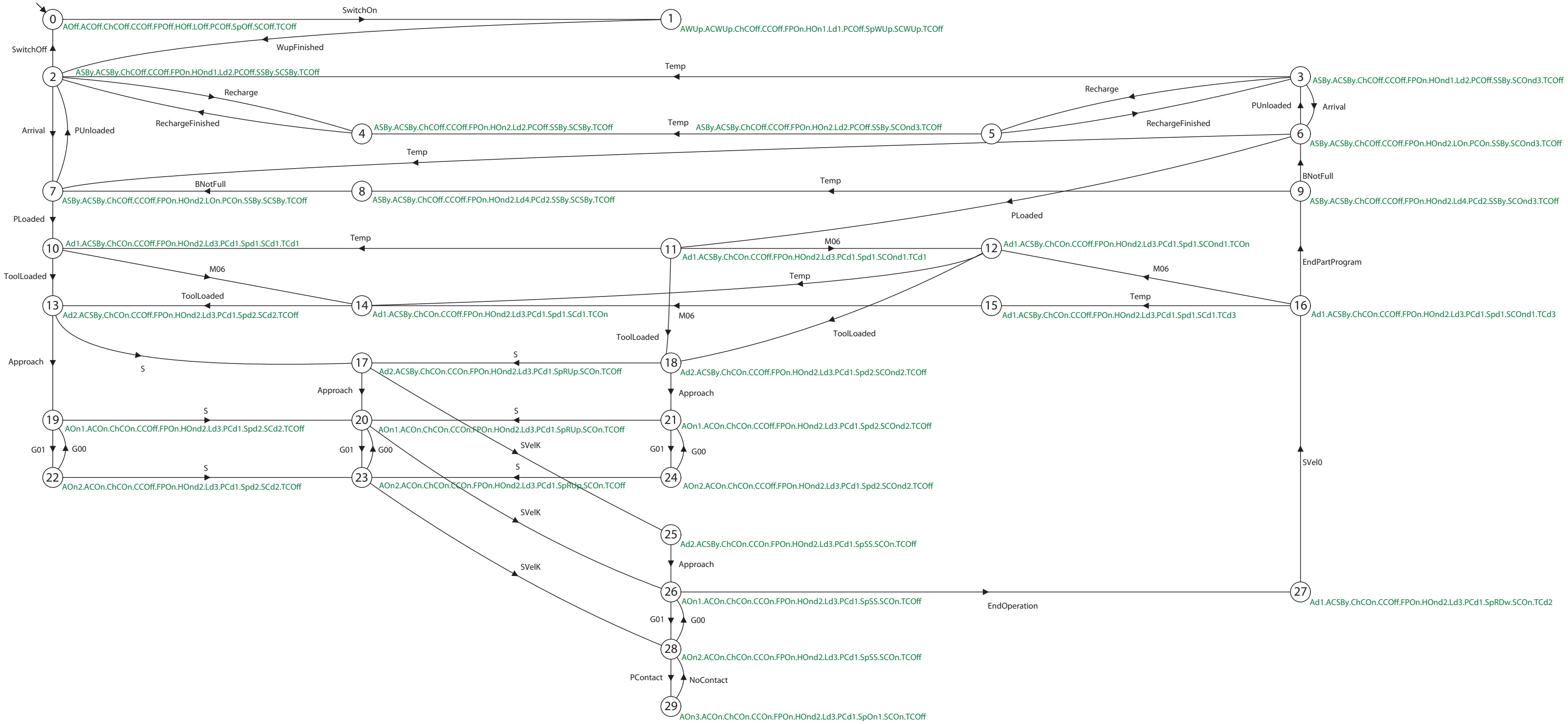


FIGURE 4.24: State diagram- complete model

ID	***State***	***Axis***	***Axis Cooler***	***Chip Conveyor***	***Cutting Coolant***	***Fixed Power***	***Hydraulic***	***Loader***	***Pallet Clamp***	***Spindle***	***Spindle Cooler***	***Tool Changer***
0	Machine off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off
1	Warm Up	Warm Up	Warm Up	Off	Off	On	On	Off	Off	Warm Up	Warm Up	Off
2	Starvation	Standby	Standby	Off	Off	On	On	Off	Off	Standby	Standby	Off
3	Starvation-Spindle Cooler On	Standby	Standby	Off	Off	On	On	Off	Off	Standby	On	Off
4	Recharge Hydraulic	Standby	Standby	Off	Off	On	Charge	Off	Off	Standby	Standby	Off
5	Recharge Hydraulic-Spindle Cooler On	Standby	Standby	Charge	Off	On	On	Off	Off	Standby	On	Off
6	Loading/Unloading-Spindle Cooler On	Standby	Standby	Off	Off	On	On	On	On	Standby	On	Off
7	Loading/Unloading	Standby	Standby	Off	Off	On	On	On	On	Standby	Standby	Off
8	Blocking	Standby	Standby	Off	Off	On	On	Off	Off	Standby	Standby	Off
9	Blocking-Spindle Cooler On	Standby	Standby	Off	Off	On	On	Off	Off	Standby	On	Off
10	Idle	Standby	Standby	On	Off	On	On	Off	Off	Standby	Standby	Off
11	Idle-Spindle Cooler On	Standby	Standby	On	Off	On	On	Off	Off	Standby	On	Off
12	Tool Change-Spindle Cooler On	Standby	Standby	On	Off	On	On	Off	Off	Standby	On	On
13	Idle	Standby	Standby	On	Off	On	On	Off	Off	Standby	Standby	Off
14	Tool Change	Standby	Standby	On	Off	On	On	Off	Off	Standby	Standby	On
15	Idle	Standby	Standby	On	Off	On	On	Off	Off	Standby	Standby	Off
16	Idle-Spindle Cooler On	Standby	Standby	On	Off	On	On	Off	Off	Standby	On	Off
17	Axis Standby-Spindle Ramp up	Standby	Standby	On	On	On	On	Off	Off	Rampup	On	Off
18	Idle-Spindle Cooler On	Standby	Standby	On	Off	On	On	Off	Off	Standby	On	Off
19	Axis Rapid-Spindle Standby	Rapid	On	On	Off	On	On	Off	Off	Standby	Standby	Off
20	Axis Rapid-Spindle Ramp up	Rapid	On	On	On	On	On	Off	Off	Rampup	On	Off
21	Axis Rapid-Spindle Standby-Spindle Cooler On	Rapid	On	On	Off	On	On	Off	Off	Standby	On	Off
22	Axis Interpolating-Spindle Standby	Feed	On	On	Off	On	On	Off	Off	Standby	Standby	Off
23	Axis Interpolating-Spindle Ramp up	Feed	On	On	On	On	On	Off	Off	Rampup	On	Off
24	Axis Interpolating-Spindle Standby-Spindle Cooler On	Feed	On	On	Off	On	On	Off	Off	Standby	On	Off
25	Axis Standby-Spindle Steady State	Standby	Standby	On	On	On	On	Off	Off	SteadyS	On	Off
26	Axis Rapid-Spindle Steady State	Rapid	On	On	On	On	On	Off	Off	SteadyS	On	Off
27	Axis Standby-Spindle Ramp Down	Standby	Standby	On	Off	On	On	Off	Off	RampDw	On	Off
28	Axis Interpolating-Spindle Steady State	Feed	On	On	On	On	On	Off	Off	SteadyS	On	Off
29	Machining	Machining	On	On	On	On	On	Off	Off	SteadyS	Machining	Off

TABLE 4.3: Set of states

		TO																													
		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
FROM	0		18																												
	1			21																											
	2	17				12			0																						
	3			19			12	0																							
	4			13																											
	5				13	19																									
	6				11				19				10																		
	7			11								10																			
	8								1																						
	9							1		19																					
	10														20	6															
	11											19		6						20											
	12															19				20											
	13																		14		7										
	14														20																
	15															6															
	16										3			6			19														
	17																					7					16				
	18																		14				7								
	19																					14		5							
	20																								5			16			
	21																					14				5					
	22																				4				14						
	23																					4								16	
	24																						4		14						
	25																											7			
	26																												2	5	
	27																	15													
	28																											4			9
	29																													8	

Table 4.4: Transition function

4.6 Clustering and Reduced Model

The idea of elaborating a clustered model is conceived with the purpose of simplifying the model, allowing a better comprehension of the energy distribution within the machine, composed by states with analogous energy consumption mutually gathered.

As a result of the clustering process there were found three states with the same energy consumption (ST24,ST25,ST27) characterized by the fixed power, hydraulic system and chip conveyor on, the axis, axis cooler, spindle and spindle cooler in standby and the rest of the components in a non-energy consuming state. Those three states can be clustered in an idle state since the machine is ready for starting the process.

There was found that two other states (ST13 and ST17), corresponding to the starvation and blocking of the machine, which are characterized by the fixed power and the hydraulic system *on*, the axis, axis cooler, spindle and spindle cooler in standby and the rest of the components in a non-energy consuming state, require the same energy consumption.

In correspondence with the two clustered energetic states mentioned before (Idle and Blocking/Starvation), two additional states were manifested respectively, the Idle SCOn state (ST21, ST22, ST26) and the Blocking/Starvation SCOn (ST16/ ST12), in which the only difference resides in the activation of the spindle cooler component.

Another clustering criterion was applied by considering the axis in the same energy consumption state along with the spindle on an accelerating (Ramp Up), steady state and decelerating (Ramp Dawn). This criterion was based in the fact that even though acceleration and deceleration are related to high peak power, they only contribute in a small quantity in the cumulated energy consumption [Die08] which is the target to be aimed in this analysis.

Regarding table 4.5 format, the background with a white color indicates that the state has an energy consumption that cannot be clustered with any others. For the states that share the same background color, a clustering rule was applied, and its energy consumption can be considered as one.

Similarly, a reduced model of the machine composed by 20 states, 19 events, and 42 transitions is shown in the figure 4.25.

Cluster 1	0	Machine off	AOff.ACOff.ChCOff.CCOff.FPOff.HOff.LOff.PCOff.SpOff.SCOff.TCOff
Cluster 2	18	Warm Up	AWUp.ACWUp.ChCOff.CCOff.FPOn.HOn1.Ld1.PCOff.SpWUp.SCWUp.TCOff
Cluster 3	11	Recharge hydraulic services	ASBy.ACSBy.ChCOff.CCOff.FPOn.HOn2.Ld2.PCOff.SSBy.SCSBy.TCOff
Cluster 4	10	Recharge hydraulic services-Spindle Cooler On	ASBy.ACSBy.ChCOff.CCOff.FPOn.HOn2.Ld2.PCOff.SSBy.SCOnd3.TCOff
Cluster 5	13	Starvation	ASBy.ACSBy.ChCOff.CCOff.FPOn.HOnd1.Ld2.PCOff.SSBy.SCSBy.TCOff
	17	Blocking	ASBy.ACSBy.ChCOff.CCOff.FPOn.HOnd2.Ld4.PCd2.SSBy.SCSBy.TCOff
Cluster 6	12	Starvation-Spindle Cooler On	ASBy.ACSBy.ChCOff.CCOff.FPOn.HOnd1.Ld2.PCOff.SSBy.SCOnd3.TCOff
	16	Blockin-Spindle Cooler On	ASBy.ACSBy.ChCOff.CCOff.FPOn.HOnd2.Ld4.PCd2.SSBy.SCOnd3.TCOff
Cluster 7	15	Loading/Unloading	ASBy.ACSBy.ChCOff.CCOff.FPOn.HOnd2.LOn.PCOn.SSBy.SCSBy.TCOff
Cluster 8	14	Loading/Unloading-Spindle Cooler On	ASBy.ACSBy.ChCOff.CCOff.FPOn.HOnd2.LOn.PCOn.SSBy.SCOnd3.TCOff
Cluster 9	24	Idle	Ad1.ACSBy.ChCOn.CCOff.FPOn.HOnd2.Ld3.PCd1.Spd1.SCd1.TCd1
	25		Ad1.ACSBy.ChCOn.CCOff.FPOn.HOnd2.Ld3.PCd1.Spd1.SCd1.TCd3
	27		Ad2.ACSBy.ChCOn.CCOff.FPOn.HOnd2.Ld3.PCd1.Spd2.SCd2.TCOff
Cluster 10	21	Idle-Spindle Cooler On	Ad1.ACSBy.ChCOn.CCOff.FPOn.HOnd2.Ld3.PCd1.Spd1.SCOnd1.TCd1
	22		Ad1.ACSBy.ChCOn.CCOff.FPOn.HOnd2.Ld3.PCd1.Spd1.SCOnd1.TCd3
	26		Ad2.ACSBy.ChCOn.CCOff.FPOn.HOnd2.Ld3.PCd1.Spd2.SCOnd2.TCOff
Cluster 11	23	Tool Change	Ad1.ACSBy.ChCOn.CCOff.FPOn.HOnd2.Ld3.PCd1.Spd1.SCd1.TCOn
Cluster 12	20	Tool Change-Spindle Cooler On	Ad1.ACSBy.ChCOn.CCOff.FPOn.HOnd2.Ld3.PCd1.Spd1.SCOnd1.TCOn
Cluster 13	2	Axis Rapid-Spindle Standby	AOn1.ACOn.ChCOn.CCOff.FPOn.HOnd2.Ld3.PCd1.Spd2.SCd2.TCOff
Cluster 14	1	Axis Rapid-Spindle Standby-Spindle Cooler On	AOn1.ACOn.ChCOn.CCOff.FPOn.HOnd2.Ld3.PCd1.Spd2.SCOnd2.TCOff
Cluster 15	6	Axis Interpolating-Spindle Standby	AOn2.ACOn.ChCOn.CCOff.FPOn.HOnd2.Ld3.PCd1.Spd2.SCd2.TCOff
Cluster 16	5	Axis Interpolating-Spindle Standby-Spindle Cooler On	AOn2.ACOn.ChCOn.CCOff.FPOn.HOnd2.Ld3.PCd1.Spd2.SCOnd2.TCOff
Cluster 17	28	Axis Standby-Spindle Ramp	Ad2.ACSBy.ChCOn.CCOn.FPOn.HOnd2.Ld3.PCd1.SpRUp.SCOn.TCOff
	29	Axis Standby-Spindle Steady State	Ad2.ACSBy.ChCOn.CCOn.FPOn.HOnd2.Ld3.PCd1.SpSS.SCOn.TCOff
Cluster 18	3	Axis Rapid-Spindle Ramp	AOn1.ACOn.ChCOn.CCOn.FPOn.HOnd2.Ld3.PCd1.SpRUp.SCOn.TCOff
	4	Axis Rapid-Spindle Steady State	AOn1.ACOn.ChCOn.CCOn.FPOn.HOnd2.Ld3.PCd1.SpSS.SCOn.TCOff
	19	Axis Standby-Spindle Ramp down	Ad1.ACSBy.ChCOn.CCOff.FPOn.HOnd2.Ld3.PCd1.SpRDw.SCOn.TCd2
Cluster 19	7	Axis Interpolating-Spindle Ramp	AOn2.ACOn.ChCOn.CCOn.FPOn.HOnd2.Ld3.PCd1.SpRUp.SCOn.TCOff
	8	Axis Interpolating-Spindle Steady State	AOn2.ACOn.ChCOn.CCOn.FPOn.HOnd2.Ld3.PCd1.SpSS.SCOn.TCOff
Cluster 16	9	Machining	AOn3.ACOn.ChCOn.CCOn.FPOn.HOnd2.Ld3.PCd1.SpOn1.SCOn.TCOff

Table 4.5: Clustering

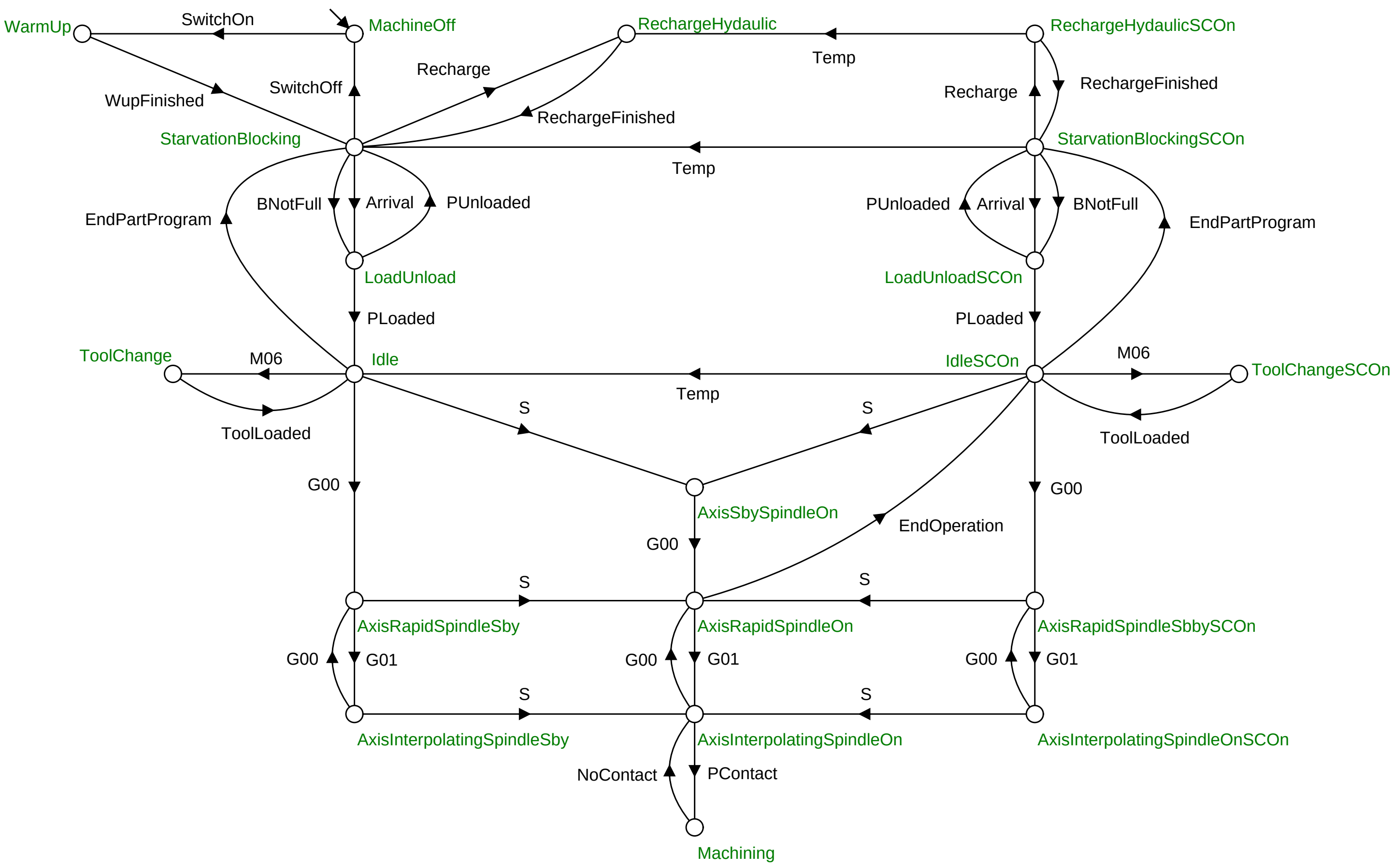


FIGURE 4.25: Clustered model

Chapter 5

Control Problems and Policies

In this chapter a brief classification of the problems concerning the objective of minimizing energy consumption of non-value adding tasks is presented. Subsequently, some control problems are defined and the respective policies required for minimizing the energy in such a context are developed.

5.1 Problems Description

The design of a control policy changes depending on the conditions of the system to be controlled. Control problems related with switching strategies of machine tools to minimize energy, can be affected by different causes, such as the level at which the control is aimed to be applied and the configuration of the production system to which the machine belongs.

A general classification of the control problems is presented in figure 5.1. The selection of different characteristic of the problem will lead to diverse approaches for designing the controller.

The first stage of the diagram (figure 5.1) represents the two primary characteristics that must be defined to properly describe the element to be controlled, the level of control and its boundaries. The following stages of the diagram represent a possible classification of each one of these characteristics.

5.1.1 Level of control

The design of a controller depends on the element to be controlled and its interaction with other components, that is why, for control problems regarding machine tools, it is important to define the level in which the controller will act.

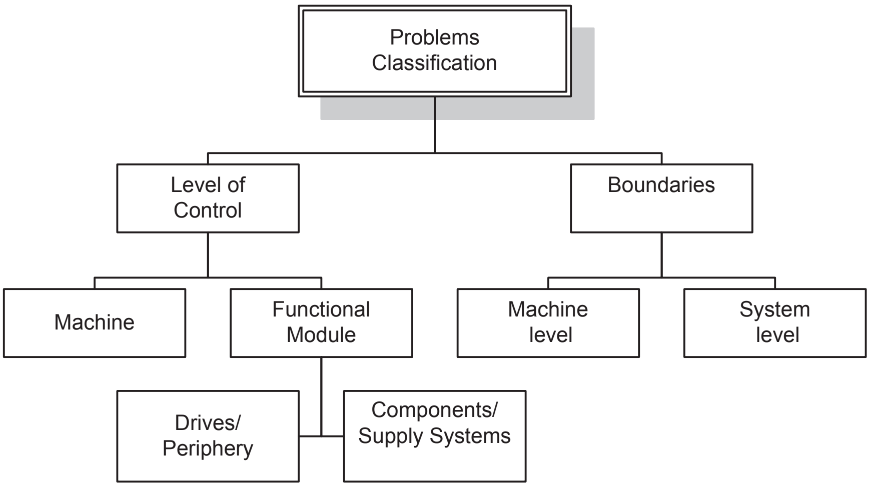


FIGURE 5.1: Control problems layout

Since machine tools can be considered as an agglomeration of components or functional modules, a control action can be applied to the complete system (machine) or to a module (functional module), and the problem of selecting a control policy can significantly change.

- Machine level: At this level of control only one controller will be used with energy saving purposes. In this category, the controller treats the machine as a whole entity, even though it is composed of an agglomeration of components, and decides to which state lead the entire system depending on different pre-established modes.

  A machine tool can have additional energetic states that will be reached under special circumstances defined by the user. These modes includes for example the standby, that corresponds to an state in which the machine is waiting for a piece to process, a sleep state that can emulate a low consumption state that is used when the machine has long waiting periods, or the emergency stop that will be reached in the event of an important failure in the system.

- Functional Modules: A functional module is an agglomeration of components (consumers) representing the different systems that interact in a machine tool.

  If the problem is defined to belong to the functional module category, the different functional modules of the machine are operated and controlled independently in order to save energy, but providing the fulfillment of the requirement of the entire machining process.

An additional observation must be done; each functional module is in turn composed of components or consumers, and the control policy will depend on the selected classification for these components, as follows:

– A traditional concept defines two groups of consumers on machine tools: **Drives**, such as Spindle and Feed Drives with its electronics, and **Periphery**, such as cooling and coolant components.

  If the functional module is decomposed using this classification, the control at this level requires one controller for each consumer, independently of the particular services provided to the machining process.

– In [Sch11], a different approach classifies machine components depending on their energy consumption. This classification is made with the aim of delimit the relations between the components, and highlight their energy saving potentials, categorizing the consumers as **machine components** and **supply systems**.

  In this manner, a control action can trigger commands and operations for machine components that should execute a specific job, which in turn will absorb energy from the common supply systems as it can be seen in figure 5.2.

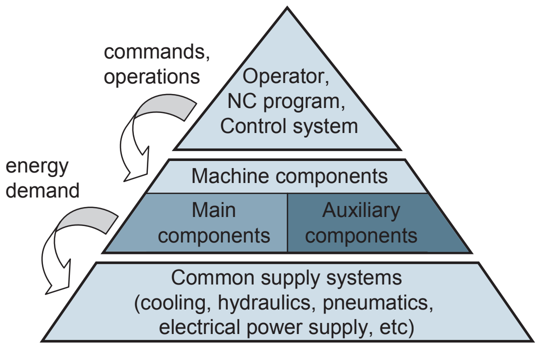


FIGURE 5.2: Machine structure and development of energy demand

  Within this decomposition of the functional modules, only supply systems require energy savings controllers, since the energy consumption is directly provided by them.

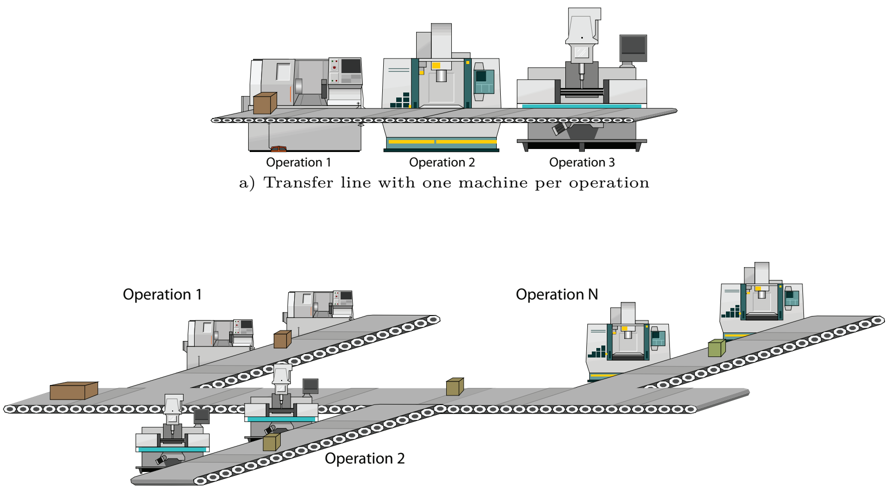
5.1.2 Boundaries

A boundary represents the limit whit which the controller and the respective control policy will be designed, regarding the consideration of the machine as singular entity, or as a part of a production system. The selection of one scenario or the other might create relevant differences in the behavior of the controller.

- System Level: The design of the controller at system level represents that the machine is not seen as an isolated entity, but it is considered as a part of a production system.

  The definition of the energy saving policies can vary considerably depending on the different configurations where the machine can be arranged, since the interaction of the machine with the production system must be taken in to consideration during the design phase.

  Examples of control at system level boundary correspond to a design based on production configurations like transfer lines with only one machine per operation or with parallel machines, where switching strategies for minimizing energy consumption can be used if the flow of parts is interrupted due to external factors such as failures of maintenance. This boundary is an important decision factor, since the input information of one machine is determined by the output information of another one.



a) Transfer line with one machine per operation

b) Transfer line with parallel machines

FIGURE 5.3: Different transfer line configuration

- Machine level: This classification comprehends the problems that arise when the controller is designed for a standalone machine, considering only the interaction with some particular elements such as input or output buffers, but disregarding the contact with other machines.

  The problem varies depending on the different information provided to the controller like:

  - Information on the arrival of a piece which can obey different behaviors like a deterministic arrival, an arrival based on a probability distribution (stochastic) or arrivals following random events.
  - Information on the utilization level of the input buffer over time might be used as an input, since a decreasing behavior of this indicator can

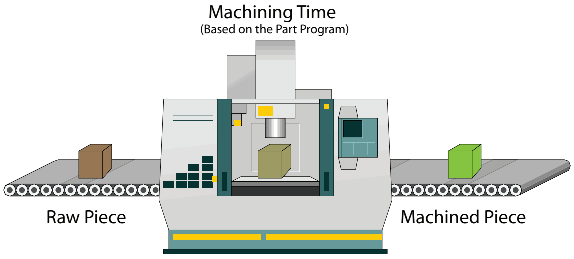


FIGURE 5.4: Standalone machine representation

open opportunities to stop the process with the aim of accumulating a great amount of pieces to machine. A similar analysis can be done with the utilization level of the output buffer.

- Delivery deadlines for machined pieces.

5.2 Assumptions and Modeling

In this section, some control problems will be characterized according to the classification presented in section 5.1. For each problem, a control policy for minimizing energy consumption during non-value adding tasks will be proposed; problems will vary based on the arrival information of the piece and the selection of the control actions; the design of the control policies is aligned with the utilization of switching strategies and will be performed using a continuous time approach.

The characterization of an energy saving control problem, and the development of its corresponding control policy, requires the definition of some important information regarding the system to be controlled and its input data. In the following paragraphs it will be presented the assumptions, energetic model, possible control actions and input data, under which the control policies presented in this chapter are designed.

5.2.1 Assumptions

- The **level of control** corresponds to the **machine** considered as an entire element
- The **boundaries** considered regard a **standalone machine**
- The machine is perfect reliable; this assumption implies that the machine never fails
- The input and output buffer of the machine have infinite capacity

- All the pieces to be machined are the same
- The processing time of an element is known and is deterministic
- Production planning constrains such as maintenance or desired delivery dates are not taken into consideration

5.2.2 Energetic model of the controlled machine

The design of a control policy at machine level requires the definition of the different energetic states of the machine and its evolution and behavior.

The energetic behavior of the machine here considered, is represented with a simplified version of the model of the energetic states of a machine tool developed in chapter 4; in this simplified model, the entire machining process, including the operation of the auxiliary elements such as tool changer and chip conveyor, is reduced to one state. This simplification is valid for this specific case, since the objective of the control strategy is to minimize only the energy of non-value adding tasks.

With the previous considerations in mind, the reduced energetic model of the machine is composed of 4 states (Starvation, Machining, Machine *off* and Warm Up), and 5 transitions; its graphic representation using the *automata* language can be seen in figure 5.5.

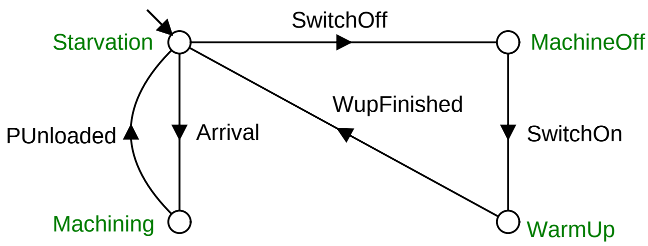


FIGURE 5.5: Simplified energetic model of a machine tool

This model corresponds to a machine that is located initially in the Starvation state and remains there unless a piece arrives to the system or an instruction for switching *off* is given, leading the machine either to the Machining state or the Machine *off* state respectively.

When the Machining state is active (after the Arrival of a piece) a piece is being processed, and the evolution of the state of the machine is subjected to the completion of the machining process and the unloading of the piece (Punloaded), to return to the Starvation state.

On the other hand, if a command to switch *off* the machine is executed, the active state will correspond to the Machine *off* until a new command with the purpose of switching *on* the machine is given. When the last action takes place (SwitchOn), a new state will be reached corresponding to the Warm Up, and this state will be active until the completion of the warming up process; once this process is finalized (WupFinished), the machine will be directed again to the Starvation state.

The events labeling the different transitions of the model can be characterized as controllable, if are subjected to influence by the controller, or uncontrollable otherwise [Fab06].

In this particular model, the uncontrollable events correspond to: the arrival of a piece (Arrival), the completion of the machining process and the corresponding unloading of the piece to leave the machine ready for a new process (PUnloaded), and the conclusion of the warm up process after a switch *off*/switch *on* cycle (WupFinished). These events belong to the uncontrollable category because they are automatically administered by the machine or the process.

On the other hand the controllable events of the model are the commands for switching *off* (SwitchOff) and switching *on* (SwitchOn) the machine; these two events will determine the possible control actions that can be applied, and will influence the design of the control policy.

5.2.3 Control actions

As explained before, the control actions that can be performed, based on the simplified model of the machine, are related with the two controllable events present in the system:

- Switch *off* the machine ($u_1(t)$)
- Switch *on* the machine (obviously if a previous action of switch *off* was executed) and perform the respective warm up cycle ($u_2(t)$)

According to this behavior of the machine and its corresponding energetic model, only two possible scenarios can arise regarding energy savings:

1. Leave the machine in starvation state while waiting a new piece
2. Turn *off* the machine and then turn it *on* after a time has elapsed

The control actions analyzed in this type of problems can be executed at each time instant, and its action can be represented with binary values (1: execute the control action, 0: do not execute the control action).

5.2.4 Input Data

The control policies that will be developed aim to minimize energy consumption of a machine tool, therefore the logic selection of input data will correspond to the energy consumption in the different states of the analyzed machine.

Energy consumed by a machine can be expressed as:

$$Energy = Power \times Time \tag{5.1}$$

Thus, the energy consumption in the different states will change based on the instantaneous power demand of the state, and the time that the machine remains in that particular state.

In a framework of energy minimization, as is the one used in the development of this thesis, the values used must correspond to instantaneous power, but in the case that a cost minimization is aimed, this values can be changed to instantaneous cost and the problem formulation and solution will remain equal.

Power data directly related with the state of the machine used in the different problems will be denoted as follows:

- Warm up power demand (W_1): Instantaneous power demand due to the execution of a warm up process in the machine. This power depends on the different elements that are involved in the warming up process and the operations executed.
- Starvation power demand (W_2): Instantaneous power requirement of the machine when all its components are ready and waiting for start a machining process.

The power demanded during the machine *off* state (W_0) is assumed to be zero so it will not be taken into consideration; on the other hand, the machining phase is not considered as required input data, since this process will be performed no matter the selected control policy, and the power related with the machining process (W_3) will always be present, thus it will not influence the minimization process.

For some particular problems, an additional input parameter is taken into consideration; this parameter represents power consumed when a piece has arrived to the system and is waiting for the machine to be ready to start the machining phase. It is important to remark that the estimation of this power is beyond the scope of this thesis. The waiting power (if used) will be denoted as:

- Instantaneous power demand of a piece waiting to be machined (W_q)

The periods of time that the system will remain in the Machine *on* and Starvation states will be dictated by the control policy, hence are not utilized as input of the system; on the other hand, the time of the warm up process should be known a priori and influences the policy selection; this time will correspond to an input parameter denoted as:

- Duration of the warm up process (t_w)

5.3 Standby Policy

The standby policy represents the most common used policy in the market nowadays. This policy consists in: *Leaving the machine in the starvation state while waiting for a piece, without taking into consideration the information on the piece arrival.*

The aim of this policy is to maintain the machine in a thermal steady condition with the purpose of preserving a high accuracy and avoid production losses.

The energy consumed by this type of policy is a function of the starvation power and the time that the machine remains unproductive and will be given by:

$$g_{starvation} = \int_0^{t_a} W_2(t)\,\mathrm{d}t \tag{5.2}$$

Where t_a is the time of arrival of a piece.

For this particular policy the control actions are given by:

$$u_1(t) = 0 \quad \forall t \geq 0 \qquad u_2(t) = 0 \quad \forall t \geq 0 \tag{5.3}$$

Representing that no control action is taken.

This policy will be later compared with the different strategies developed in this thesis.

5.4 Deterministic Arrival Time: Switch *off*/ Switch *on* Strategy

The control policy developed in this section aims to minimize the energy consumption during non-value adding task if the inter-arrival time is deterministic, based on the assumptions and energetic model previously explained.

This policy consists in: *Executing a switch off command at specific point in time after a piece has been machined, and restarting the machine with a switch on command executed prior to the arrival of the piece, to perform the proper warm up cycle, if the information of the piece inter-arrival time is deterministic and the arrival time is larger than the warm up time.*

Since the arrival information (from now on denoted as t_a) is deterministic, this problem does not consider the inclusion of the waiting power; it is natural to assume that if the time at which the piece arrives is known without any type of uncertainty, the machine should be ready to move to the machining process at that particular instant.

5.4.1 Mathematical formulation

When performing a switch *off*/switch *on* cycle with complete knowledge of the inter-arrival time, it can be assumed that the warm up process will be executed just before the piece arrival, then, the optimal time for the switch *on* command can be computed straight forward as:

$$t_{o\_on} = t_a - t_w \tag{5.4}$$

Assuming that the demanded powers (W_1,W_2) have a time dependency, and that the warm up time depends on the time that the machine remains *off*, the computation of the t_{o_off} can not be obtained as straight forward as for t_{o_on}.

The time evolution of this policy is represented in figure 5.6.

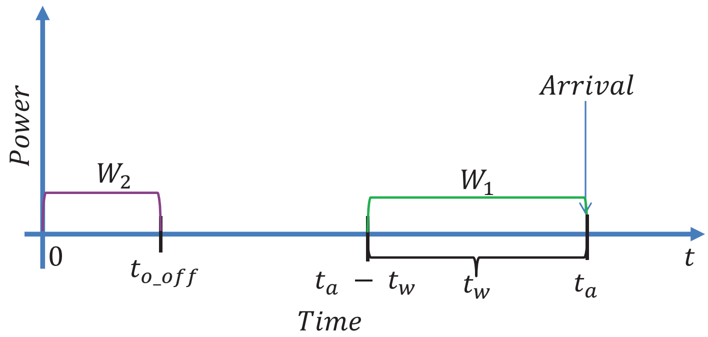


FIGURE 5.6: Time/State evolution of deterministic problem

Based on the time evolution of this policy, the energy consumption can be computed as:

$$g_{deterministic}(t_{o\_off}) = \int_0^{t_{o\_off}} W_2(t)\,\mathrm{d}t + \int_{t_a - t_w(t_{o\_off})}^{t_a} W_1(t)\,\mathrm{d}t \tag{5.5}$$

This policy can be applied using different time instants to switch *off* the machine, but the optimal time can be computed by finding the minimum, if exists, of $g_{determisnitic}(t_{off})$, such that:

$$t_{o\_off}^{opt} = \min_{t_{o\_off} \in [0, t_a - t_w)} g_2(t_{o\_off}) \tag{5.6}$$

The control actions are given by:

$$u_1(t) = \begin{cases} 1 & \text{if} \quad t = t_off \\ 0 & \text{else} \end{cases} \qquad u_2(t) = \begin{cases} 1 & \text{if} \quad t = t_a - t_w \\ 0 & \text{else} \end{cases} \tag{5.7}$$

5.4.2 Particular case: constant power demand

A particular case of this control policy can arise if the power demand of the states and the warm up time are considered to be constant.

In this situation, the energy consumption of the policy will be given by:

$$g_{deterministic} = W_1 \times t_w \tag{5.8}$$

This result comes as the natural one, given the fact that the less energy consumption will be obtained by turning *off* the machine as soon as possible, in order to spend the greatest possible amount of time in the less energy demanding scenario (machine *off*).

Then, the control policy will be optimal by turning *off* the machine at the inital time and turn it *on* at $t_a - t_w$.

$$u_1(t) = \begin{cases} 1 & \text{if} \quad t = 0 \\ 0 & \text{else} \end{cases} \qquad u_2(t) = \begin{cases} 1 & \text{if} \quad t = t_a - t_w \\ 0 & \text{else} \end{cases} \tag{5.9}$$

5.5 Stochastic Arrival Time

When dealing with problems in which the inter-arrival time correspond to a stochastic process, the objective of the control policy correspond to minimize the expected value of the energy of the non-value adding tasks, since the probability of piece arrivals are involved in the energy function.

To address problems regarding stochastic arrival times, it is important to define some parameters as follows:

- The probability density function of the inter-arrival time will be represented as $f(x)$

- The cumulative distribution function will correspond to $F(x)$ defined as

$$F_X(x) = P(X \leq x) = \int_0^x f(x)\,\mathrm{d}x \tag{5.10}$$

- The expected value of the arrival time will be denoted as λ

5.5.1 Switch *on* strategy

The control policy developed in this section aims to minimize the expected value of the energy during non-value adding task, if the inter-arrival time is stochastic and the control action of switching *off* the machine, if performed, is executed at time zero.

The switch *on* policy consists in: *Switching off the machine at the exact time at which the last processing operation has ended, leaving it in the off state for a period of time, and then switch it on at an specific point in time and execute a warming up process for starting a new operation.*

The minimization of the energy can be achieved by finding the optimal time (t_o) to switch *on* the machine when it was switched *off* at time zero, and its related expected energy.

In this and the subsequent sections, all the powers are considered to be constants.

5.5.1.1 Mathematical formulation

The implementation of this control scenario generates the appearance of three different state evolutions on the machine, based on the occurrence of the arrival of a piece.

The expected energy consumption will be given by the sum of the energy of each case multiplied by the probability of occurrence of that particular case.

1. Case 1: The arrival of the piece occurs prior to t_o ($t_a < t_o$)

   In this situation, the arrival of a piece occurs while the machine is in the *off* state. When the piece arrives, the machine will be forced to be switched *on* and will execute the warm up cycle, thus it will incur in a energy consumption equal to the power of the state multiplied by the duration of the warm up cycle.

   While the machine is in the warm up cycle, the piece is waiting without being processed, so a energy equal to the power of waiting (W_q) multiplied by the duration of the warm up cycle will be generated.

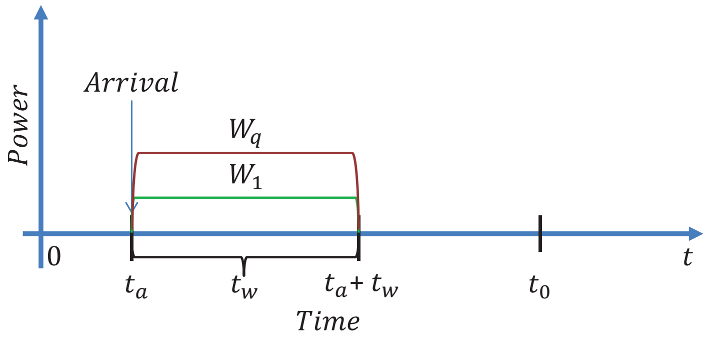


FIGURE 5.7: Time/State evolution of stochastic switch *on*- Case 1

Once the warm up cycle is finished, the piece will be processed.

The total enrgy consumption is:

$$g_{on\_c1} = (W_1 + W_q)t_w \tag{5.11}$$

2. Case 2: The arrival of the piece occurs during the execution of the warm up process ($t_0 < t_a < t_w$)

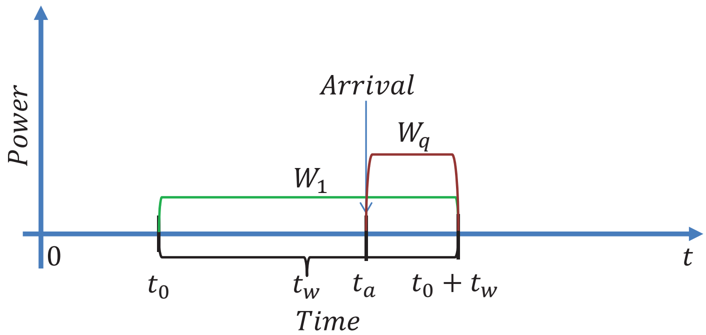


FIGURE 5.8: Time/State evolution of stochastic switch *on*- Case 2

This situation represents the fact that the machine is switched *on* at t_o, starts the warm up process and the piece arrives during this state.

The execution of the warm up generates a energy consumption corresponding to the power of the state multiplied by the duration of the warm up cycle.

On the other hand, when the piece arrives to the system, it has to wait for a portion of time for the machine to finish the warm up process; the energy of this event is given by power of waiting (W_q) multiplied by the interval that the piece have to wait.

The total energy is:

$$g_{on\_c2} = W_1 \times t_w + W_q(t_o + t_w - t_a) \tag{5.12}$$

3. Case 3: The arrival of the piece occurs after the execution of the warm up process ($t_a > t_0$)

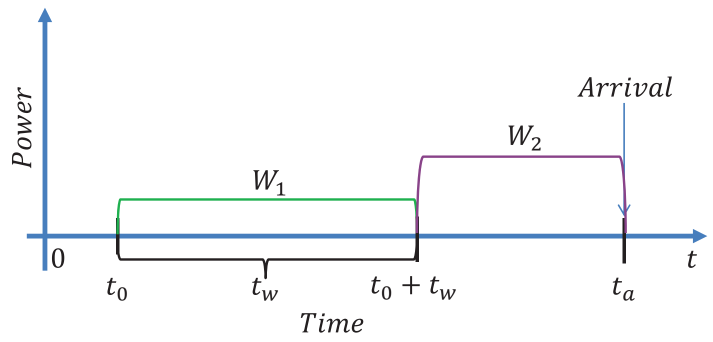


FIGURE 5.9: Time/State evolution of stochastic switch *on*- Case 3

In this situation, the machine is switched *on* at t_o and executes the corresponding warm up cycle, incurring in a energy consumption equal to the power of the state multiplied by the duration of the warm up cycle.

After the process is finished, the machine will be placed in the starvation state waiting for the arrival of the piece, and will consume an energy equal to the power of the state multiplied by the time that the machine remains in that state.

The total energy is:

$$g_{on\_c3} = W_1 t_w + W_2(t_a - (t_o + t_w)) \tag{5.13}$$

As explained before, the expected energy consumption will be given by the weighted sum of the energy of the three different cases.

$$\begin{aligned} g_{on}(t_o) = &\int_0^{t_o} f(x)(W_1 + W_q)t_w \, \mathrm{d}x \\ &+ \int_{t_o}^{t_o+t_w} f(x)(W_1 t_w + W_q(t_o + t_w - x)) \, \mathrm{d}x \\ &+ \int_{t_o+t_w}^{\infty} f(x)(W_1 t_w + W_2(x - (t_o + t_w))) \, \mathrm{d}x \end{aligned} \tag{5.14}$$

Recalling that

$$\int_a^b f(x) \, \mathrm{d}x = F(b) - F(a) \tag{5.15}$$

and after performing some computations, the expected value of the energy can be expressed as:

$$\begin{aligned} g_{on}(t_o) =& (W_q + W_2)(t_w + t_o)F(t_o + t_w) - W_q t_o F(t_o) \\ &+ (W_1 - W_2)t_w F(\infty) - W_2 t_o F(\infty) - W_q \int_{t_o}^{t_o+t_w} x f(x)\,\mathrm{d}x \\ &+ W_2 \int_{t_o+t_w}^{\infty} x f(x)\,\mathrm{d}x \end{aligned} \tag{5.16}$$

This expected energy consumption will depend on the probability distribution of the inter-arrival times. A minimum, if exists, migth be found by the proper selection of t_o such that:

$$t_o^{opt} = \min_{t_o \in [0,\infty)} g_{on}(t_o) \tag{5.17}$$

When $t_o^{opt} = 0$, this control policy should not be applied since the switch *on*/switch *off* commands will occur at the same time. On the other hand a $t_o^{opt} = \infty$ means that the optimal time to switch *on* the machine will be given by the arrival of the piece.

The control policy will be given by:

$$u_1(t) = \begin{cases} 1 & \text{if} \quad t = 0 \wedge t_o \neq 0 \\ 0 & \text{else} \end{cases} \qquad u_2(t) = \begin{cases} 1 & \text{if} \quad t = t_o \wedge t_o \neq 0 \\ 0 & \text{else} \end{cases} \tag{5.18}$$

5.5.1.2 Particular case: exponential distribution

If the inter-arrival time is set to have an exponential distribution with arrival rate equal to λ, it is known that:

$$f(x) = \lambda \cdot e^{-\lambda x} \tag{5.19}$$

$$F(x) = 1 - e^{-\lambda x} \tag{5.20}$$

$$\tag{5.21}$$

Recalling the energy function derived in the previous section, and performing some computation it can be obtained:

$$\begin{aligned} g_{on}(t_o) =& (W_q + W_2)(t_w + t_o)(1 - e^{-\lambda(t_o+t_w)}) + W_q t_o(1 - e^{-\lambda t_0}) \\ &+ (W_1 - W_2)t_w(1 - e^{-\lambda\infty}) - W_2 t_o(1 - e^{-\lambda\infty}) \\ &- W_q \int_{t_o}^{t_o+t_w} x f(x)\,\mathrm{d}x + W_2 \int_{t_o+t_w}^{\infty} x f(x)\,\mathrm{d}x \end{aligned} \tag{5.22}$$

$$g_{on}(t_o) = (W_1 + W_q)t_w - (W_q + W_2)(t_w + t_o)e^{-\lambda(t_o+t_w)} + W_q t_o e^{-\lambda t_0} - W_q \int_{t_o}^{t_o+t_w} x f(x)\,\mathrm{d}x + W_2 \int_{t_o+t_w}^{\infty} x f(x)\,\mathrm{d}x \tag{5.23}$$

Solving the remaining items using mathematical properties of the improper integrals, the expect value of the energy can be expressed as:

$$g_{on}(t_o) = (W_1 + W_q)t_w + \frac{(W_q + W_2)}{\lambda} e^{-\lambda(t_o+t_w)} - \frac{W_q}{\lambda} e^{-\lambda t_0} \tag{5.24}$$

To minimize the energy function by the appropriate selection of t_o, is necessary to take the derivative with respect to t_o and set it equal to zero.

$$g'_{on}(t_o) = W_q e^{-\lambda t_0} - (W_q + W_2)e^{-\lambda(t_o+t_w)} \tag{5.25}$$

In this case, it can be appreciated that the derivative of the energy is always different from zero; hence a minimum does not exists. This asseveration implies that the optimal time can take only two values: zero or infinite.

The result obtained for the optimal time to switch *on* the machine when using an exponential distribution are aligned with the memoryless property (each event is completely independent from the previous one) of this probability distribution, since waiting additional periods to take a control action will not change the probability of arrival of a piece, thus it will not change the expected value of the energy.

As for the general case, a $t_o = 0$ implies that the switch *off*/switch *on* cycle should not be executed and a $t_o = \infty$, that the optimal time to switch on the machine will correpond to the instant of the piece arrival.

The decision that this policy will give as a result, is based on the behavior of the previous energy function in the following way:

- If a decreasing exponential function is obtained, the decision will be to never switch *on* the machine (or switch *on* the machine once the piece arrives).
- If an increasing exponential function is obtained, the decision will be to switch *on* the machine at the beginning of the process, which in turn will correspond to never perform the swtich *off*/switch *on* cycle.

Since the first term of the energy function does not depend on the probability distribution and can be treated as a constant, the behavior of the exponential function will depend on the sign of the terms that multiplied it.

$$e^{-\lambda t_0}\left(\frac{(W_q + W_2)}{\lambda} e^{-\lambda t_w} - \frac{W_q}{\lambda}\right) \tag{5.26}$$

If the term that multypies the exponential funtion is negative, the behavior of the function will correspond to an increasing one, and the control policy will dictate that the machine should be turned *on* once the piece has arrived.

$$\frac{(W_q + W_2)}{\lambda} e^{-\lambda t_w} < \frac{W_q}{\lambda} \tag{5.27}$$

$$\frac{W_2}{W_q} < e^{\lambda t_w} - 1 \tag{5.28}$$

After solving the inequality, a ratio between the starvation power (W_2) and the waiting power (W_q) and its dependance on the arrival rate and the warm up time will defined the control policy as:

$$u_1(t) = \begin{cases} 1 & \text{if} \quad t = 0 \wedge \frac{W_2}{W_q} > e^{-\lambda t_w} \\ 0 & \text{else} \end{cases} \tag{5.29}$$

$$u_2(t) = \begin{cases} 1 & \text{if} \quad t = t_a \wedge \frac{W_2}{W_q} > e^{-\lambda t_w} \\ 0 & \text{else} \end{cases}$$

5.5.2 Switch *off* strategy

As for the previous section, the control policy developed in this section aims to minimize the expected value of the energy during non-value adding task if the inter-arrival time is stochastic.

Since the strategy regards the control of the switch *off*, the policy consists in: *Switching off the machine some time after the last processing operation has ended, and then switch it on and execute a warming up process once a new piece has arrived to the machine.*

5.5.2.1 Mathematical formulation

The implementation of this control strategy generates the appearance of two different state evolutions on the machine, based on the occurrence of the arrival of a piece.

The expected energy consumption will be given by the sum of the energy of each case multiplied by the probability of occurrence of that particular case.

1. Case 1: The arrival of the piece occurs prior to t_o ($t_a < t_o$)

   In this situation, the arrival of a piece occurs while the machine is still in the starvation state, then the only energy generated correspond to the power of

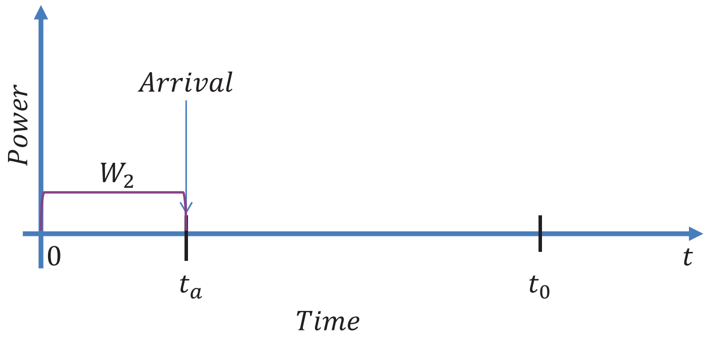


FIGURE 5.10: Time/State evolution of stochastic switch *off*- Case 1

the state multiplied by the arrival time.

$$g_{off\_c1} = W_2 t_a \tag{5.30}$$

2. Case 2: The arrival of the piece occurs after the machine has been switched *off* ($t_a > t_o$)

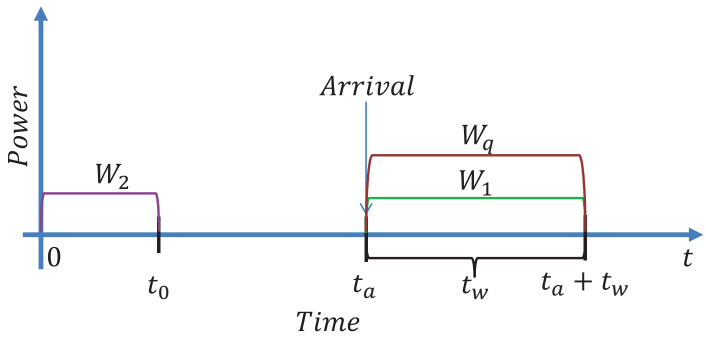


FIGURE 5.11: Time/State evolution of stochastic switch *off*- Case 2

This situation represents the fact that the machine is switched *off* at t_o and waits for a piece arrival to be switched *on*.

The energy consumed prior to the execution of the first control action depends on the starvation power demand and the time of the execution of the control action.

During the time in which the machine is in the *off* state and the piece has not arrive, the energy will be zero. Then, when the piece arrives to the system, the machine should be commanded to swtich *on* and will execute a warm up cycle during which the piece will have to wait to be machined.

The energy of this case is:

$$g_{off\_c2} = W_2 t_o + (W_1 + W_q) t_w \tag{5.31}$$

As explained before, the expected energy consumption will be given by the weighted sum of the energy of the two different situations

$$g_{off}(t_o) = \int_0^{t_o} f(x) W_2 x \, \mathrm{d}x + \int_{t_o}^{\infty} f(x)(W_2 t_o + (W_1 + W_q)t_w) \, \mathrm{d}x \tag{5.32}$$

This expected energy will depend on the probability distribution of the inter-arrival times. A minimun, if exists, can be found by the proper selection of t_o such that:

$$t_o^{opt} = \min_{t_o \in [0,\infty)} g_{off}(t_o) \tag{5.33}$$

When $t_o^{opt} = \infty$, this case should not be taken into consideration since an optimal time to switch *off* the machine does not exist.

The control policy will be given by:

$$u_1(t) = \begin{cases} 1 & \text{if} \quad t = t_o \wedge t_o \neq \infty \\ 0 & \text{else} \end{cases} \qquad u_2(t) = \begin{cases} 1 & \text{if} \quad t = t_a \wedge t_o \neq \infty \\ 0 & \text{else} \end{cases} \tag{5.34}$$

5.5.2.2 Particular case: exponential distribution

Using the same notation for the inter-arrival time distribution as in section 5.5.1.2, and recalling the energy function derived in the previous section, it can be obtained that:

$$g_{off}(t_o) = W_2 \int_0^{t_o} f(x) x \, \mathrm{d}xt + (W_1 + W_q)t_w(1 - F(t_o)) \tag{5.35}$$

$$g_{off}(t_o) = \frac{W_2}{\lambda} + \left((W_1 + W_q)t_w - \frac{W_2}{\lambda}\right) e^{(-\lambda t_o)} \tag{5.36}$$

To minimize the energy function by the appropriate selection of t_o, is necessary to take the derivative with respect to t_o and set it equal to zero. The results obtained in the minimization are aligned with the ones of section 5.5.1.2, where the derivative is never equal to zero, hence a minimum depending on t_o does not exist.

As for the general case, a $t_o^{opt} = \infty$ implies that this scenario should not be taken into consideration, since an optimal time to switch *off* the machine does not exist.

Since the first term of the energy function does not depend on the probability distribution and can be treated as a constant, the behavior of the exponential function will depend on the sign of the terms that multiplied it.

$$e^{-\lambda t_0}\left((W_1 + W_q)t_w - \frac{W_2}{\lambda}\right) \tag{5.37}$$

If the term that multypies the exponential funtion is negative, the behavior of the function will correspond to an increasing one, and the control policy will dictated that the machine should be turned *off* at $t_o = 0$ and turned *on* when the piece arrives .

$$(W_1 + W_q)t_w < \frac{W_2}{\lambda} \tag{5.38}$$

$$\frac{W_2}{W_1 + W_q} > \lambda t_w \tag{5.39}$$

After solving the inequality, a ratio between the starvation power (W_2) and the waiting power (W_q) and its dependance on the arrival rate and the warm up time will defined the control policy as:

$$u_1(t) = \begin{cases} 1 & \text{if} \quad t = 0 \wedge \frac{W_2}{W_1+W_q} > \lambda t_w \\ 0 & \text{else} \end{cases} \tag{5.40}$$

$$u_2(t) = \begin{cases} 1 & \text{if} \quad t = t_a \wedge \frac{W_2}{W_1+W_q} > \lambda t_w \\ 0 & \text{else} \end{cases}$$

5.6 Discussion on the Policies

Summarizing some important consideration about the policies previously developed, it is important to highlight some particular behaviors of the policies under different results of optimal times:

- Regarding the switch *on* startegy an optimal time equal to zero is equivalent to the standby policy presented in section 5.3, since the control actions of switch *off* and switch *on* will ocurr in the same time instant and thus, they should not be performed.
- As for the switch *off* policy, a similar behavior is obtained when the optimal time tends to infinity, since this will imply that the best decision for minimizing energy consumption corresponds to remain in the starvation state while waiting for a piece, which in turn has the same energy consumption that the standby policy currently used and presented in section 5.3.

Another important consideration regards the warm up energy consumption which affects the two strategies in a different way. When considering the switch *on* strategy the warm up power demand is always present, since the initial scenario consider that the machine goes to the *off* state immediately after finishing an operation, and thus it does not influence the results of the policy. In contrast, for the switch *off* strategy the warm up is not always present, and its probability of occurrence is associated with the probability of having an arrival after the selected optimal time.

Chapter 6

Results and Analysis

This chapter contains an analysis for the switch *on* and switch *off* strategies with stochastic arrival time presented in the previous chapter.

The first section encloses an analysis based on the results obtained by means of an algorithm developed in MATLAB® of the switch *on* and switch *off* strategies, subjected to two different continuous probability distributions: Exponential and Weibull.

The second section, makes a comparison between the approaches ussed in this work and the on presented in [Pra12a], to find the proper time to switch *off* a machine using a exponential distribution.

For a further details on the developed MATLAB® code refer to appendix A.

6.1 Numeric Results

In order to operate, the algorithm developed in MATLAB® requires different data about the problem such as values for the power, time required for the warm up stage, and data regarding the probability distributions that will follow the inter-arrival time of the piece to be machined.

The input data is compiled and processed depending on the desired strategy (switch *on*/*off*) and the algorithm will return as a result the optimal time, along with the minimum expected energy when using this value.

6.1.1 Exponential distribution

The influence of the different parameters will be presented using a base scenario with the values reported in table 6.1.

Warm up power demand	$\boldsymbol{W_1}$	3 [kW]
Starvation power demand	$\boldsymbol{W_2}$	5 [kW]
Warm up time	$\boldsymbol{t_w}$	3 [min]
Inter-arrival time	$\boldsymbol{\lambda}$	0.5 [$pieces/min$]

Table 6.1: Exponential distribution- switch *on*: Base scenario parameters

- Waiting cost

  When using the previous values in the policies of switch *on* and switch *off*, a critical value of the waiting cost can be computed, and this value, represent the limit at which the decision of the policy changes. Since the two policies have different ratios that influence this critical value, the results of the influence in the waiting cost will be presented separately.

  – Switch *on* policy

    Equation 5.28 governs the effect of the waiting cost in the decision making process. The critical value for this case corresponds to 1.4360 kW.

    At values of W_q smaller than $W_{q\_critical}$ ($W_q = 1.3\ kW$), a decreasing exponential function is obtained , and the inequality 5.28 is not fulfilled, so the decision will consist on switching on the machine when a piece arrives to the system; in figure 6.1b the energy is a monotone decreasing function in parameter t_o.

    On the contrary at values of W_q larger than $W_{q\_critical}$ ($W_q = 1.5\ kW$) the energy function increases over time, the inequality is fulfilled and the optimal time to switch *on* the machine will correspond to zero (which in practice will be associated with never switching *off* the machine).

    In the case of a waiting power equal to $W_{q\_critical}$, the energy will be constant and both decisions will lead to the same result. Indeed, in figure 6.1a the energy consumtion is independent from the selected parameter t_o.

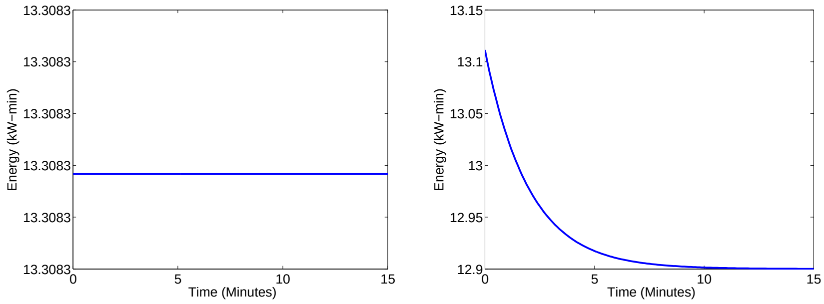
  – Switch *off* policy

    Equation 5.39 governs the effect of the waiting cost in the decision making process. The critical value for this case corresponds to 0.33 kW.

    At values of W_q smaller than $W_{q\_critical}$ ($W_q = 0.3\ kW$), an increasing exponential function is obtained , and the inequality 5.39 is fulfilled so the decision will consist on switching *off* the machine at time zero.

On the contrary at values of W_q larger than $W_{q\_critical}$ ($W_q = 0.4\ kW$) the energy function decreases over time, the inequality is not fulfilled and the optimal time to switch *off* the machine tends to infinite (which in practice will be associated with never switching *off* the machine).

In the case of a power of waiting equal to $W_{q\_critical}$, the energy will be constant and all possible switch *off* times will lead to the same result.



a) $W_q = W_{q\_critical} = 1.4360\ kW$ b) $W_q = 1.3\ kW < W_{q\_critical}$

FIGURE 6.1: Exponential distribution- switch *on*: Variation of W_q

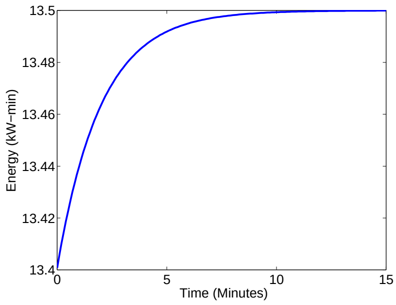
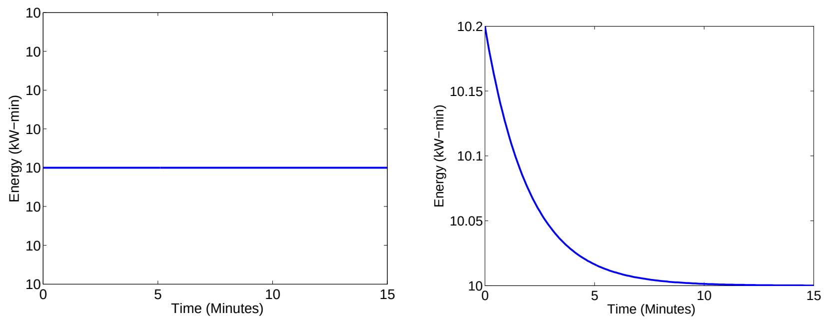


FIGURE 6.2: Exponential distribution- switch *on*: $W_q = 1.5 > W_{q-critical}$



a) $Wq = W_{q\_critical} = 0.33\ kW$ b) $Wq = 0.4 > W_{q\_critical}$

FIGURE 6.3: Exponential distribution- switch *off*: Variation of W_q

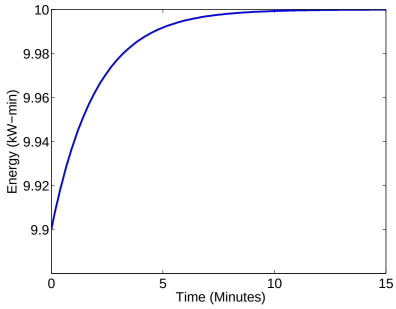


FIGURE 6.4: Exponential distribution- switch *off*: $W_q = 0.3\ kW < W_{q-critical}$

A more detailed dependace of the energy consumption with respect to the variation of W_q is presented in figure 6.5.

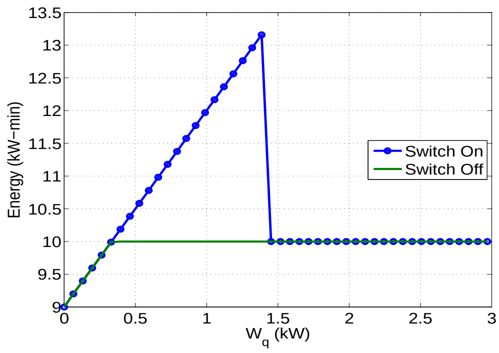
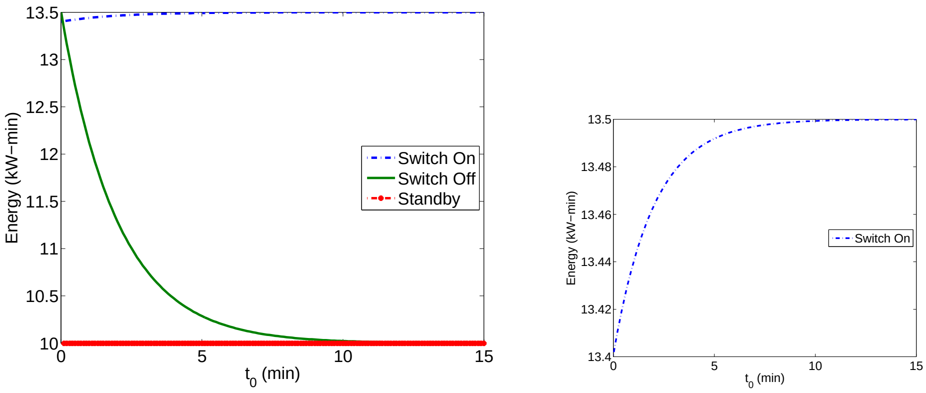


FIGURE 6.5: Energy consumtion variation with respect to W_q

The base scenario for both switch *on* and switch *off* strategy, will be given by the value of $W_q = 1.5\ kW$ (Figure 6.6)



a) Policies comparison- Base scenario b) Detailed view: Switch *on* strategy

FIGURE 6.6: Exponential distribution: Base Scenario

The policies in this scenario will correspond to:

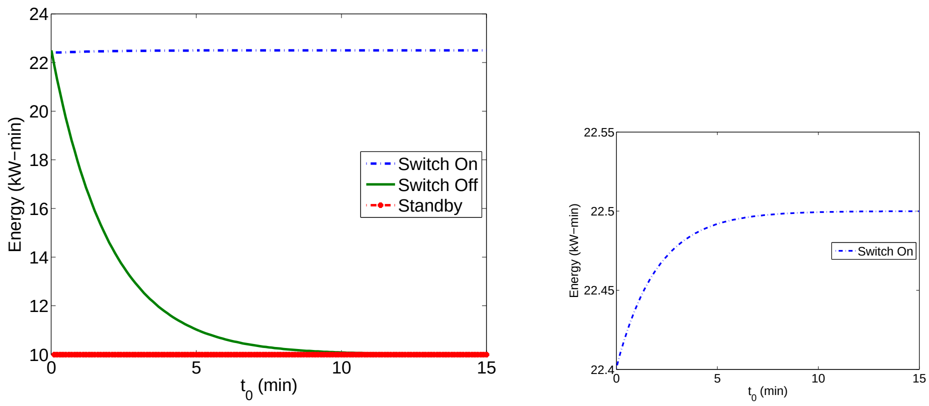
1. Switch *on* strategy: Optimal time to switch *on* the machine equal to zero (which in practice will be associated with never switching *off* the machine)
2. Switch *off* strategy: Optimal time to switch *off* the machine equal to ∞ (which in practice will be associated with never switching *off* the machine)

- Warm up power

  – Increment of the warm up power: $W_1 = 6\ kW$ (Figure 6.7)

    The warm up power does not influence the result of the **switch *on*** strategy decision, but only the expected value of the energy. Increasing the warm up power demand will only shift upwards the energy function without affecting its shape, so the decision of switching on a $t_o = 0$ will remain.

    On the contrary, the warm up power is an important factor that influences the decision of the **switch *off*** strategy, and the increment of this power will change the shape of the energy function, thus the policy will correspond to never switch *off* the machine. This modification comes as a result that a larger warm up power, will increase the energy consumed during the switch *off*/switch *on* cycle making it undesirable.



a) Policies comparison- Increase of W_1 b) Detailed view: Switch *on* strategy

FIGURE 6.7: Exponential distribution: $W_1 = 6\ kW$

  – Decrement of the warm up power: $W_1 = 1.5\ kW$ (Figure 6.8)

    As for the increasing of this value in the **switch *on*** strategy, a diminishing of the warm up power demand will not affect the optimal time to switch *on* the machine but only will shift downwards the energy function.

The results of the **switch *off*** strategy, show that decreasing the warm up power with respect to the base scenario will not change the result of the optimal time (switch *off* at time zero), but only will decrease the expected value of the energy consumption.

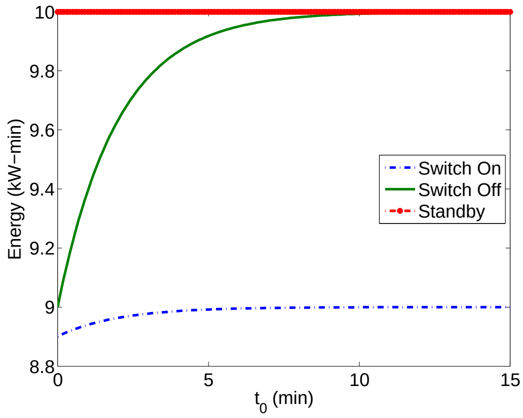


FIGURE 6.8: Exponential distribution: $W_1 = 1.5\ kW$

A more detailed dependace of the energy consumption with respect to the variation of W_1 is presented in figure 6.9.

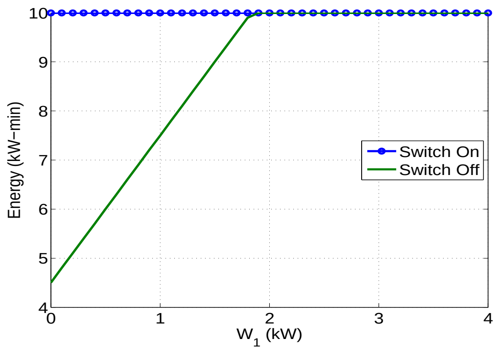


FIGURE 6.9: Energy consumption variation with respect to W_1

- Starvation Power
  - Increment of the starvation power: $W_2 = 10\ kW$ (Figure 6.10)
    The increment of the power demand of the starvation state affects directly the decision making process for both **switch *on*** and **switch *off*** strategies, and for both strategies this value (10 kW) will change the optimal time and thus the shape of the energy function.

Raising the power of the starvation state will affect the **switch *on*** strategy in such a way that the energy function will decrease over time, and the policy will correspond to switching *on* when the piece arrives. This change in the result is due to the fact that a higher power demand of the starvation state will increase the energy consumed when the machine is switched *on* at the beginning (or remains in starvation for the entire period), hence it will be more reasonable to go to *off* and wait for the piece arrival to switch *on* the machine, avoiding completely the starvation state.

Increasing the starvation power for the **switch *off*** strategy will change the shape of the energy function to an increasing one, and the policy will be changed to switch *off* the machine at time zero. This change is due to the fact that a greater power demand of the starvation state will increase the energy consumed when the machine is in starvation, hence it will be better to switch *off* the machine an perform a complete warm up cycle.

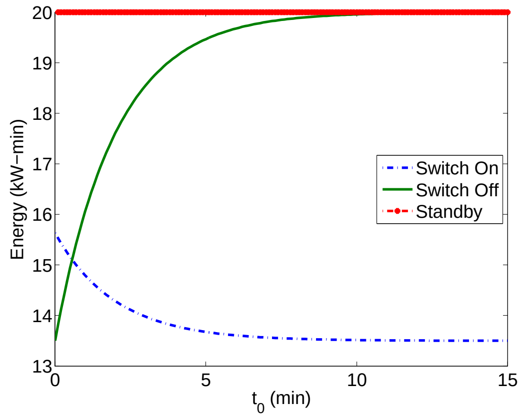


FIGURE 6.10: Exponential distribution: $W_2 = 10\ kW$

– Decrement of the starvation power: $W_2 = 2.5\ kW$ (Figure 6.11)

  A decrement in this value will have no effect on the shape of the energy function for neither one of the control policies, so the results will remain equal as for the base scenario and given by: for the **switch *on*** strategy will consist in an optimal time to equal to zero and for the **switch *off*** strategy an optimal time equal to ∞.

  The real effect that decreasing this value has on the strategies consists on a reduction of the expected value of the energy consumption.

A more detailed dependace of the energy consumption with respect to the variation of W_2 is presented in figure 6.12.

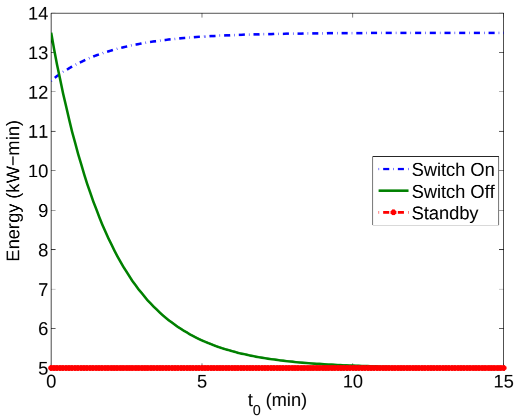


FIGURE 6.11: Exponential distribution: $W_2 = 2.5\ kW$

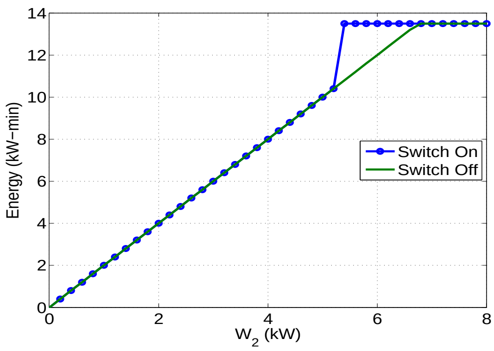


FIGURE 6.12: Energy consumption variation with respect to W_2

- Warm up time
  - Increment of the warm up time: $t_w = 9\ min$ (Figure 6.13)

    Increasing the warm up time with respect to the base scenario for the **switch *on*** strategy, will result in a significant growth of the expected value of the energy, but will not affect the decision since the function will continue to be an increasing exponential.

    The results for the **switch *off*** strategy are also align with maintaining the decision of the base scenario (optimal time equal to ∞), and the effect of increasing the time consist in the augment of the expected value of the energy.
  - Decrement of the warm up time: $t_w = 1\ min$ (Figure 6.14)

    The decreasing of the value has the opposite effect in the result of the control strategies. A warm up time reduction for the **switch *on*** stategy will result in changes on the shape of the energy function and the policy will consist on switching *on* the machine at the piece arrival. This result is a consequence of a short warm up phase, thus smaller energy used

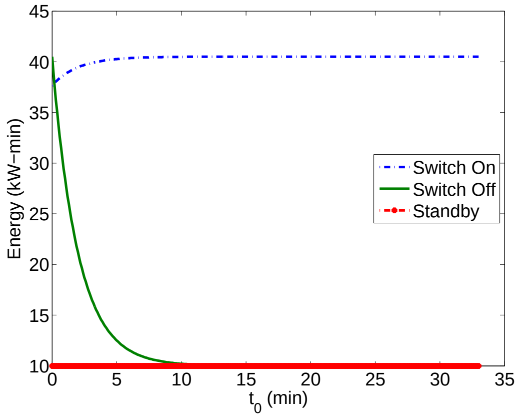


FIGURE 6.13: Exponential distribution: $t_w = 9\ min$

in this process, and also a shorter time in which the piece will have to wait for being process; all of this factors contribute to smaller energy consumption of the switch *off*/switch *on* cycle.

For the **switch *off*** strategy, a decrement on the warm up time will change the energy function and the policy will consist on switch *off* the machine at time zero. This result is a consequence of a shorter warm up phase, thus less energy consumption in the switch *off*/ switch *on* process.

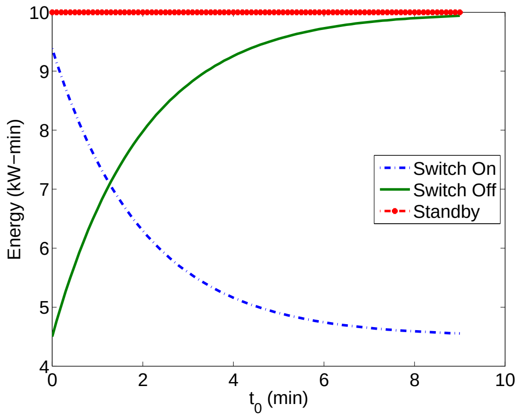


FIGURE 6.14: Exponential distribution: $t_w = 1\ min$

A more detailed dependace of the energy consumption with respect to the variation of warm up time t_w is presented in figure 6.15.

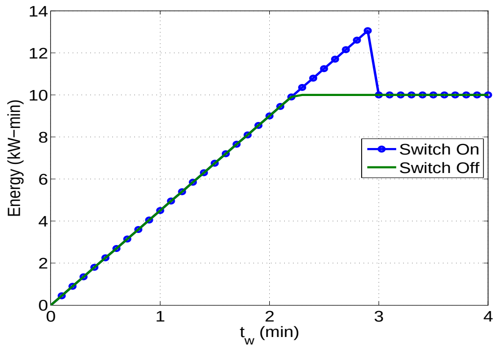


FIGURE 6.15: Energy consumption variation with respect to t_w

- Inter-arrival rate

  The inter-arrival rate has a similar behavior to the warm up time, since in both policies decision process these two parameters are multiplied, making their effects on the energy function totally aligned.

  - Increment of the inter-arrival rate: $\lambda = 0.7$ *pieces/min* (Figure 6.16)

    Increasing the inter-arrival rate time with respect to the base scenario for the **switch *on*** strategy, will result in a significant growth of the expected value of the energy, but will not affect the decision since the function will continue to be an increasing exponential.

    The results for the **switch *off*** strategy are also align with maintaining the decision of the base scenario (optimal time equal to ∞), and the effect of increasing the inter-arrival rate consist in the augment of the expected value of the energy.

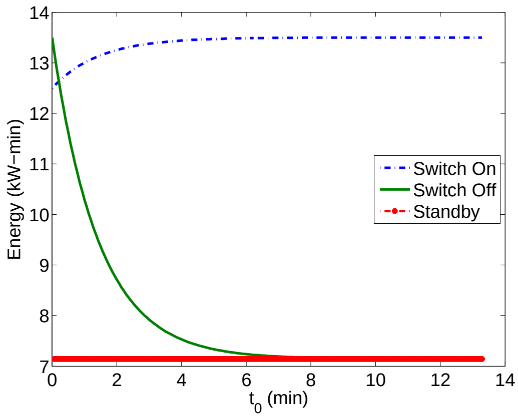


FIGURE 6.16: Exponential distribution: $\lambda = 0.7$ *pieces/min*

– Decrement the inter-arrival rate: $\lambda = 0.3\ pieces/min$ (Figure 6.17)
  An inter-arrival rate reduction for the **switch *on*** stategy will result in changes on the shape of the energy function and the policy will consist on switching *on* the machine at the piece arrival.
  For the **switch *off*** strategy, a decrement of the inter-arrival rate will also change the shape of the energy function with respect to the base scenario, and the policy will consist on switching *off* the machine at time zero.

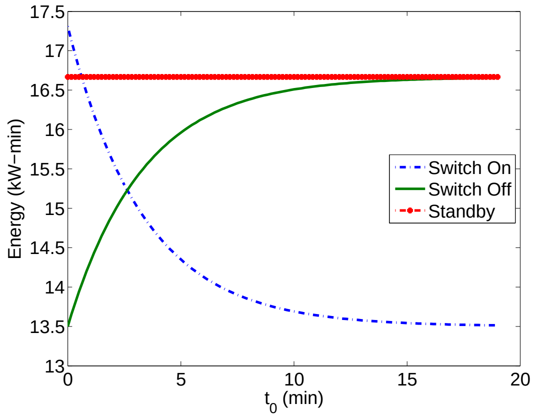


FIGURE 6.17: Exponential distribution: $\lambda = 0.3\ pieces/min$

A more detailed dependace of the energy consumption with respect to the variation of the inter-arrival rate λ is presented in figure 6.18.

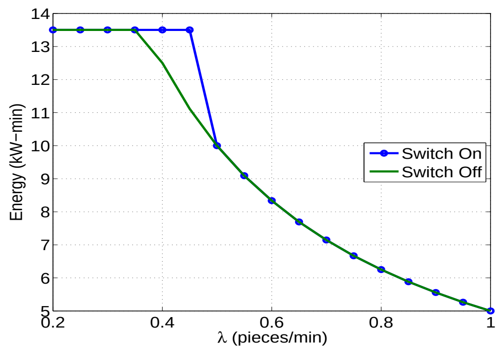


FIGURE 6.18: Energy consumption variation with respect to λ

6.1.2 Weibull distribution

Explicit mathematical formulation of the different strategies with Weibull distribution was not computed, since the analytical integrals related with this problem were difficult to calculate, therefore all the numerical results presented in this section are obtained by means of the MATLAB® program using a numerical integration algorithm.

The Weibull probability density function is expressed in equation (6.1). This function has as arguments the shape parameter k and the scale parameter λ.

$$f(x;\lambda,k)=\begin{cases}\frac{k}{\lambda}\left(\frac{x}{\lambda}\right)^{k-1}e^{-\left(\frac{x}{\lambda}\right)^{k}} & x\geq 0,\\ 0 & x<0.\end{cases} \quad (6.1)$$

In a probability density function, the shape parameter k, as its name expresses, affect the shape of the function rather than shifting or stretching it. The weibull distribution function is affected by particular ranges of the value of k as follow:

1. If $k < 1$ the probability of occurrence of an event decreases over time.
2. If $k = 1$ the probability of occurrence of an event is constant over time, so the weibull distribution will behave as an exponential one.
3. If $k > 1$ the probability of occurrence of an event increases over time.

Based on the previous explanation, the definition of a switch *on* time when arrival times have a weibull distribution will only make sense if the probability of occurrence on an event (arrival) increases over time ($k > 1$), and the switch *off* strategy when the probability decreases over time ($k < 1$). In the case that the shape parameter is one, the results will coincide with the ones of the exponential distribution.

Unlike the behavior of the different strategies with exponential distributions, the energy function obtained using a weibull distribution can present a minimum value indicating the optimal times to switch *on* or switch *off* the machine depending on the selected strategy.

6.1.2.1 Switch *on* strategy ($k > 1$)

The influence of the variation of the different parameters will be presented using as a base scenario the one obtained with the values of table 6.2.

The results of the base scenario correspond to a particular situation in which the energy function has a minimum value with respect to the time. In this case, the machine must be switched *on* at a time equal to 6.77 min to consume the less possible energy equal to 25.55 $kW \cdot min$. (Figure 6.19)

Warm up power demand	$\boldsymbol{W_1}$	5 [kW]
Starvation power demand	$\boldsymbol{W_2}$	2 [kW]
Waiting power demand	$\boldsymbol{W_q}$	4 [kW]
Warm up time	$\boldsymbol{t_w}$	3 [min]
Scale parameter	$\boldsymbol{\lambda}$	10 [min]
Shape parameter	$\boldsymbol{k}$	1.5

TABLE 6.2: Weibull Distribution- switch *on*: Base scenario parameters

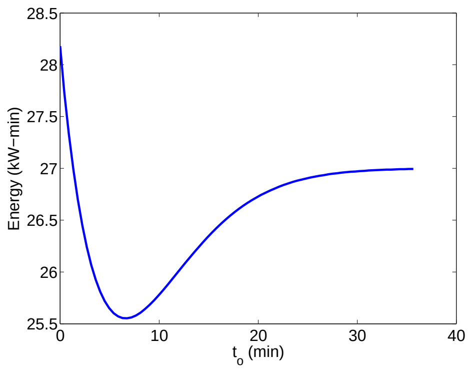


FIGURE 6.19: Weibull distribution- switch *on*: Base scenario parameters

- Waiting power (W_q) (Figure 6.20)

  Depending on the proportion in which the values varies, the energy function can change drastically its shape.

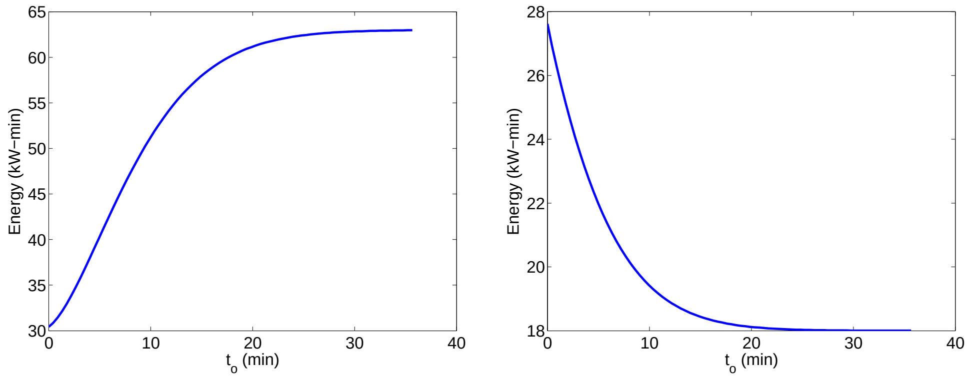
  An increase of the waiting power demand to 16 kW will give as a result an energy function with the shape of an increasing exponential distribution, hence a minimum value in the range $[0, \infty)$ does not exit, and the decision will consist on switching *on* the machine at $t_o = 0$ min (in practice, it will consist of remaining in starvation during the entire time).

  On the contrary, a decrement of the waiting power to 1 kW, will create a decreasing exponential function and the decision will correspond to switch *on* the machine when the piece arrives.

- Warm up power (W_1) (Figure 6.21)

  Similar to the results obtained with the exponential distribution in the switch *on* strategy, the warm up power does not influence the result of the policy, but only the expected value of the energy.

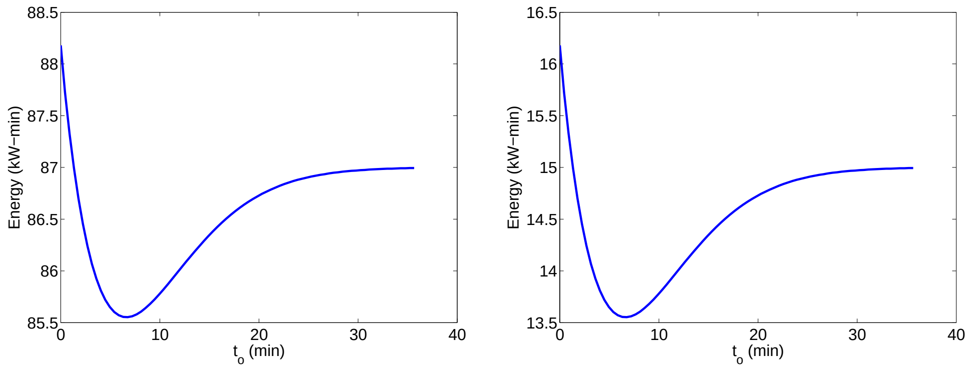
  Increasing ($W_1 = 25$ kW) or decreasing ($W_1 = 1$ kW) the warm up power demand will only shift upwards or downwards the energy function without affecting its shape, thus the optimal time will remain unaltered an equal to 6.77 min, while the expected value of the energy consumption will increase to



a) $W_q = 16\ kW$ b) $W_q = 1\ kW$

FIGURE 6.20: Weibull Distribution- switch *on*: Variation of W_q

85.5 $kW \cdot min$ in the case of intensification of the power demand, or decrease to 13.5 $kW \cdot min$ in the opposite case (diminishing of the power demand).



a) $W_1 = 25\ kW$ b) $W_1 = 1\ kW$

FIGURE 6.21: Weibull Distribution- switch *on*: Variation of W_1

- Starvation power (W_2) (Figure 6.22)

  Large increments in the starvation power ($W_2 = 8\ kW$) will contribute to radical changes in the energy consumption, altering the function in such a way that it becomes a decreasing exponential one. This change indicates (as for the exponential analysis) that the optimal time to switch *on* the machine will be when the piece arrives to the system.

  On the other hand, if the starvation power is reduced, the optimal time will tend to decrease as well, and can become zero. In this case, the energy consumption will be represented by an increasing exponential function whose smallest energy consumption is obtained at the beginning of the process.

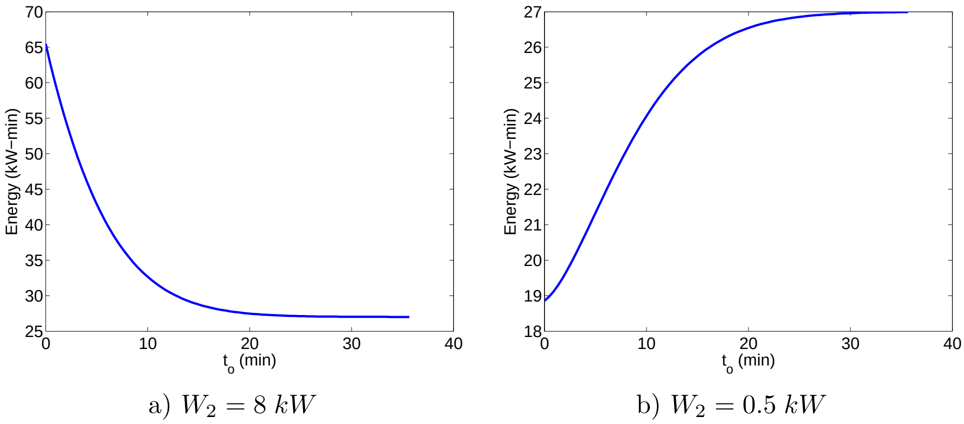


FIGURE 6.22: Weibull Distribution- switch *on*: Variation of W_2

Figure 6.23 shows a more detailed dependence of the optimal time to switch *on* the machine and the energy consumption due to this decision, with respect to the variation of the starvation power. It is noticeable that the optimal time increases with the instantaneous power demand of the starvation state (W_2) for some values of this parameter, that initially it maintains a value of zero for a range of W_2, and after the power demand overcomes a threshold, the optimal time becomes infinite.

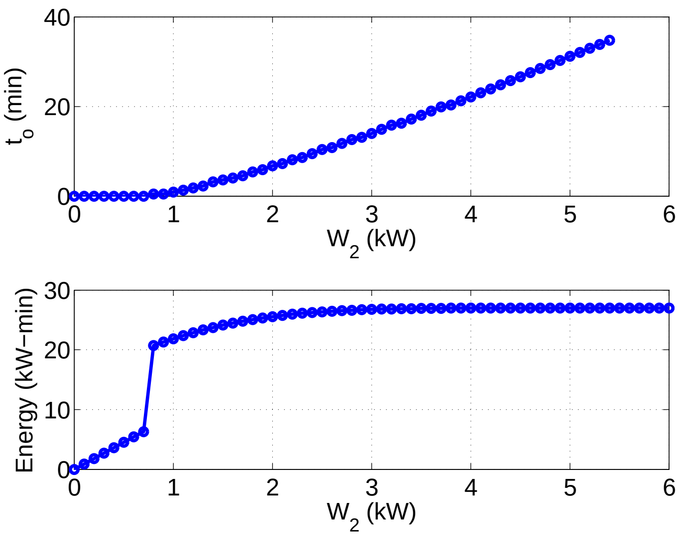


FIGURE 6.23: Optimal time and energy consumption with respect to W_2

The energy consumption is also an increasing function with respect to W_2; it can be appreciated that it has a radical change at the point in which the optimal time changes from zero to a different value, and also that when the optimal time becomes infinite, the energy consumption is constant and equal to the one of the standby policy.

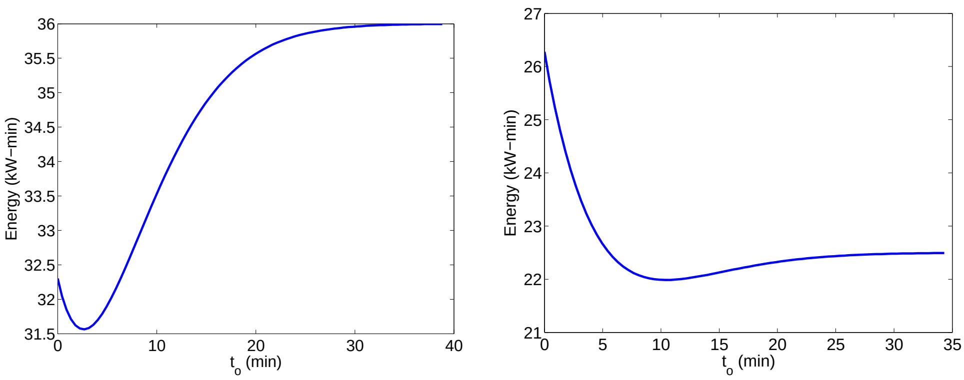
Similar graphs can be obtained for parameters, W_1, W_q, λ, t_w, that influence the decision making process switch *on*.

- Warm up time (t_w) (Figure 6.24)

  When the variations in the parameters are not as radical as in the previous analysis, the energy function can still present a minimum in the interval $[0, \infty)$.

  If the warm up time is set to be 4 min (increased) the effect in the energy function will not be radical, the shape will be similar and the main difference will be that the optimal time to switch *on* the machine will reduce to 2.7 min and the expected value of the energy consumption will increase to 31.56 $kW \cdot min$. This behavior is governed by the fact that a larger warm up time will increase the period in which the piece is waiting, so the machine should start the warm up process sooner to be ready to process the piece at its arrival to the system.

  The opposite effect will have a reduction of the warm up time ($t_w = 2.5\ min$); since the waiting time is smaller, the optimal time to switch *on* the machine will increase ($t_o = 10.3\ min$) and the expected value of the energy will have a smaller value (21.9 $kW \cdot min$).



a) $t_w = 4\ min$ b) $t_w = 2.5\ min$

FIGURE 6.24: Weibull Distribution- switch *on*: Variation of t_w

6.1.2.2 Switch *off* strategy ($k < 1$)

The influence of the variation of the different parameters will be presented using as a base scenario the one obtained with the values of table 6.3.

Warm up power	$\boldsymbol{W_1}$	4 $[kW]$
Starvation power	$\boldsymbol{W_2}$	1 $[kW]$
Waiting power	$\boldsymbol{W_q}$	3 $[kW]$
Warm up time	$\boldsymbol{t_w}$	3 $[min]$
Scale parameter	$\boldsymbol{\lambda}$	10 $[min]$
Shape parameter	$\boldsymbol{k}$	0.5

TABLE 6.3: Weibull distribution- switch *off*: Base scenario parameters

The results of the base scenario represent a situation in which the energy function has a minimum value with respect to the time. In this case, the machine must be switched *off* at a time equal to 11 min to consume the less possible energy equal to 13 $kW \cdot min$. (Figure 6.25)

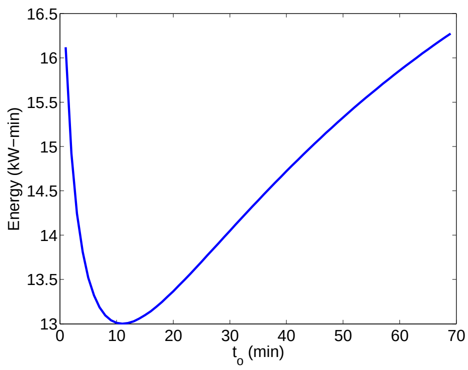


FIGURE 6.25: Weibull distribution- switch *off*: Base scenario parameters

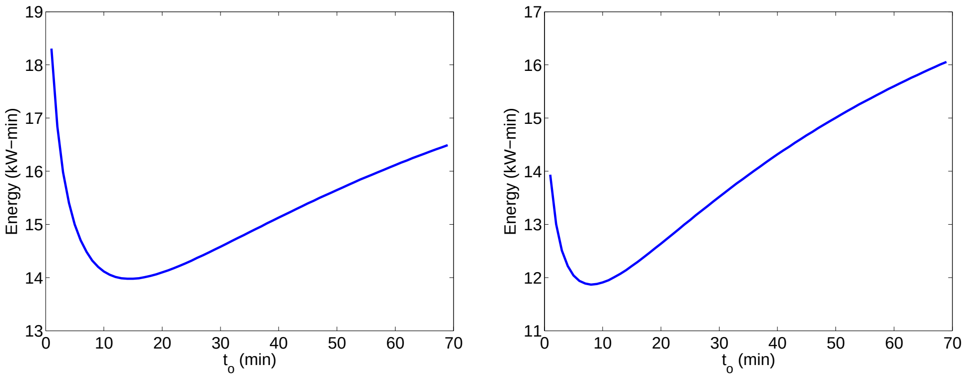
- Waiting power (W_q) (Figure 6.26)

  An increase of the waiting power demand to 4 kW will increase the value of optimal time to switch *off* the machine to a value of 4 min and also will change the expected value of the energy to 13.9 $kW \cdot min$; if the power increases in a bigger proportion, the time will tend to infinite and the policy will correspond to remaining in starvation.

  On the contrary, a decrement of the waiting power to 2 kW will decrease the optimal time to switch *off* to 8 min, so that the machine remains in starvation a shorter period. In this situation the expected value of the energy will also decrease to 11.8 $kW \cdot min$.

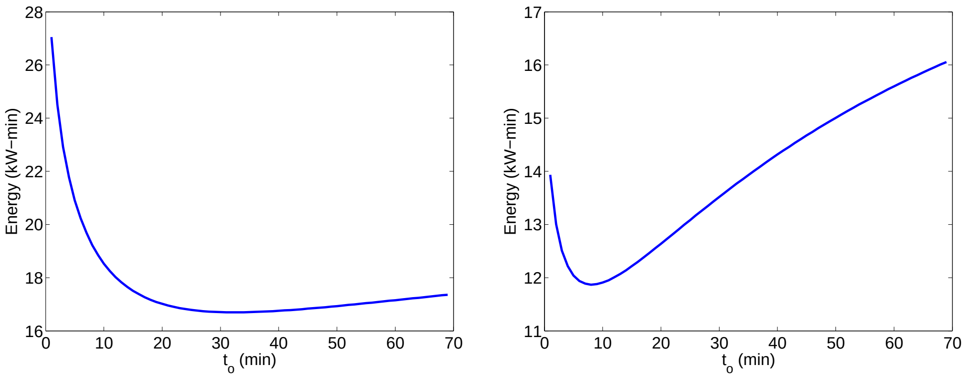
- Warm up power (W_1) (Figure 6.27)

  Increasing the power demand ($W_1 = 8$ kW) will increase the optimal time to switch *off* the machine ($t_o = 27$ min) and also the expected value of the energy consumption (16.1 $kW \cdot min$).



a) $W_q = 4\ kW$ b) $W_q = 2\ kW$

FIGURE 6.26: Weibull Distribution- switch *off*: Variation of W_q



a) $W_1 = 8\ kW$ b) $W_1 = 2\ kW$

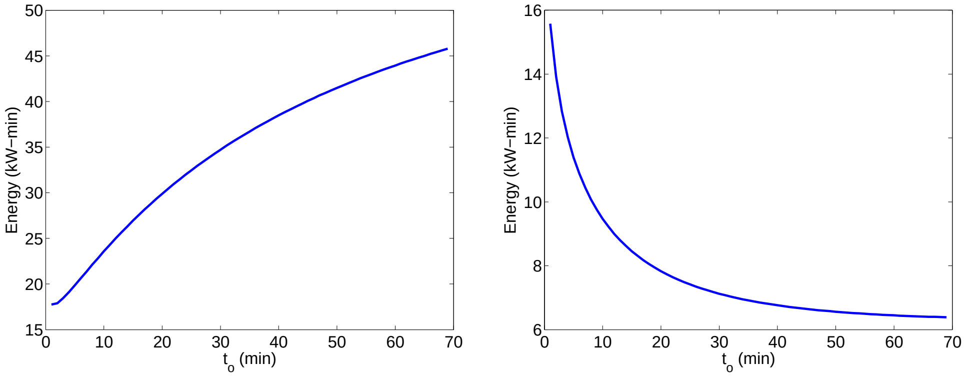
FIGURE 6.27: Weibull Distribution- switch *off*: Variation of W_1

On the other hand, a power decrement ($2\ kW$) will result in the opposite effect given by a decrement on the optimal time ($t_o = 6\ min$) and a consequent diminishing of the energy consumption ($10.5\ kW \cdot min$).

- Starvation power (W_2) (Figure 6.28)

  An increasing in the starvation power ($W_2 = 3\ kW$) will generate larger energy consumptions while the machine is in the starvation state, so the optimal time to switch *off* decreases ($t_o = 1\ min$), but the expected value of the energy might increase with respect to the base scenario ($17.74\ kW \cdot min$).

  On the other hand, if the starvation power is reduced, the optimal time tends to increase and can become ∞ with a value of $W_2 = 0,33\ kW$. In this case, the energy consumption will be a decreasing exponential function whose smallest energy consumption, equal to $6.43\,kW \cdot min$, is obtained if the machine is never switched *off*.



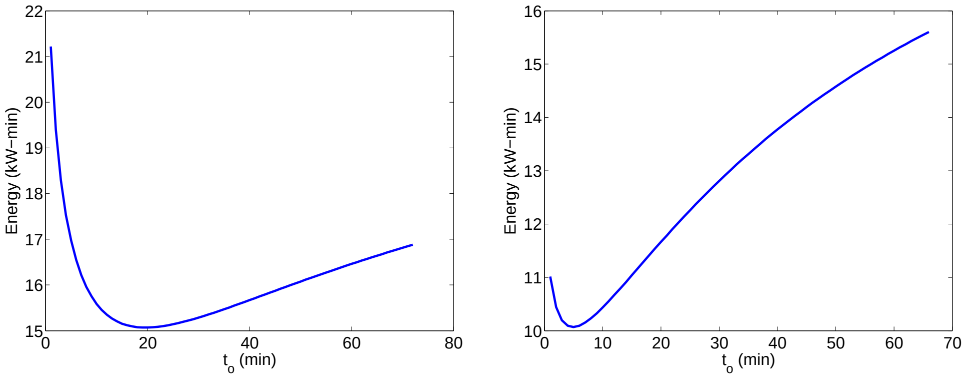
a) $W_2 = 3\ kW$ b) $W_2 = 0.33\ kW$

FIGURE 6.28: Weibull Distribution- switch *off*: Variation of W_2

- Warm up time (t_w) (Figure 6.29)

  Changing the warm up time for a greater value equal of 4 min, will increase the optimal time to switch *off* the machine ($t_o = 20\ min$) as well as the expected value of the energy consumption ($15\ kW \cdot min$). This behavior is governed by the fact that the warm up phase energy consumption will increase, so it is better to avoid the process.

  The opposite effect will have a reduction of the warm up time ($2\ min$); the optimal time to switch *off* the machine will decrease to 5 min and the expected value of the energy will have a smaller value equal to $10\ kW \cdot min$.



a) $t_w = 4\ min$ b) $t_w = 2\ min$

FIGURE 6.29: Weibull Distribution- switch *off*: Variation of t_w

Figure 6.30 shows a dependence of the optimal time to switch *off* the machine with respect to the warm up time. It can be seen that with smaller values of t_w the optimal time to switch *off* is zero, since shorts warm up time represent a low energy consumption of a switch *off* /switch on cycle making it a situation more desirable than the starvation state. As the warm up increases, the optimal time tends also to increase, and after a threshold it becomes infinite implying that it will be better to remain in starvation while waiting for a new piece. Regarding the energy function, its behavior is monotone increasing with respect to the warm up parameter until the optimal time reaches infinite value, at which condition the energy is constant and equal to the one of the standby policy.

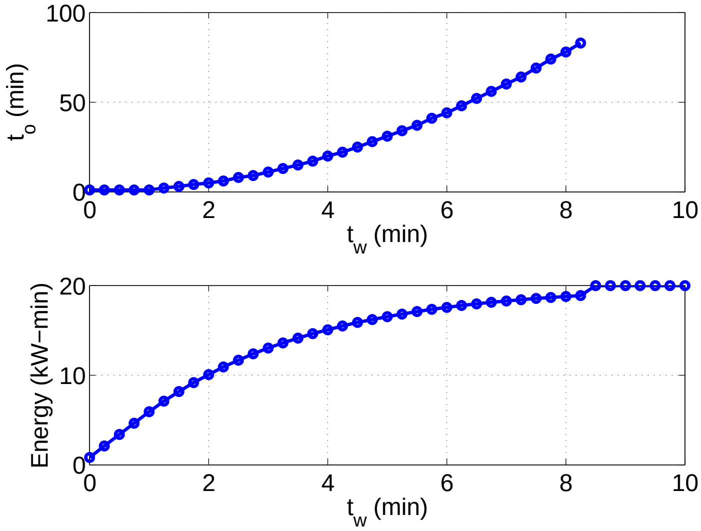


FIGURE 6.30: Optimal time and energy consumption with respect to t_w

Similar graphs can be obtained for the parameters, W_1, W_2, W_q, λ, that influence the decision making process of the switch *off*.

6.2 Different Approaches to Select the Time to Switch *off* a Machine Tool

In this section a brief introduction of an approach used by Prabhu et. al (EC1) in [Pra12a] will be presented with the purpose of giving the necessary background for a further comparison. After that, the switch *off* strategy for stochastic arrival time presented in this work, will be located in framework similar to the one presented by Prabhu, with the aim of allowing a comprehensive comparison between these two approaches. Finally the difference between the two approaches will be presented based on similar frameworks.

By comparing EC1 with the switch *off* strategy for stochastic arrival time presented in section 5.5.2, it is possible to conclude that in essence the policies employed are equal, but Prabhu et. al use a different approach to select the time (not necessarily optimal) to switch *off* a machine. EC1 aims to find out minimization of energy consumption in non-value adding tasks by the selection of different objectives (such as control the ratio of utilization of the machine) and also the use of different parameters to achieve the result.

6.2.1 Description of the energy control policy EC1

The main objective of EC1 (Energy control policy presented in [Pra12a]) is "to reduce wasted energy such as reducing the amount of energy consumed when the machine is idle". Specifically, the policy operates in such a way that "when the idle time of a machine will exceed (τ) then it is switched to a lower power consumption state".

EC1 considers three machine states whose power is defined as follows

- W_p: Power of the busy state where the machine is processing a piece
- W_l: Power of the low idling state, where the machine will be placed after a τ has elapsed
- W_h: Power of the nominal idling state, where the machine is located (if it is not machining) before τ has elapsed

The problem is formulated using the queuing theory with exponential distributions, so the utilization of a machine is expressed in equation 6.2, and the probability of an inter-arrival time greater than τ in equation 6.3.

$$\rho = \frac{\lambda}{\mu} \tag{6.2}$$

$$P(x > \tau) = e^{-\lambda\tau} \tag{6.3}$$

Therefore the probability of an inter-arrival time smaller than τ is:

$$P(x < \tau) = 1 - e^{-\lambda\tau} \tag{6.4}$$

With the previously defined parameters, the long term energy consumption of a machine over a time horizon T is dictated by:

$$E = (W_p\rho + W_h(1-\rho)(1-e^{-\lambda\tau}) + W_l(1-\rho)e^{-\lambda\tau})T \tag{6.5}$$

The ratio of the energy "wasted" during non-value adding tasks (E_w) with respect to the energy employed in processing (E_p), is expressed as:

$$\frac{E_w}{E_p} = \frac{W_h(1-\rho)(1-e^{-\lambda\tau})}{W_p\rho} + \frac{W_l(1-\rho)e^{-\lambda\tau}}{W_p\rho} \tag{6.6}$$

If values of $W_0 = 0.1W_p$, and $W_1 = W_p$ are used, figure 6.31 shows the impact of various parameters in the energy ratio (Equation 6.6).

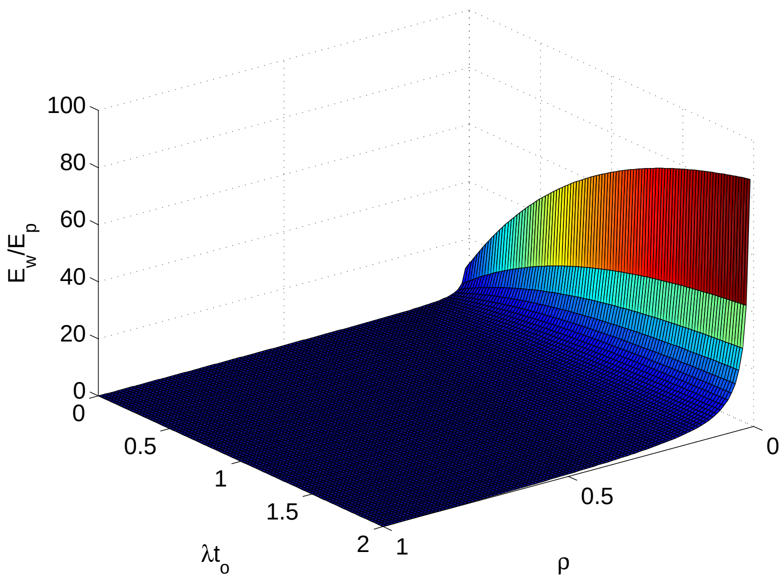


FIGURE 6.31: Impact of utilization and idle time threshold on energy wasted

As a main analysis of this graph the authors concluded that "energy wasted during idling is close to 0 under almost all conditions except when the utilization is less than 10%, which is an extreme and practically unlikely situation".

6.2.2 Definition of switch *off* strategy for stochastic arrival time in a common framework

In order to compare the problem solved by using the switch *off* strategy for stochastic arrival time presented in 5.5.2 with Prabhu et al. approach [Pra12a], a similar framework should be analyzed and the following considerations taken:

- The comparison encloses the analysis of the switch *off* strategy for stochastic arrival time in the special case of exponential probability distribution.
- The main difference between the approaches is that EC1 does not consider an intermediate state between the low energy consumption state and the

machining one, therefore the machine is able to process a piece immediately after its arrival. In contrast, the switch *off* strategy for stochastic arrival time employs a "Warm up" state every time the machine is switched *on*. Indeed, without a warm up state the EC1 approach does not consider neither the time spent to perform warm up, nor the power aligned with this wasted time.

- Another important difference is that the switch *off* strategy for stochastic arrival time considers a waiting power related to the time that the piece has to wait if the machine is executing the warm up process.
- The differences mentioned above will generate discrepancies in the final results obtained by the two policies.

The development of a common framework between EC1 and the switch *off* strategy for stochastic arrival time starts with defining the utilization (ρ) of the last approach, which might vary depending on the energetic state of the machine when the piece arrives.

Defining μ as processing rate so the machining time (t_m) takes the value of $1/\mu$, λ as the arrival rate, and using the same notation for the times and powers of the different states of the machine employed in 5.2, the utilization can be computed for the two different scenarios.

The first scenario considers the piece arrival prior to the selected t_o . In this case, and as for EC1 the utilization can be defined equally.

$$\rho_0 = \frac{t_m}{t_a} = \frac{\frac{1}{\mu}}{\frac{1}{\lambda}} = \frac{\lambda}{\mu} \tag{6.7}$$

The second scenario considers the piece arrival after the selected t_o. In this case since a time is needed to prepare the machine for processing the piece, the utilization reduces and can be defined as:

$$\rho_1 = \frac{t_m}{t_a + t_w} = \frac{\frac{1}{\mu}}{\frac{1}{\lambda} + t_w} = \frac{\lambda}{\mu(1 + \lambda t_w)} = \rho_0 \left(\frac{1}{(1 + \frac{t_w}{t_a})} \right) \tag{6.8}$$

Since this policy deals with stochastic process, the total utilization can be computed as the expected value that depends on the probability of occurrence of the two previous scenarios:

$$\overline{\rho} = \rho_0 \cdot P(x < t_0) + \rho_1 \cdot P(x > t_0) = \frac{\lambda}{\mu} \int_0^{t_o} \lambda e^{-\lambda x} \, \mathrm{d}x + \frac{\lambda}{\mu(1 + \lambda t_w)} \int_{t_o}^{\infty} \lambda e^{-\lambda x} \, \mathrm{d}x \tag{6.9}$$

$$\overline{\rho} = \frac{\lambda}{\mu}(1 - e^{-\lambda t_0}) + \frac{\lambda}{\mu(1 + \lambda t_w)} e^{-\lambda t_0} \tag{6.10}$$

Defining the expected value of the energy in a similar way as in [Pra12a], it is obtained:

$$E = (W_3\overline{\rho} + W_2(1-\overline{\rho})(1-e^{-\lambda t_0}) + W_a(1-\overline{\rho})e^{-\lambda t_0})T \tag{6.11}$$

Where W_a corresponds to the power of the second scenario that should be found using some additional computations.

The power of W_a in the switch *off* strategy for stochastic arrival time is not the same as the low energy idle power in EC1, because this power depends not only in the time that the machine remains in the machine *off* state, but also on the warm up time.

Figure 6.32 represents a general distribution of power during the machine *off* and warm up state.

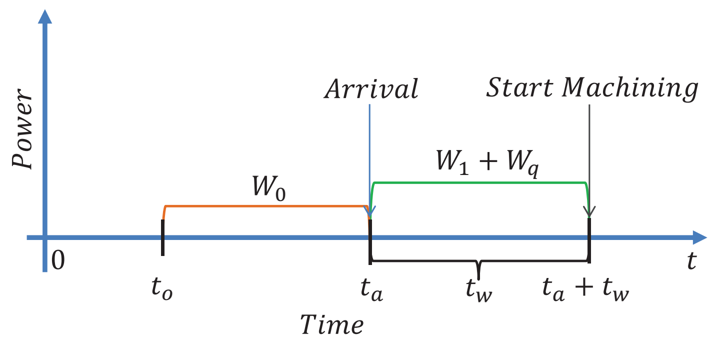


FIGURE 6.32: Power distribution the "low energy" consumption state

Form figure 6.32 it is possible to state that the energy consumption of this particular state is a function of W_0,W_1, W_q, t_a and t_w.

The total amount of energy with which machine *off* and warm up phase contributes to W_a is given by:

$$E_{off} = W_0 t_a \tag{6.12}$$

$$E_{wup} = (W_1 + W_q) t_w \tag{6.13}$$

While the total time that the machine will remain in the low consumption state will be given by $t_a + t_w$.

To be able to compute W_a is necessary to normalize the energy consumed in machine *off* and warm up phase over the entire interval of W_a, so equivalent power should be computed and $W_a = W_{eq\_off} + W_{eq\_wup}$.

$$W_{eq\_off} = \frac{W_0 t_a}{t_a + t_w} \tag{6.14}$$

$$W_{eq\_wup} = \frac{(W_1 + W_q)t_w}{t_a + t_w} \tag{6.15}$$

It is known that t_a (arrival time) is not a deterministic variable, so some computation regarding the expected value of the arrival after t_o has elapsed should be done, obtaining as final result:

$$W_{eq\_off} = \frac{W_0 \int_{t_0}^{\infty} x f(x)\, \mathrm{d}x}{\int_{t_0}^{\infty} x f(x)\, \mathrm{d}x + t_w} = \frac{W_0 e^{-\lambda t_0}(\frac{\lambda t_0 + 1}{\lambda})}{(\frac{\lambda t_0 + 1}{\lambda})e^{-\lambda t_0} + t_w} \tag{6.16}$$

$$W_{eq\_wup} = \frac{(W_1 + W_q)t_w}{\int_{t_0}^{\infty} x f(x)\, \mathrm{d}x + t_w} = \frac{\lambda t_w (W_1 + W_q)}{(\frac{\lambda t_0 + 1}{\lambda})e^{-\lambda t_0} + t_w} \tag{6.17}$$

Finally, computing the ratio between the energy consumed during idle time and the energy of processing as it was done in [Pra12a], it is obtained:

$$\frac{E_w}{E_p} = \frac{W_2(1 - \overline{\rho})(1 - e^{-\lambda t_0})}{(W_3 \overline{\rho})} + \frac{(W_a(1 - \overline{\rho})e^{-\lambda t_0})}{(W_3 \overline{\rho})} \tag{6.18}$$

Where:

$$W_a = \frac{W_0(\lambda t_0 + 1)e^{-\lambda t_0}}{(\lambda t_0 + 1)e^{-\lambda t_0} + \lambda t_w} + \frac{(\lambda W_1 + W_q)t_w)}{(\lambda t_0 + 1)e^{-\lambda t_0} + \lambda t_w} \tag{6.19}$$

The optimization objective of EC1 is limited to the energy consumption, while the energy ratio previously developed can express a cost due to the introduction of W_q. During the comparision of the two approaches, the waiting power (W_q) will be equal to zero with the aim of including only costs related with energy and keep a similar context.

It is important to remark that in the case of a t_w equal to zero , and W_0 different from zero, equations 6.6 and 6.18 are identical.

6.2.3 Comparison between switch ***off*** strategy for stochastic arrival time and EC1

6.2.3.1 Influence of the additional parametes (t_w and W_q) in the energy ratio

Based on the parameters presented in table 6.4, and using the equation 6.6 a ratio of energies of 13% is obtained when using EC1 policy.

$$\frac{E_w}{E_p} = \frac{1000(1-0.5)(1-e^{-(0.1)(2.5)})}{(2140)(0.5)} + \frac{100(1-0.5)e^{-(0.1)(2.5)}}{2140(0.5)} = 0.13 \qquad (6.20)$$

Parameter	Value
λ	0.1 jobs/s
μ	0.2 jobs/s
τ	2.5 s
W_p	2140 watts
W_1	1000 watts
W_0	100 watts
T	2000 s

Table 6.4: Parameters used in experiment 1

The introduction of the warm up time affects the utilization of the system, influencing also the energy ratio. Figure 6.33 presents the results of the change in the energy ratio due to a variation in the warm up time.

This behavior is consistent with the fact that with a greater amount of time invested in the warm up phase, the machine will spend more time on the non-production states, diminishing the utilization and generating an increase of the ratio of energy as was shown in figure 6.33.

Focusing now on the analysis of the waiting power (W_q), it can be appreciated on figure 6.34 that, like the warm up time, influences the energy ratio. The behavior of this energy ratio (increasing as Wq increases) is coherent with the fact that if an additional power is considered for having the piece waiting to be machined while the warm up process is taking place, the energy that is being wasted in a non-machining process increases. It has to be emphasized that the increase of the energy ratio is not in the same proportion as for the warm up time as was appreciated in figure 6.34.

In order to clarify the difference of proportions in which the energy ratio is being affected by W_q and t_w, a comparison between these values is presented in figure 6.35. In this graph an almost linear dependence is found, counting for the fact that the influence on the change of the energy ratio is minimal, but still exists, and will also depend on the warm up time. This behavior is consistent with equation 6.19, since this power is multiplied only by the warm up time, representing that W_q might only influence the energy ratio if a piece arrives during a warm up phase, otherwise even if there is a high value for this power, it will not affect the energy ratio since there is no piece waiting.

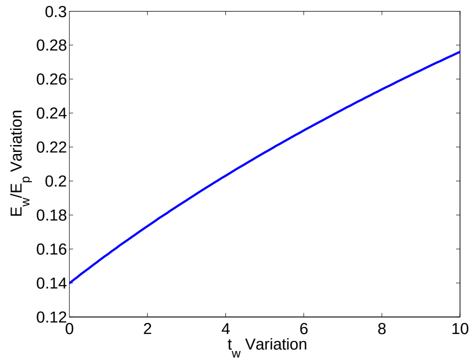


FIGURE 6.33: Variation of energy ratio with respect to t_w

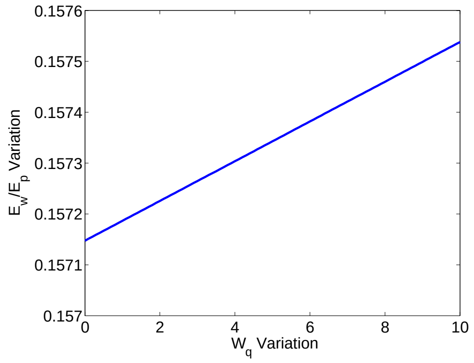


FIGURE 6.34: Variation of energy ratio with respect to W_q

Finally a representation of the impact of the energy ratio with respect to the variation of t_w and W_q is presented in figure 6.36, in which a high variation of the energy ratio is presented with a variation of the warm up time, but a not so noticeable variation of this ratio is presented with the variation of the the waiting power, as was explained in the previous paragraphs.

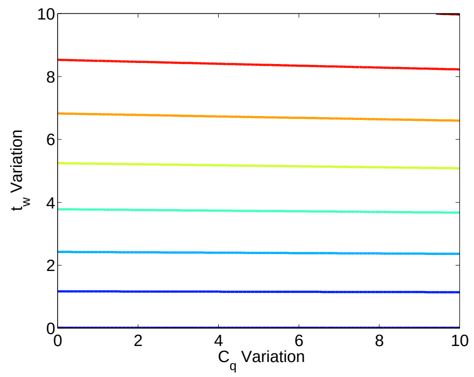


FIGURE 6.35: Variation of t_w with respect to W_q

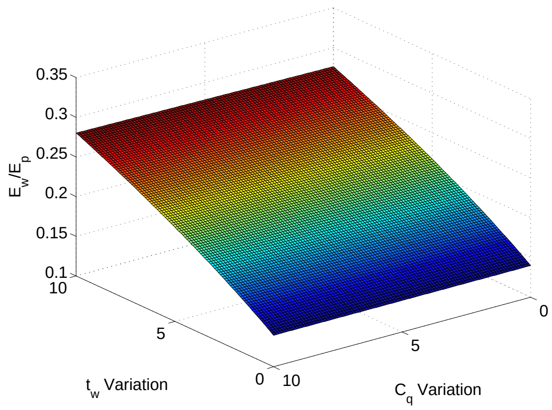


FIGURE 6.36: Impact of W_q and t_w on energy wasted

6.2.3.2 Energy control vs Energy minimization

Analyzing again the impact of utilization and idle time threshold on energy wasted as in figure 6.31, it will be shown the impact of changing the values of warm up power and time in the energy ratio.

In this analysis the values that will be kept as constant are related with the ones used in EC1 and are shown in table 6.5.

Parameter	Value
W_0	0
W_2	W_h=W_p
W_3	W_p
W_q	0

TABLE 6.5: Parameters used in experiment 2

- Initially setting $t_w = 2$ and $W_1 = 0.1W_3$, which are small values, the result obtained are shown in figure 6.37.

  In this case, the two energy ratios (EC1 and switch *off* strategy for stochastic arriva) have similar behaviors since the warm up time and the power associated with this phase are small enough that have low influence in the result. It can be seen that low values of the energy ratios are obtained at even at high vales of t_0, but for the utilization levels in which this policy has the largest impact (ρ from 0.4 to 0.7 approximately), the smallest ratio is obtained when the machine is turned *off* at zero time, as can be seen in figure 6.38. Within this case, in an utilization equal to 70%, the energy ratio at zero time corresponds to 2.2%, while the energy ratio at $t_0 = 2$ is of 5%.

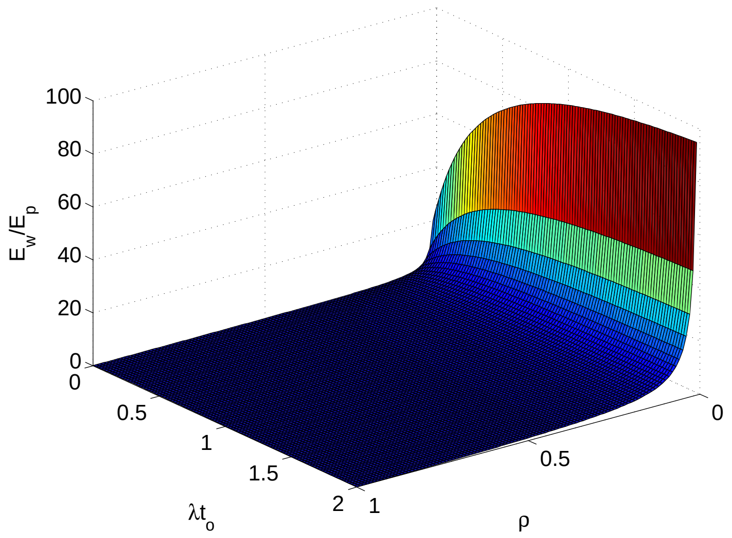


FIGURE 6.37: Influence of small t_w and W_q on energy wasted

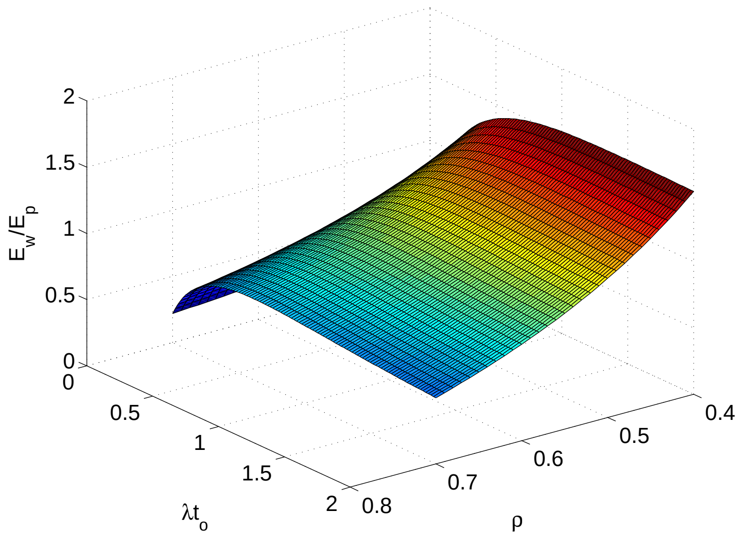


FIGURE 6.38: Influence of small t_w and W_q on energy wasted at specific ρ

Introducing the same values in the switch *off* startegy developed in this thesis, the result shows that the minimization of energy is obtained if the machine is switched *off* at $t_o = 0$, which is consistent with the previous analysis. This result is shown in figure 6.39 and is also consistent with the equation 5.39 developed for this type of policy.

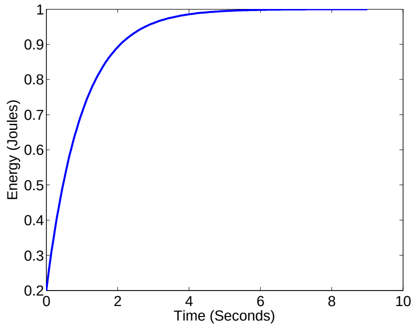


FIGURE 6.39: Result of the switch *off* strategy for stochastic arrival time with $t_w = 2$ and $W_1 = 0.1$

- Fixing the value of t_w as in the previous case, and increasing W_1 to $10W_3$ it can be appreciated in figure 6.40 that the shape of the energy ratio function drastically changes and even in some values of utilization, no energy saving is achieved.

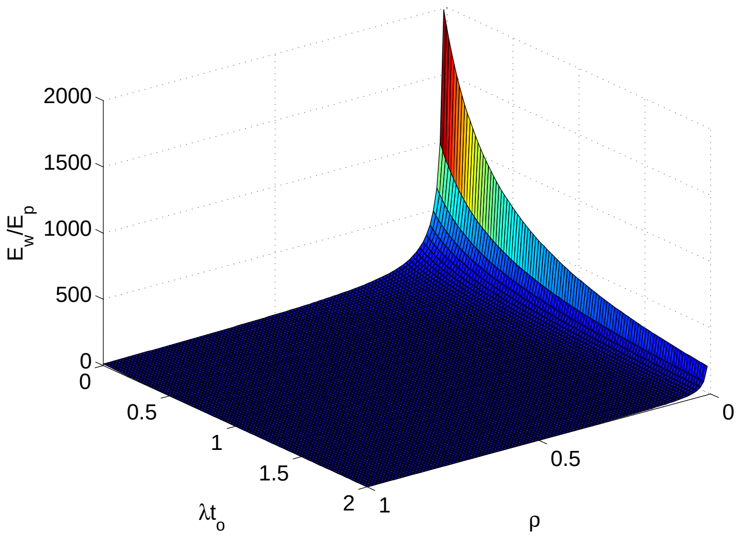


FIGURE 6.40: Influence of larger W_q on energy wasted

To be able to better acknowledge the behavior of this energy function, again focusing on the small portion of ρ which concern this policy, it can be seen that contrary to what was shown with an smaller value of W_1, the largest energy saving potential increases with t_0, as can be seen in figure 6.41.

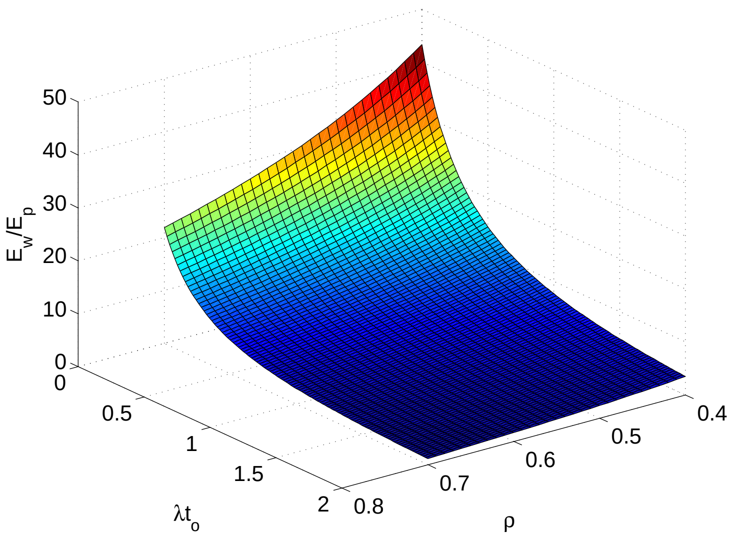


FIGURE 6.41: Influence of larger W_q on energy wasted at specific ρ

Comparing again with the approach used in this work to find the optimal time, the results obtained are consistent, since it implies that the optimal time to switch *off* the machine, in order to minimize energy, tends to infinite. This result can be seen in figure 6.42.

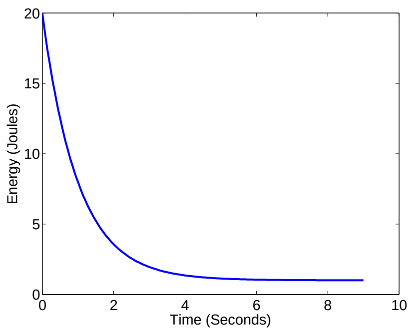


FIGURE 6.42: Result of the switch *off* strategy for stochastic arrival time with $t_w = 2$ and $W_1 = 10$

- Finally, keeping the warm up power in a small value ($W_1 = 0.1W_3$) and increasing the warm up time to 15 figure 6.43 is obtained. Analyzing again for the portion of ρ in which this policy is focused, similar results to the one in which the power was varied are obtained. This results show that the greater energy saving is obtained at larger values of t_o.

  Again the results are consistent with the ones of the switch *off* strategy for stochastic arrival time, obtained by using the MATLAB® algorithm.

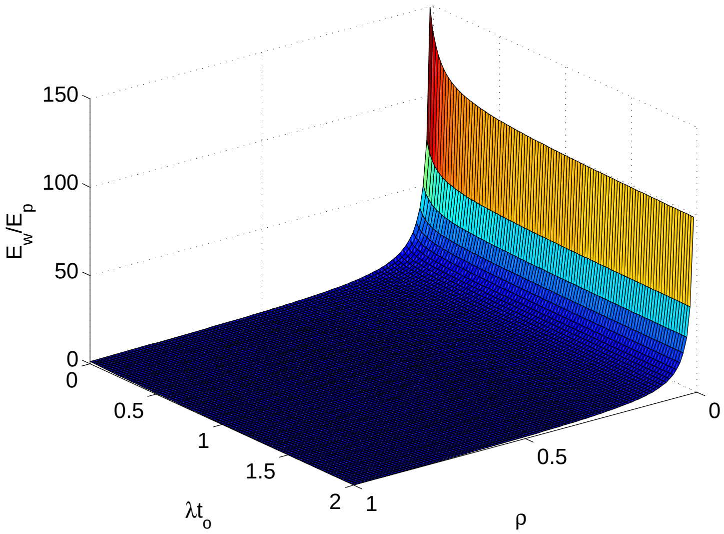


FIGURE 6.43: Influence of larger t_w on energy wasted

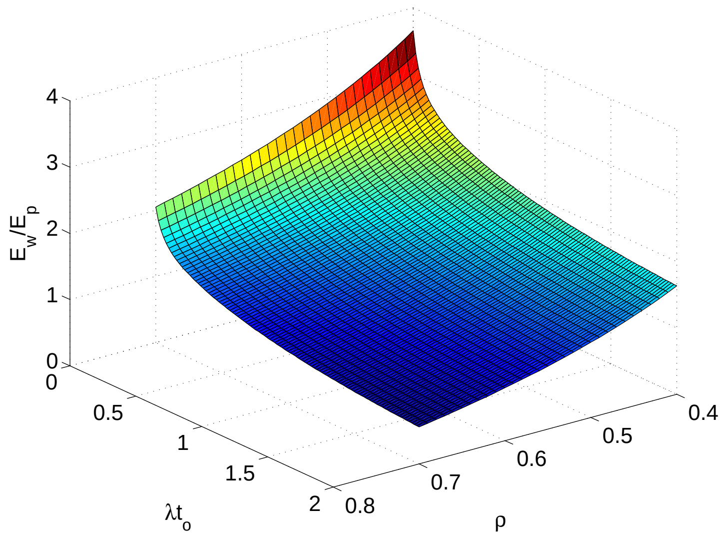


FIGURE 6.44: Influence of larger t_w on energy wasted at specific ρ

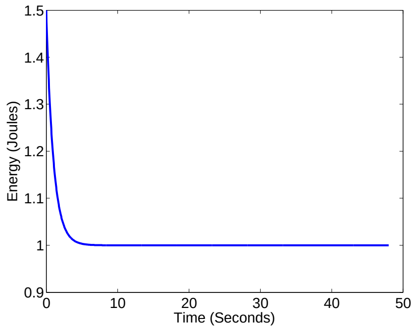


FIGURE 6.45: Result of the switch *off* strategy for stochastic arrival time with $t_w = 15$ and $W_1 = 0.1$

6.2.3.3 Energy losses related with use of non-optimal policies

As explained in [Pra12a], the energetic model developed "can be potentially useful in practice to determine t_o for example to meet energy waste reduction targets", hence the obtained value does not necessarily correspond to the optimal one for an energy minimization objective.

Let the target energy waste limit (E_w/E_p) be denoted by α. Replacing this parameter in equation 6.6 it can be obtained that:

$$e^{-\lambda t_0} = \frac{(\alpha W_p + W_h)\rho - W_h}{(1-\rho)(W_l - W_h)} \tag{6.21}$$

And the value of the optimal time to meet such a limit will correspond to:

$$t_0 = \frac{Ln\left(\frac{-(W_l - W_h)(\rho-1)}{(\alpha W_p + W_h)\rho - W_h}\right)}{\lambda} \tag{6.22}$$

From equation 6.5 the energy consumed during the idle time (non-value adding times) correspond to:

$$E_w = (W_h(1-\rho)(1-e^{-\lambda t_0})) + W_l(1-\rho)e^{-\lambda t_0})T \tag{6.23}$$

Replacing the value of t_o on equation 6.23 for the one obtained in equation 6.22 as a function of the target energy waste limit α and the values of utilization and power, the energy wasted is expressed as:

$$E_w(\alpha) = \Bigg((W_h(1-\rho)\Bigg(1 - \frac{(\alpha W_p + W_h)\rho - W_h}{(1-\rho)(W_l - W_h)}\Bigg) + W_l(1-\rho)\Bigg(\frac{(\alpha W_p + W_h)\rho - W_h}{(1-\rho)(W_l - W_h)}\Bigg)\Bigg)T \tag{6.24}$$

Finally, by making some computations, the total wasted energy as a function of α is

$$E_w(\alpha) = (\alpha W_p \rho)T \tag{6.25}$$

When the objective is energy minimization, and assuming that the low energy consumption state (W_l) consumes in fact less energy than the nominal one (for the switch *off* strategy for stochastic arrival time , $W_a < W_2$) and that the warm up time is sufficiently short, it was demonstrated that the optimal time to change the state corresponds to $t_o^{opt} = 0$.

With this consideration in mind, and replacing t_o by zero in equation 6.23, the energy waste of the optimal scenario correspond to:

$$E_{wt_0=0} = (W_l(1-\rho))T \tag{6.26}$$

The energy losses related with the utilization of a non-optimal policy can be characterized as a ratio of the energy consumed during idle when using a t_o computed with the aim of meeting energy waste reduction targets, to the energy consumed during idle when using the optimal time that minimizes the energy consumed during non-value adding tasks. It can be seen that the losses increases proportionally to the target energy waste limit (α).

$$\frac{E_w(\alpha)}{E_{wt_0=0}} = \frac{\alpha W_p \rho}{W_l(1-\rho)} \tag{6.27}$$

To better understand the energy losses generated when using an energy control approach to decide t_o instead of an energy minimization approach, the absolute difference of energy consumption given by these two approaches is presented in equation 6.28.

$$E_w(\alpha) - E_{wt_0=0} = (\rho(\alpha W_p + W_l) - W_l)T \tag{6.28}$$

Chapter 7

Conclusions and Future Work

The description of an energetic model of the machine tool based on single energetic models of its components is a useful tool that allows to identify easily not only the energy consumption of the entire machine, but also a discrete energetic state in which the machine tool can be located, using as reference the states of the single components and events connected with the production process belonging to the part program or external ones that might be controlled by the user.

The modular approach with which this model was developed permits its application to different machines (even if they are not machine tools), following a similar methodology to the one of chapter 4 and taking important advantage of the operations belonging to the automata language.

Energy savings in discrete production systems with machine tools can be obtained by the use of switching strategies since the energy consumption during the idle period is relatively large and the use of an accurate policy might achieve a proper tradeoff between energy savings and production loses.

A proper design of the switching strategies can be obtained with the correct utilization of the energetic states of the machine tool and by defining relevant characteristics, of the system and the machine, such as information regarding the level at which the control is aimed to be applied and information on the piece arrival or utilization of the machine.

In this thesis 3 different policies where developed, varying the information on the piece arrival from deterministic to stochastic, and the results obtained consist in optimal times for either switching *on* or *off* the machine in such a way that the energy consumption during non-value adding tasks (unproductive periods) was minimized. The policies presented reasonable numerical results when they were submitted to variations in the different input parameters that influence the decision making process and that in this work correspond to power demand of the different states and warm up time.

The policies were evaluated using two types of probabilistic distributions: exponential and weibull. The results obtained when using an exponential distribution consisted on optimal times (either to switch *of* or switch *on*) equal to zero or infinite, that are aligned with the memory less property of this type of inter-arrival probability distribution. Otherwise, when using a weibull distribution optimal times belonging to the interval $(0,\infty)$ were found, but also depending on the proportions between power demand of the different states, similar results to the exponential distribution were obtained.

The policies currently designed are based in energetic states common to most of the machine tools used in the actual market, so its use should be easy, extensive and not so upsetting in terms of physical modifications, however as a future work it is possible to explore the inclusion of new states that allow better control of the machine whose addition will require changes in the design and construction process of new machine tools, or modification in the ones that are actually operating.

Since the mathematical formulation of the control problems and its respective policies was made in a general way, the minimizing objective, which for this work corresponds to energy, can be changed to other indicators such as costs of the process.

As a primary future work it is suggested to implement these control policies in areal application to determine its real impact in the machine, taking into consideration not only energy savings, but also different indicators such as machine utilization, product quality, among others.

Another possibility to improve the current policies corresponds to de development of the controls strategies based on different input data and mixing in one policy the switch *on* and switch *off* strategy that in this work were analyzed separately.

Further extensions can be included changing the level of control, in such a way that different policies are developed for each component of the machine with the objective of gaining controllability and creating greater impact in the components that influence largely the energy consumption of the machine tool.

Finally, similar control policies should be developed, including initially the buffers that interact with the machine, going through the control of a set of machines, until arriving to control an entire production system in such a way that the energy savings can increase.

Appendix A

MATLAB Code

This appendix encloses comments and a concise explanation of the MATLAB® routine employed for obtaining the results presented in chapter 6.

The first part briefly explains the interface created for generating the data and its implications, afterwards an explanation on the declared functions is presented, in order to understand its later use in the final part, where the proper subroutine is presented linking the interface and functions with the algorithm for obtaining results.

The graphical interface allows the user initially to select which strategy is going to be analyzed (Switch On or Switch Off). The parameters that should be introduced in order to execute the analysis are grouped by power parameters (different powers affecting the analysis), time parameters (warm up time) and the arrival information that changes depending on the probability distribution.Tthe selection of the last parameters varies depending on a weibull or exponential distribution.

With the "Compute" button the data graph of energy vs time is presented and the minimum expected power and the optimal time are shown.

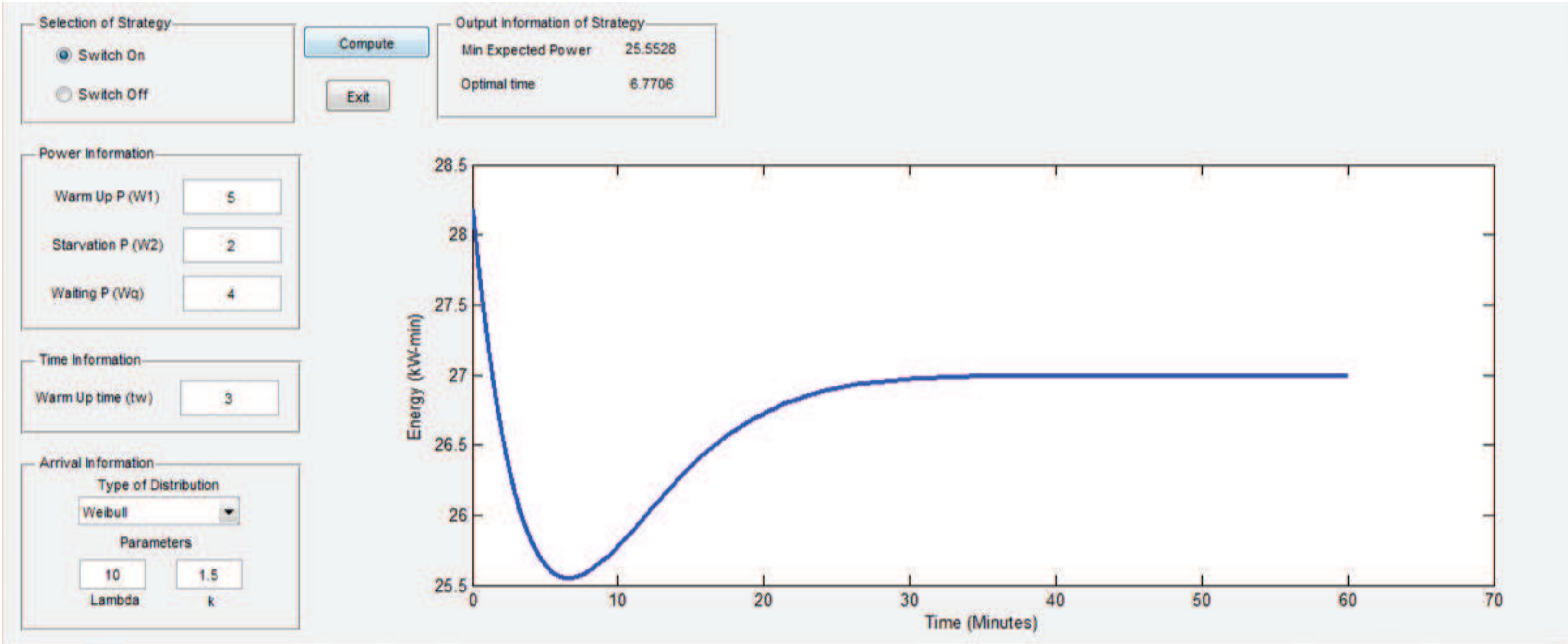


FIGURE A.1: Graphic user interface

The functions employed (expo, expox, weib,weibx) in order to facilitate the comprehension and development of the code are related with the exponential and weibull probability distributions and relate the following equations respecrtively: 5.19 and 6.1.

The last function employed is “integral” that is predefined by MATLAB®. This function approximates the integral of a on determined limits using global adaptive quadrature and default error tolerances.

The following lines show the main subroutine employed:

```
clear all
msg = {'processing.................'}; %Message for busy during
     % integration
        hmsg = msgbox(msg);

% Definition of the input data and the corresponding handle for
% interacting with the graphical interface interface
auxdis=findobj('Tag', 'Distribution');
auxW1=findobj('Tag','W1');
auxW2=findobj('Tag','W2');
auxWq=findobj('Tag','Wq');
auxtwup=findobj('Tag','tw');
auxk=findobj('Tag','k');
auxl=findobj('Tag','Lambda');
auxcm=findobj('Tag', 'mincost');
auxot=findobj('Tag', 'optimalt');
auxSOn=findobj('Tag', 'SwitchOn');
auxSOff=findobj('Tag', 'SwitchOff');

SOn=get(auxSOn,'Value');
SOff=get(auxSOff,'Value');
distribution=get(auxdis,'Value');
W1=str2num(get(auxW1,'String'));
W2=str2num(get(auxW2,'String'));
Wq=str2num(get(auxWq,'String'));
twup=str2num(get(auxtwup,'String'));
k=str2num(get(auxk,'String'));
lambda=str2num(get(auxl,'String'));


if (SOn == 1) %Decision of Strategy to analyze
  %1= Switch On, 0 = Switch Off
```

```
switch distribution

        case 1 % Analysis of Switch On strategy with
         %exponential probability distribution

            mean=1/lambda; %Computation of parameters required for
%the exponential distribution
            rate=mean/20;
            n=(mean+twup)*5;

            t0=[0:rate:n]; %Limit on time of the analysis

            for i=1:length(t0) %Computation of energy functions by
%numerical integrating using functions:
%"integral","expo"and "expox"

                i11=integral(@(x)expo(x,lambda),0,t0(i));
                i21=integral(@(x)expo(x,lambda),t0(i),t0(i)+twup);
                i22=integral(@(x)expox(x,lambda),t0(i),t0(i)+twup);
                i31=integral(@(x)expo(x,lambda),t0(i)+twup, Inf);
                i32=integral(@(x)expox(x,lambda),t0(i)+twup, Inf);

                g1=(W1+Wq)*twup*i11;
                g2=(((W1+Wq)*twup+Wq*t0(i))*i21)-(Wq*i22);
                g3=(((W1-W2)*twup-W2*t0(i))*i31)+(W2*i32);

                gtotal(i)=g1+g2+g3; %Total energy

            end

        case 2 %Analysis of Switch On strategy with weiblull
%probability distribution

            mean=lambda*gamma(1+1/k); %Computation of parameters
%required for the weibull distribution
            rate=mean/20;
            n=(mean+twup)*5;

            t0=[0:rate:n];%Limit on time of the analysis

            for i=1:length(t0)%Computation of energy functions by
%numerical integrating using
%functions: "integral","weib"and "weibx"
```

```
                i11=integral(@(x)weib(x,lambda,k),0,t0(i));
                i21=integral(@(x)weib(x,lambda,k),t0(i),t0(i)+twup);
                i22=integral(@(x)weibx(x,lambda,k),t0(i),t0(i)+twup);
                i31=integral(@(x)weib(x,lambda,k),t0(i)+twup, Inf);
                i32=integral(@(x)weibx(x,lambda,k),t0(i)+twup, Inf);

                g1=(W1+Wq)*twup*i11;
                g2=(((W1+Wq)*twup+Wq*t0(i))*i21)-(Wq*i22);
                g3=(((W1-W2)*twup-W2*t0(i))*i31)+(W2*i32);

                gtotal(i)=g1+g2+g3;%Total energy

            end

    end
else


    switch distribution

        case 1 % Analysis of Switch Off strategy with exponential
%probability distribution

            mean=1/lambda; %Computation of parameters required
%for the exponential distribution
            rate=mean/20;
            n=(mean+twup)*5;

            t0=[0:rate:n];%Limit on time of the analysis

            for i=1:length(t0) %Computation of energy functions by
%numerical integrating using functions:
% "integral","expo"and "expox"

                i11=integral(@(x)expox(x,lambda),0,t0(i));
                i21=integral(@(x)expo(x,lambda),t0(i),Inf);

                g1=W2*i11;
                g2=((W1+Wq)*twup+W2*t0(i))*i21;

                gtotal(i)=g1+g2;

            end
```

```
        case 2 % Analysis of Switch Off strategy with weibull
% probability distribution

            mean=lambda*gamma(1+1/k);%Computation of parameters
%required for the weibull distribution
            rate=mean/20;
            n=(mean+twup)*5;

            t0=[0:rate:n];%Limit on time of the analysis

            for i=1:length(t0) %Computation of energy functions by
%numerical integrating
%using functions: "integral","weib"and "weibx"

                i11=integral(@(x)weibx(x,lambda,k),0,t0(i));
                i21=integral(@(x)weib(x,lambda,k),t0(i),Inf);

                g1=W2*i11;
                g2=((W1+Wq)*twup+W2*t0(i))*i21;

                gtotal(i)=g1+g2;%Total energy

            end

    end

end
delete(hmsg) %End of the integrating process (erase the busy message)


mincost=min(gtotal); %Computation of the minimun energy for Switch on
%strategy
index=find(gtotal== mincost); %Search for the time where the minimun
%energy is located
if length(t0)==index %If the minimun found is the limit of the
%analysys,then the minimun
% time is infinite
    optimalt=Inf;
else
    optimalt=t0(index);%If an optimal time is found it retreives
%its value
end
```

```
set(auxcm, 'String',num2str(mincost)); %Display of minimun values
% on the graphical interface
set(auxot, 'String',num2str(optimalt));

set(auxcm, 'String',num2str(mincost));
set(auxot, 'String',num2str(optimalt));

subplot('Position',[0.3 0.1 0.65 0.65]); %Plot of the total energy
%during the analysis as a
%function of time
figura=plot(t0,gtotal, 'Linewidth', 2.5);
xlabel('Time (Minutes)')
ylabel('Energy (kW-min)')
%
```

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