Machine Tool Utilisation Phase: Costs and Environmental Impacts with a Life Cycle View

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Abstract

The main objective of this project is to investigate the costs and environmental impacts generated at the use phase of the machine tools. Machine tools are essential elements for the manufacturing sector.

Cost estimation model has been developed based on previous studies. The cost model has 6 main groups: Energy, consumables, resources, waste, space and labour costs parameters. The importance of the use phase in the whole life cycle is underlined. This is related to the high energy consumptions of the machine. Therefore, special attention has been paid to the electricity consumption, developing an accurate model with a life cycle view: Apart from cutting energy, auxiliary machinery and stand-by situations has been defined in this model.

The environmental impact analysis has been divided into material, use, disposal and transport categories, with special focus on consumables (cutting fluids, filters, cutting tools and lubricant oil) and energy consumption for the using phase.

A LCA analysis in EcoScan software has been carried out with a real example: The FS-8000 milling machine. The analysis has confirmed that impacts related to the high electricity consumption during using phase are the most important burdens with almost 70% of the total impact. This is follow by hazardous oil disposal (13.9%), cutting tools (7.7%) and transport (6.6%).

Last, a sensitivity study for environmental impacts has been conducted. The correlations between parameters have revealed that although the impact ranking determined from the EcoScan analysis is appropriate, there are some deviations when parameter variability is taken into account. Therefore, the report suggest conducting a sensitivity study along with the LCA for more precise results.

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1. INTRODUCTION

Manufacturing technology has been always evolving to achieve high performance at low cost. The reduction of environmental burdens is, however, required in recent years. Environmental factors are becoming an emerging dimension in manufacturing processes due to increasingly stringent regulations on health and safety, the importance of manufacturing wastes on the product life cycle, emerging international standards on environmental performance, and a growing consumer preference for green products. Thus, it is believed that environmental issues will be treated the same way as manufacturing cost in near future. Actually, DfE (Design for environment) and LCA (Life Cycle Assessment) tools are often used in manufacturing fields.

This report aims to investigate both cost and environmental impacts of the machine tools, with special focus on the using phase of the machine. Indeed, it should be underlined that costs and environmental impacts are related issues.

1.1. Manufacturing and machining

Within manufacturing processes, machining is widely used. Machining can be defined as the process of removing material from a workpiece in the form of chips. The term ‘metal cutting’ is used when the removal material is metallic.

In terms of costs, machining is the most important of the manufacturing processes. Most machining has very low set-up cost compared to forming, moulding, and casting processes. However, machining is much more expensive for high volumes. Machining is necessary where tight tolerances on dimensions and finishes are required.

For the traditional machining, the activities can be divided into drilling, turning, milling and grinding categories (Figure 1 to Figure 4 respectively):

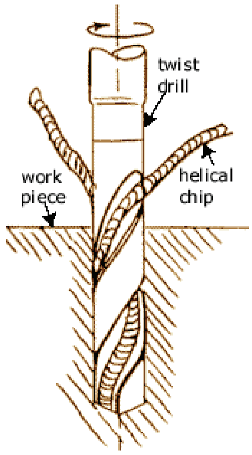


Figure 1: Drilling

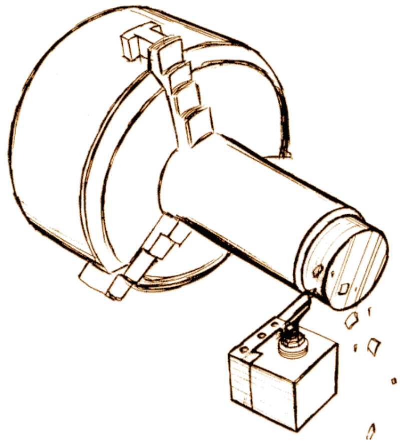


Figure 2: Turning

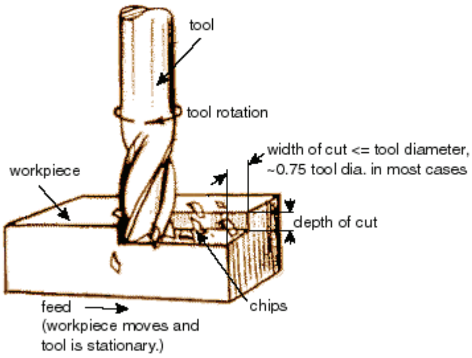


Figure 3: Milling

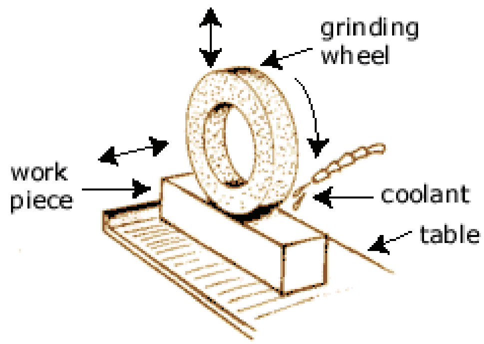


Figure 4: Grinding

Machining is conducted by the machine tools. Examples of these machines are illustrated in Figure 5, Figure 6 and Figure 7. It can be assumed that in general these machines are quite similar, since they are built with the same material type (mainly grey cast and steel), they have the same operation basis, and they have some common consumables, such as lubricants, cutting tools or coolant fluids.

Figure 5: Milling machine

Figure 6: Turning machine

Figure 7: Centerless grinding machine

1.2. State of art

A great deal of researches has been carried out in the field of machining, specially focused on process-level activities and improvements. These improvements have been pursued in order to achieve high productivity, high quality and low cost. However, as mentioned before, environmental factors are also emerging in machining studies.

Life cycle cost (LCC) thinking is becoming popular in the cost analysis field. In short, the aim of LCC is to avoid the iceberg effect (see Figure 8) when purchasing a product or service. At present, the Ford Company has carried out a LCC methodology called FRED (Facility Reliability Evaluation Development process). Providers of the Ford Company have to fulfil a form with this methodology before selling a product. Similarly, TCO tool (Total cost of ownership), is also based on LCC analysis and is used by companies such as Chrysler-Daimler.

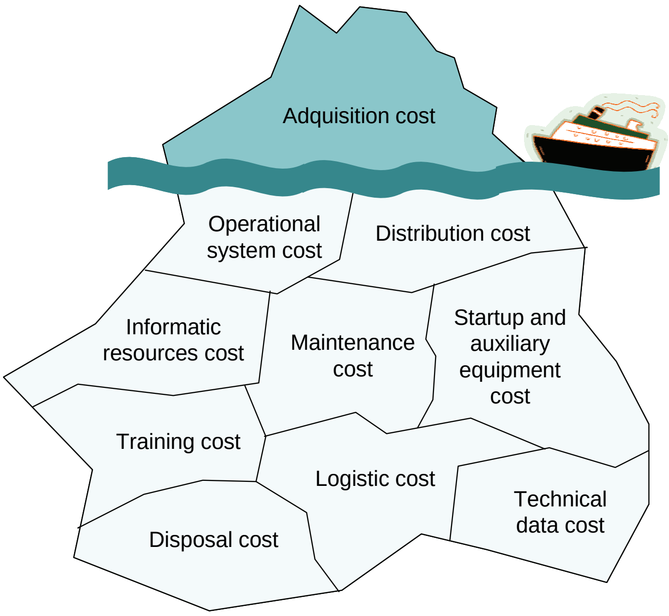


Figure 8: Total cost visibility problem, the iceberg model

Prolima is the name of a European project [27] that studies the lifecycle view of the machine tools, integrating information on Life Cycle Cost (LCC), Life Cycle Assessment (LCA) and Reliability, Availability, Maintainability and Safety (RAMS). Annex 4 shows LCC structure proposed by the Prolima project. Some reports have already been presented within this project about LCC issues [12].

It is stated that while there are some general equations for machining economics, costs have much in common with environmental issues. For instance, a higher electrical consumption leads to an increase in costs and also in the environmental impacts related to electricity production.

Various studies have been conducted to try to link machining and environmental impacts. The first papers highlighting the importance of this relationship appeared at the beginning of the 90' [7]. Since then, new terms such as 'Green machining', 'Environmental benign manufacturing', and 'Environmentally conscious manufacturing' have appeared.

For instance, founded on the first studies, a more comprehensive system analysis of machining, which addresses energy utilization and mass flow, has been completed [4,5]. Feature-based process planning studies [6,8], state that environmental impacts of a machine tool are dependent on machined part geometry, which may increase complexity. One of these studies includes an environmental impact analysis based on a health hazard scoring index [6], a first approach to evaluate the impacts. On the other hand, a newer algorithm to calculate the machining environmental burden has been examined [2]. This algorithm evaluates the global warming impact by converting the values of electricity, coolant and cutting tools consumptions and metal chips generation into CO_2 emissions.

Energy consumption in machining is an important parameter, if not the most important one. Thus, various researches have taken into account the significant influence of auxiliary machinery in electricity consumption [1,9,11]. There are some newer approaches based on exergy analysis for describing electric energy consumption in machines as well [3].

Apart from research studies, there are different pollution prevention guides containing information about consumables for machine tools, such as cooling fluids, lubricants or filters [14,16,19]. Cleaning systems and health problems are also included.

In addition to this, uncertainty has been also mentioned together with environmental impact analysis [8] and with both environmental and cost analysis as well [10]. This last work applies the Monte Carlo simulation for the uncertainty study. Both uncertainty and sensitivity issues has been examined by different researchers. Uncertainty types and some estimation methods are mentioned in various investigations [23]. More specific cases, such as uncertainties in LCA, have been studied as well [22,24].

Besides, some reports have applied ecoindicator methodology for the environmental analysis of the machine tool [10]. Ecoindicators are an easy way to quantify and prioritise environmental impacts and are implemented in different life cycle assessment softwares.

Finally, some researches are currently working on the definition and improvements towards the machine tool of the future, machines that include environmental issues [20,21].

1.3. Objectives

The aim of this study is to investigate the costs and environmental impacts generated at the use phase of the machine tools, which indeed is the most important stage of all. Thus, the project has been divided into two main parts:

- Cost estimation
- Environmental impact classification and analysis.

The manufacturing costs at using phase has been studied based on Life Cycle Cost (LCC) methodology, while for environmental analysis Life Cycle Assessment (LCA) methodology has been applied.

Apart from the theoretical assessment of manufacturing cost and environmental impacts for the using phase, a second objective of the project has been to conduct a LCA of a real machine. This LCA has studied the whole cycle of the machine, not only the use phase. LCA analysis has been conducted using EcoScan software, which has helped to identify the most problematic aspects of the machine.

The project has also aimed to deal with uncertainty issues. The third goal has been to conduct a sensitive study for the environmental impact analysis to find out parameters that can influence the results.

1.4. Methodology

This report has been written mainly based on scientific research articles, especially for the cost estimation category. The study has been complemented with some guides, in case of LCA methodology and environmental impact analysis, and on internet searching.

While the cost analysis has a theoretical approach, the environmental burden analysis has applied both theoretical and practical approach, with a real example.

In both cases the study has tried follow the life cycle thinking, which enhances the analysis.

2. COST ANALYSIS IN MACHINING USE PHASE

Despite the fact that a machine tool has various stages, the use phase is considered the most important when it comes to costs. The reason is that, as shown in Figure 9, the use phase of a machine tool is far longer than other stages; Actually, it is known that the power consumption during all these operational years is the higher cost source of a machine tool.

A coffee machine, for instance, may have the same time distribution as in Figure 9; it can be working for 10 years in a kitchen. But, while a coffee machine will be used 2-3 times in a day, a machine tool may be running around 70% of the total time. For that reason, power consumption is so significant in machine tools.

On the other hand, and as it will be explained in following chapters, environmental impacts are also highly important in the using phase.

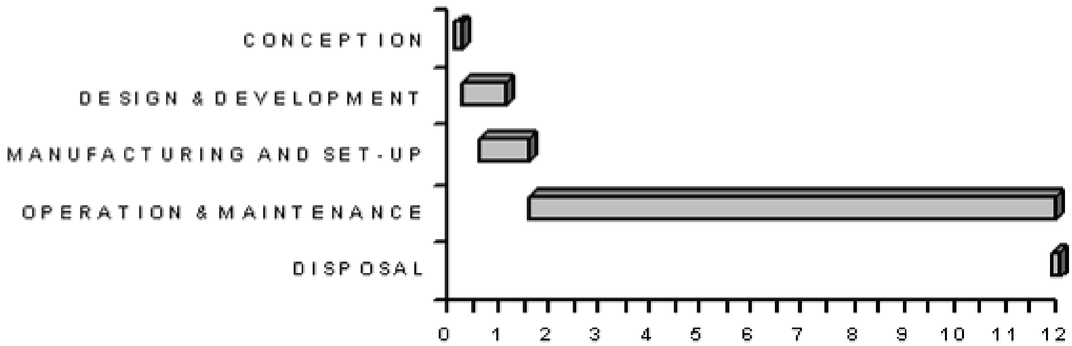


Figure 9: Machine Tool Life Phases, in years [12]

Currently, most companies use simple equations to define the costs related to machining. For instance, energy cost and material cost can be defined roughly as follows:

*Material cost = Material consumed * material cost*

*Power supply = Power consumed * Hourly cost*

However, and especially when it comes to energy, more accurate equations can be developed, and this results in a better knowledge about when, where and how the money is spent.

The aim of this cost analysis is to develop a model that represents the main costs that show up in the using phase of a machine tool, with a special focus on the electrical consumption.

2.1. System boundaries

First, system boundaries must be defined. Costs will be grouped into the following categories:

1. Energy supply.
2. Resources.
3. Consumables.

4. Waste handling.
5. Space.
6. Labour costs.

It is assumed that maintenance is not included in this study, only the operation costs. In other words, costs during the time that the machine is running.

Figure 10 and Figure 11 illustrate the system boundaries of the machine tool in the use phase:

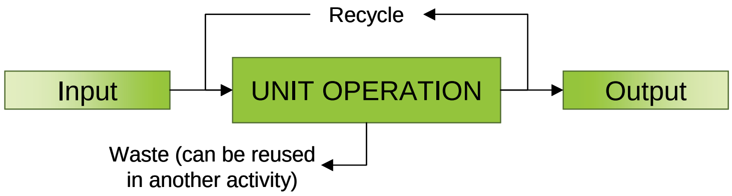


Figure 10: Input-process-output diagram

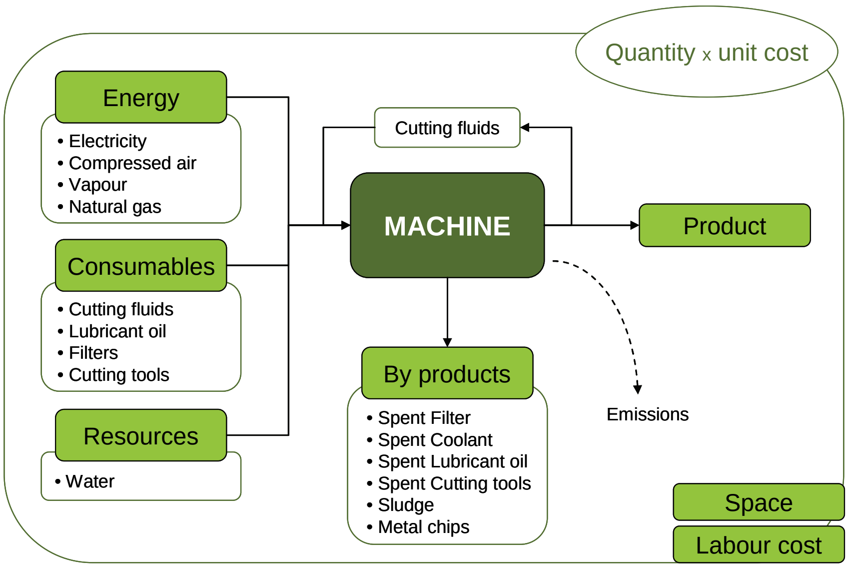


Figure 11: Detailed material balance diagram. Variables within the diagram must be quantified for cost calculations.

2.1.1. Functional unit

The cost model needs a functional unit, a reference unit to which the inputs and outputs can be related. In this case, 1000 hours of work is selected.

This functional unit, 1000 hours of work, refers to the working hours of the factory, which does not mean that the machine is running all that time. In other words, if the factory is running 8 hours per day, it is equivalent to 125 working days.

As mentioned before, maintenance work is not included within these 1000 hours. However, it should be underlined that maintenance costs can be significant, not only for the spare part cost, but also because during maintenance time the machine is not working (loss of production) and because of the labour cost of the worker that is fixing the machine. Many studies are trying to model the maintenance cost, for instance the prolima project [27], but it is actually quite complex.

Once the system boundaries, the cost groups and the functional unit are defined, the cost model and equations can be developed.

2.2. Electricity requirements in the using phase

As stated before, most of the costs from the material removal process stems from the energy use.

When estimating the energy requirements for the material removal, specific cutting energies are often used. Cutting energies for machining can depend on many factors, including material properties of the workpiece, presence of cutting fluids, sharpness of cutting tool, and process variables.

However, this cutting energy estimation is far from the total energy required in real production. In production machining, apart from cutting energy needs, additional energy must be provided to power auxiliary equipment, such as workpiece handling equipment, cutting fluid handling equipment, chip handling equipment, tool changers, computers, and lubrication systems. In short, auxiliary machinery is defined as the equipment that supports the main processing steps but is not directly involved in creating the part itself, so it is frequently overlooked.

Actually, some researches assure that “The energy requirement of the auxiliary equipment can far exceed the actual cutting energy requirements” [1], whereas others argue that it does not exceed, but is still significant. At present, the trend appears to be moving towards more efficient auxiliary equipment on one hand, but a bigger amount of this machinery on each machine on the other one. In brief, the energy cost model should include a detailed study of this kind of equipment.

For example, Figure 12 describes the energy breakdown of a milling machine taking into account primary and auxiliary equipment. 65,8% of the total energy requirements is used in cutting operations, while 34,2% is used in auxiliary or non-cutting operations:

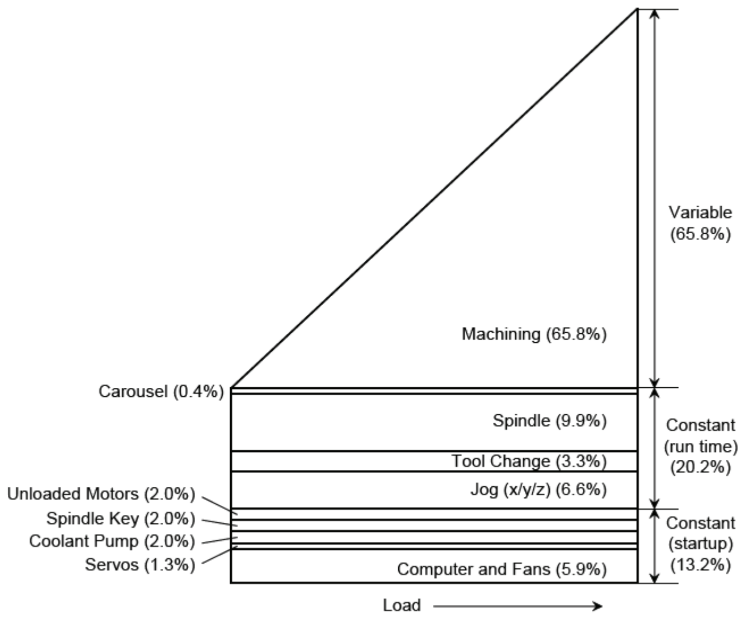


Figure 12: Energy breakdown for a 1998 automated milling machine. [1]

2.2.1. Electricity analysis assumptions

In order to achieve an accurate energy analysis, the model has to fulfil two main goals:

- To consider not only cutting energy but total energy requirements.
- To distinguish time stages during energy use phase (time breakdown).

It would be completely wrong to assume that the machine is cutting all the time that is running. There are other operations, like switching on the machine or translations in x/y/z, where much of the time is spent.

First, the operational time must be defined. This time corresponds to the time the machine is available, since the machine can be switched off for different reasons. It can be assumed that the machine will be operational the 90% of the time, and the rest 10% will be switched off. Next, within this 90%, it is important to identify three main stages:

- Constant start-up operations: This stage describes the stand-by or idle state of the machine. Following elements will be switched on and waiting:
  - Computers and fans
  - Servos
  - Coolant pump
  - Spindle key
  - Unloaded motors
- Run-time operations: The machine is active and moving, comprising operations such as:

- x/y/z axis translation
- Tool change
- Carousel rotation
- Spindle translation
- Chip conveyor

o Material removal operations: Energy involved in cutting; the tool is in contact with the part.

As shown in Figure 13, the power consumption during machining varies depending on these three main stages.

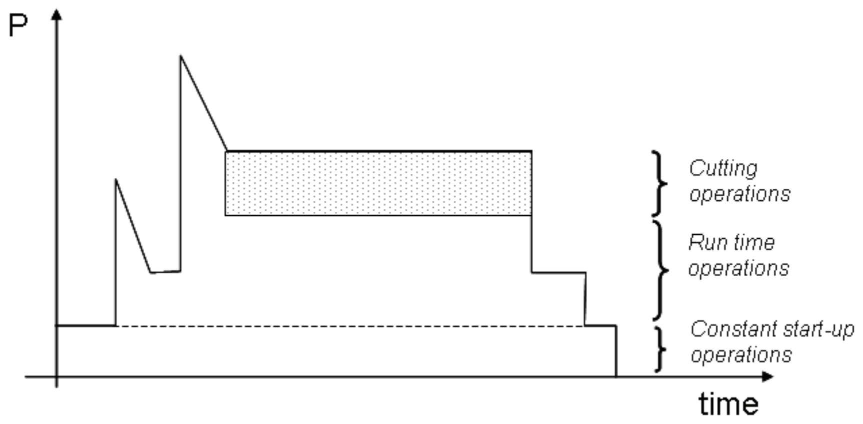


Figure 13: Power absorption during one machining operation. [11]

Besides, the importance of constant start-up and run-time operations can be seen in Figure 14, where cutting operation is only a small portion of the whole cycle of machining a part.

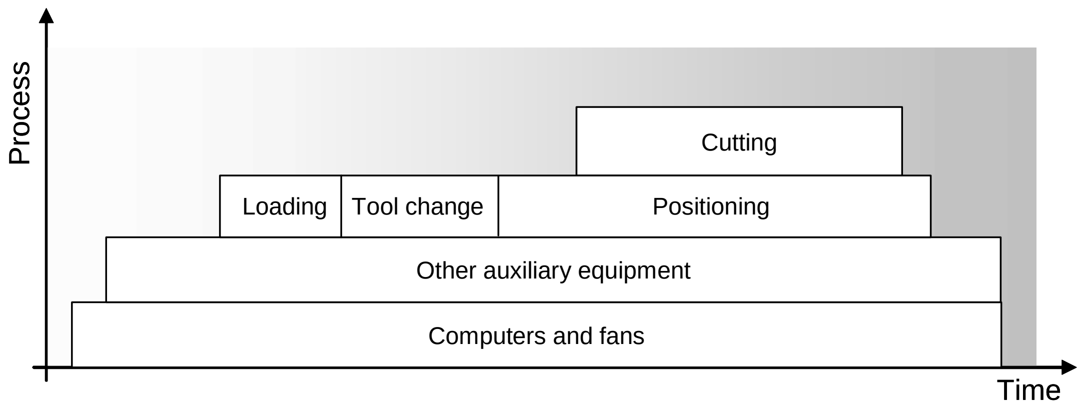


Figure 14: Step by step illustration of a machine tool going through the process of creating a part.

2.2.1.1. <u>Time breakdown assumptions</u>

In summary, in order to calculate start-up, runtime and cutting operation times, next variables must be known:

- Percentage of operational time, A% from the functional unit(1000 hours)

- Percentage of the machine hours spent idle (start-up), B%
- Percentage of the machine hours spent positioning (runtime operations, including activities such as loading and tool change), C%
- Percentage of the machine hours spent in cut, D%

Time percentages		Functional unit (1000h) divided in the three stages			
Operational time A%	90%	Operational hours	900 h	**T1**	1000h * 90%
Idle B%	15%	Start-up operations hours	900 h	**T2**	
Positioning C%	80%	Runtime operations hours	765 h	**T3**	900h * (100-15)%
Cutting D%	20%	Cutting operations hours	153 h	**T4**	765h * 20%

Table 1: Example of time distribution in machining activities for 1000 hours.

According to the step by step process shown in Figure 14, the example of time distribution on Table 1 will look as in Figure 15:

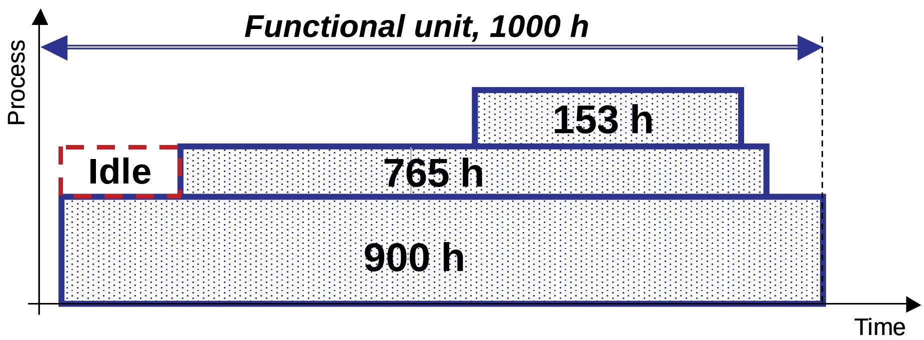


Figure 15: Example of the time distribution for the functional unit, based on Table 1.

For an accurate definition of cost equations in following chapters, next classification will be used:

- Operational time: = functional unit [T1]
- Start-up time: = functional unit [T2] = functional unit [T1]
- Runtime = functional unit [T3]
- Cutting time: = functional unit [T4]

In order to select the appropriate time percentage values for idle, positioning and cutting stages, there are four general machining scenarios:

- Highly-automated production machine.
- Modern smaller scale automated machine
- Older smaller scale automated machine
- Manual machine.

A highly-automated production machine, for example, involves a higher capital cost; therefore, in order to recover the investment, it will be rarely idle compared to modern automated machines (B%↓). For the same reason, positioning and loading operations are faster and equipments such as pallets can be used for this purpose, so more time is spent in cutting (D%↑, C%↓).

Furthermore, the machine age is also an important parameter. The auxiliary energy requirements of an old machine represent a much larger percentage of the total energy use, compared to a newer one.

2.2.1.2. Shared auxiliary machinery

In previous works, Kordonowy [9] developed a model with the above explained approach, dividing power consumptions in different stages. However, this methodology does not take into account the auxiliary equipment that can be shared with other machines in the workshop. Next, some examples of shared equipment are mentioned, which should be added to constant start-up operations:

- Air compressors
- Coolant system
- Material/waste handling
- Oil mist/dust collector
- Lubricant oil system

For instance, the cooling system that is circulating and filtering the cutting fluid used in cutting operations is frequently shared by multiple machines. Electrical energy of this cooling system associated to each machine tool is define in eq.(1). The meaning of the variable in all the equations are described in Annex 5.

$$E_{Cooling} = \frac{P_{Cooling}}{N^{o}_{Machines}} \cdot functional\_unit = \frac{P_{Cooling}}{N^{o}_{Machines}} \cdot 1000h \quad [kWh] \tag{1}$$

2.2.2. Electricity analysis model

The most time demanding task in this methodology is to measure the power requirements on each stage. For accurate results experimental measure is needed. Kordonowy [9] proposes to first measure the power consumption during the different activities of the start-up of the machine (first turning the computer and fans on and measure, then the servos in charge of manipulating the clamps and measure, next the spindle motor…). Afterwards, different run-time operations are measured (jogging x/y/z axis, changing the cutting tools, rotating the carousel…). Finally, the power is measured while machining at various material removal rates (MRR) and the most suitable is selected.

Briefly, for an accurate energy analysis, power consumption information should be collected as shown in Table 2. Once energy requirements for each stage are established, analysis for estimating the overall power consumption can be carried out. Finally, for cost estimation, overall power consumption (kWh) must be multiplied by energy hourly cost, eq.(2).

$$Energy\_cost = Overall\_Power\_Consumption[kWh] \cdot Euros/_{kWh} \quad \textbf{(2)}$$

	Process	Power consumption (W)	Nº machines
Shared	Coolant system		
	Air compressor		
	Mist/dust collector		
	Material/waste handling		
	Computer and Fans		
	Servos		
	Coolant pump		
	Spindle key		
	Unloaded motors		
	Jog (x/y/z axis translation)		
	Tool change		
	Spindle (z axis translation		
	Carousel rotation		
	Machining		

Table 2: Proposed datasheet for collecting energy breakdown information of a machine tool. It can vary depending on the machine type

Figure 16 represents an energy analysis model example. Energy requirements data has been taken from an example of Kordonowy [9] report. As a result, the total energy consumed in 1000 hours for this machine tool is 5721,12 kWh.

On the other hand, the energy consumption is distributed as follows: 56% for cutting energy, 25% for runtime operations and 19% for start-up. Real energy distribution is represented in Figure 17. Besides, 108 hours is spent idle, which multiplied by 1.2 kW makes 129.6 kWh, a 2.26% of the total. This idle energy is generally ignored.

The machine analysed in the example is 8 years old. It can be assumed that current machines will have higher auxiliary equipment requirements(kW). Next, shared equipment has not been considered in the example, which may have increased the idle and start-up power consumption. As a result, the idle power, although it is small in this example, can be easily higher.

In short, this energy analysis model has three strong points:

- Electricity consumption is often estimated by multiplying what it is called “real power” and “running time“. This energy cost model wants to demonstrate that there is not a constant “real power” value, and that for an accurate estimation this model is more appropriate.
- The model considers the idle power.
- It allows to conduct a thorough analysis about where and how the electricity is consumed. This is an important fact when energy optimisation measures wants to be implemented.

It has also an important weakness: To evaluate power consumption with this model is time consuming.

General information							
Machining scenario	Modern smaller scale automated machine						
Age	8 years						
Spindle Power	8,8 kW						
Functional unit - Number of working hours	1000 hours						
Energy Requirements							
Constant start-up operations(idle)	1,2 kW						
Run-time operations(positioning, loading,etc.)	1,8 kW						
Material removal operations (in cut)	5,8 kW						
Time breakdown in precentages							
Percentage of operational time, A%	90 %						
Percentage of the machine hours spent idle, B%	12 %						
Percentage of the machine hours spent positioning, C%	30 %						
Percentage of the machine hours spent in cut, D%	70 %						
Time breakdown in hours							
Operational time	900 hours	90	%	from		1000	h
Machine hours spent idle	108 hours	12	%	from		900	h
Active machine hours per 1000 hours of work	792 hours	900		hours	-	108	h
Machine hours spent positioning	237,6 hours	30	%	from		792	h
Machine hours spent in cut	554,4 hours	70	%	from		792	h
Energy use							
Constant start-up operations(idle)	1080 kWh	900	hours	*	1,2	kW	
Run-time operations(positioning, loading,etc.)	1425,6 kWh	792	hours	*	1,8	kW	
Material removal operations (in cut)	3215,52 kWh	554	hours	*	5,8	kW	
Total energy use per 1000 hours	5721,12 kWh						

Figure 16: Example of the energy analysis model of a modern small scale automated machine.

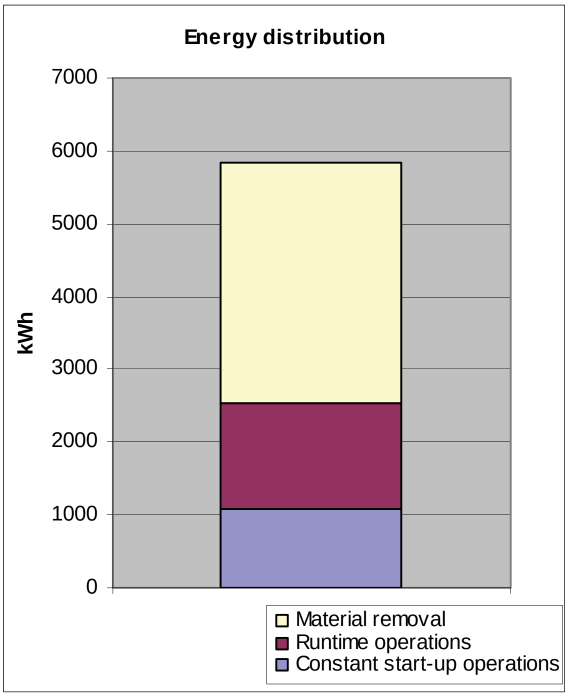


Figure 17: Real energy distribution for a modern small scale automated machine

2.2.3. Theoretical Power consumption

If accuracy wants to be obtained, experimental data should be used. However, if measures cannot be done onsite, which happens usually, there are some known equations for energy, or even some assumptions based on experience can be done.

- Estimation for cutting energy:

$$\left.\begin{aligned} P &= F_C \times v \\ MRR &= v \times \omega \times t_0 \end{aligned}\right\} \frac{P}{MRR} = \frac{F_C}{\omega \times t_0} \qquad \textbf{(3)}$$

$\left(\frac{P}{MRR}\right)$ is called unit power, K_p, and it is a property of materials.

P: Cutting power.

MRR: Material removal rate, a constant value.

F_c: Cutting force.

v: feed rate.

ω: width of cut

t_0: depth of cut.

As can be seen in equation (3), detailed information is needed, which makes the estimation complicated.

- For idle or start-up energy:

Kordonowy[9] proposed an alternative way to estimate idle or constant start-up power: Idle power is the difference between maximum rated power of the motor and maximum machine power consumption under full load.

Power is defined by voltage and current (eq.(4)) While voltage is a constant parameter, the current value changes during machining operation.

$$P = V \times I \qquad \textbf{(4)}$$

Machine voltage:		230 V
Current while machine is under full load:		38 A
Calculated maximum power consumption:	*(230*38)*	8740 W
Maximum rated power of the motor:	*(measured onsite)*	7080 W
Calculated idle power:	*(8740-7080)*	1660 W

Table 3: Example for theoretical idle power estimation.

However, this rough calculation method can be only used if the maximum power rating of a machine is similar to switching on start-up operations and having the spindle motor working at 100%. Even though this is valid for milling machines, it is not for lathes.

2.2.4. Other sources of energy

The previous section has handled with the energy requirements focused on electrical consumption. In general, apart from electricity, energy in a manufacturing facility comes in the form of:

- Natural gas
- Vapour
- Compressed air

For traditional machining (turning, milling or drilling), electricity and compressed air is used. Compressed air is supposed to be transformed from electricity within the factory.

2.3. Resources in using phase

Apart from energy, water is used as resource in manufacturing. Even though washing operations could be included, only water used for cutting fluids will be taken into account.

A high percentage of the cutting fluid is composed of water, which is mixed with oil and chemicals. There are different cutting fluids:

- Oil based
  - o Straight oils
  - o Emulsions-soluble oils
- Chemical
  - o Synthetics
  - o Semi synthetics

Soluble oils are the most common ones, which are a mixture of water, oil, additives and emulsifiers. By knowing the water percentage in the cutting fluids, equation (5) can be applied:

$$(Water)_{CF} = \%Water \times CF\_Capacity \times (1 + \%Losses) \times \frac{functinal\_unit}{Meantime\_between\_change} \quad \textbf{(5)}$$

$$Water\_Cost = (Water)_{CF} \times Euros/_{Water\_litre} \quad \textbf{(6)}$$

Equation (5) calculates the water use for cooling during the functional unit, 1000 hours. ‘Capacity’ stands for the cutting fluid system’s capacity in litres. It is assumed that the cutting fluid system will be totally emptied from time to time (meantime_between_changes) and replaced with new fluid. The parameter ‘losses’ describes fluid losses that exist, which can vary from 10% to 30%. Consequently, and taken into account that water percentage can be as much as 95% for soluble oils, water consumption can be significant. In fact, a study based on data from 1990 states that 4.07 gallons/machine/day of water is consumed for cutting fluids, which is 15.38 litres/machine/day [1].

2.4. Consumables in using phase

The main consumables utilized in a machine tool during the operational life are listed below:

- Cutting tool
- Cutting fluid
- Lubricant oil
- Filter

Spare parts are considered to be inside maintenance costs, and therefore they are not taken into account.

Consumable costs are computed as follows:

2.4.1. Cutting tool

$$Tool\_Cost = \frac{functional\_unit[T4]}{Tool\_life \times (1 + n^{o}\, regrid)} \times Euros/_{tool} \qquad (7)$$

Cutting tools, and specially the tool inserts (Figure 18) wear out while machining and must be replaced. Only a fraction of the total working time is spent in cutting and this is characterized in the equation (7). 'Tool life' parameter represents the cutting time the tool is operational. Tools could also be regrided and used again. It should be underlined that due to tool's relatively long life, costs are often amortized over numerous products manufacturing [1]

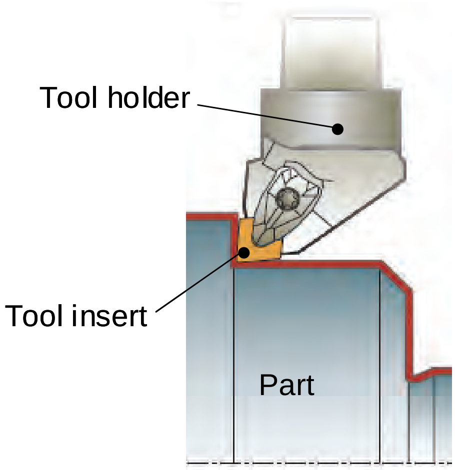


Figure 18: Tool-part contact sketch in machining

2.4.2. **Cutting fluids**

Cutting fluid cost equation is similar to equation (5) and (6):

$$CF\_Cost = CF\_Capacity \times (1 + \%Losses) \times \frac{functional\_unit}{Meantime\_between\_change} \times Euros/_{Litre} \qquad (8)$$

Besides, since the cooling system may be shared by multiple machines, the total cost has to be divided by a number of machines:

$$CF\_Cost/Machine = \frac{CF\_Cost}{N^{o}\,Machines} \tag{9}$$

Equation (8) estimates the litres of cutting fluid used in 1000 hours. It is understood that the meantime between fluid changes will be specified with a statements such as: “The 250 litres of coolant in the system is exchanged every 5 weeks”.

As mentioned before, losses in cutting fluids can vary from 10% to 30%. These losses are due to fluid coating on the chip and on the workpiece, and evaporation.

Figure 19: Flood cutting fluids cooling in a milling operation

2.4.3. Lubricant oil

$$Lubricant\_Cost = Discharge\_rate \times \frac{functional\_unit}{Meantime\_between\_Supply} \times Euros/Litre \tag{10}$$

Lubricant oil is mainly used for spindle and slide away, and it is supplied in decided interval time, since part is frequently removed by the cutting fluid. Discharge rate stands for lubricant supply quantity. It can be assumed that lubrication is independent from other machines.

2.4.4. Filters

The aim of the filters is to clean the cutting fluid from lubricant oil, metal chips and others.

$$Filter\_Cost = \frac{functional\_unit}{Meantime\_between\_F\_change} \times N^{o}\,Filters \times Euros/Filter \tag{11}$$

Filters must be changed from time to time ($Meantime\_between\_F\_change$) and more than one filter can be used in the filtering system ($N^{o}\,Filters$).

Since the filtering system may be shared by multiple machines, the total cost has to be divided by number of machines:

$$Filter\_Cost/Machine = \frac{Filter\_Cost}{N^o\ Machines} \quad \textbf{(12)}$$

Equation (11) is similar to (8). It is assumed that all the filters are changed at the same time.

2.5. By products generation in using phase

Waste handling operations generate costs. During the using phase, different waste types are generated:

- Spent filters.
- Spent Coolant.
- Sludge.
- Spent lubricant oil.
- Metal chips.
- Spent cutting tools.

Whereas some of these by-products are landfillable wastes, other have to be treated as special or hazardous wastes. This distribution highly depends on cooling fluids' composition. Besides, metal chips are generally recycled as scrap once it is separated from cutting fluids.

2.5.1. Spent filters

Number of spent filters in a period defined by the functional unit:

$$N^o\ spent\_Filters = \frac{functional\_unit}{MeanTime\_Filter\_change} \times N^o\ Filters \quad \textbf{(13)}$$

Since waste disposal costs do not depend on the number but in the mass, equation (13) should be converted into kg.

$$spent\_Filters\_mass = N^o\ spent\_Filters \times \frac{kg}{Filter} \quad \textbf{(14)}$$

Finally, mass is converted into monetary cost. Oil contaminated filters and absorbents' handling is dictated by how much cutting fluid they contain.[14]. Besides, waste handling costs has to be shared by all machines involved in filter waste generation:

$$spent\_Filter\_\cos t/machine = spent\_Filters\_mass \times \frac{Disposal\_\cos t}{N^o\ machines} \quad \textbf{(15)}$$

2.5.2. Spent cutting fluids

In order to estimate spent cutting fluid cost, equations similar to spent filters are used. First, litres of spent fluid in the functional unit are calculated in equation (16):

$$Spent\_CF = Capacity \times (1 + \%losses) \times \frac{functional\_unit}{Meantime\_between\_change} \quad \textbf{(16)}$$

Next, spent coolant costs are divided by the machines involved in the cooling system.

$$spent\_CF\_Cost/Machine = Spent\_CF \times \frac{Disposal\_\cos t}{N^{o}\,Machines} \quad \textbf{(17)}$$

Disposal cost depends on the cutting fluid composition. For instance, cutting fluids can contain chlorinated compounds for high pressure machining, as well as fail fat, oil and grease, which makes the fluid hazardous.

Actually, with increasing regulations, disposal of coolant fluids is becoming more highly controlled and more costly. Disposal costs may range anywhere from 25 to 50 cents per gallon for nonhazardous waste up to several hundred dollars per drum for hazardous waste [1].

2.5.3. Sludge

If the facility has an on-site wastewater treatment plant, sludge will be generated from this wastewater-cutting fluids streams. This sludge can sometimes be classified as hazardous waste [16].

$$Sludge\_Cost/Machine = Sludge\_mass \times \frac{Disposal\_\cos t}{N^{o}\,Machines} \quad \textbf{(18)}$$

2.5.4. Spent lubricant oil

Lubricant oil or tramp oil can be disposed as used oil [19]. Equation (19) shows lubricant disposal cost per machine, since oil quantity is measured individually.

$$spent\_Lubricant\_Cost = Disch\arg e\_rate \times \frac{functional\_unit}{Meantime\_between\_Supply} \times Disposal\_\cos t \quad \textbf{(19)}$$

2.5.5. Metal chip

Metal chips are one of the two main waste streams generated at manufacturing facilities along with the cutting fluids. Thus, It makes economic sense to recycle waste chips. The key issue in recycling metal chips is separating the cutting fluids from the chips. In addition, cutting fluids can be also recovered from metal chips and reused, although this option is not applied on this report.

First, chip mass is calculated in eq.(20) with before and after machining part volume. However, the mass could also be roughly estimated.

$$Chip\_mass = (Workpiece\_Volume - Part\_Volume) \times Density \times \frac{functional\_unit[T3]}{time\_part} \quad \textbf{(20)}$$

Equation (21) considers metal chip and fluid separating costs as well as the profits from selling clean metal chips.

$$Chip\_Cost = Chip\_mass \times [Chip\_proces\sin g\_Cost - \mathrm{Re}cycled\_chip\_income] \quad \textbf{(21)}$$

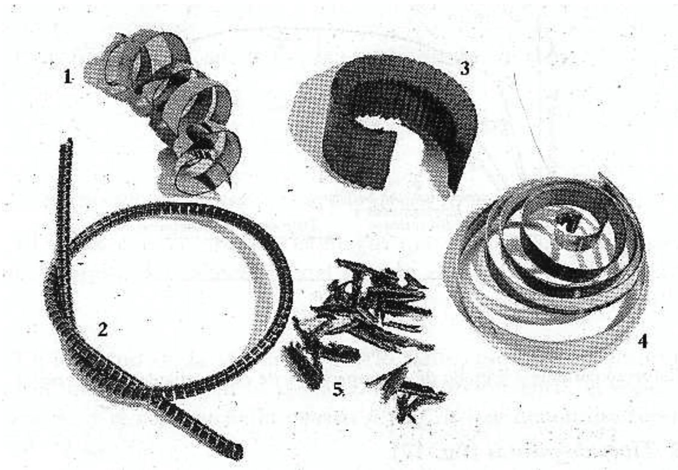


Figure 20: Different types of metal chips

2.5.6. Spent cutting tools

Spent cutting tool inserts can be treated as non-hazardous solid waste.

$$spent\_Tool\_Cost = \frac{functional\_unit[T4]}{Tool\_life \times (1 + n^{o}\,regrid)} \times Disposal\_Costs \qquad (22)$$

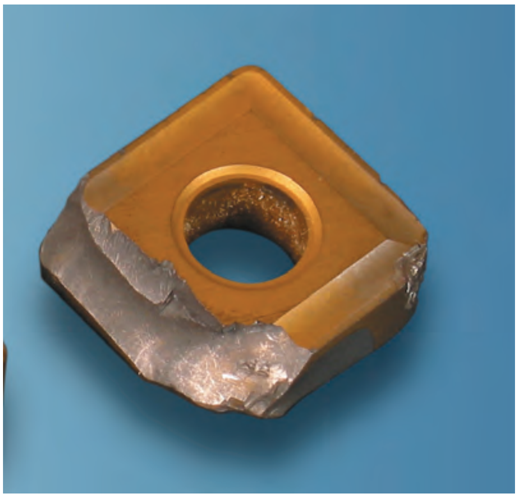


Figure 21: Example of tool insert wear; spent insert.

2.6. Floor space

During machine's operational life, the machine is kept within the factory and takes up an area. Apart from the machine dimensions, the security space in the machine periphery should also be added. For more accuracy, all the auxiliary equipment, shared or not, that is used by the machine can be included.

$$Machine\_floor\_Cost = \left(Machine\_space + auxiliary\_space + \frac{shared\_auxiliary\_space}{N^{o}\,Machines} \right) \times Floor\_\cos t \qquad (23)$$

2.7. Labour cost

Labour cost during operational life, where maintenance is not included, is estimated as follows:

$$Labour\_\cos t = Wor\ker\_\cos t \times N^{o} Wor\ker s \times functional\_unit \qquad (24)$$

3. ENVIRONMENTAL IMPACT ANALYSIS FOR A MACHINE TOOL

As mentioned before, environmental factors are becoming an emerging concern in manufacturing processes, and could become as important as cost factors for designers.

Energy use has a significant impact, not only on cost but also on environment. Thus, energy use and energy sources are important to examine when investigating environmental impacts. Besides, the problems with the cutting fluid disposal is also an key issue, since they are often classified as hazardous waste.

The Life Cycle Analysis approach can assist the designer to develop a more environmentally friendly product. This section will study the environmental impact analysis of a machine tool and for that purpose LCA methodology has been proposed.

3.1. LCA approach

LCA methodology consists of three main stages:

1. Life cycle inventory: Identification of environmental aspects.
2. Impact assessment value judgments made as to the relative importance of the findings.
3. Improvement plans: analysing the changes that are needed to bring about an environmental improvement in a product or process.

3.1.1. Life cycle inventory: Identification of environmental aspects

The first step of the LCA is to measure the inputs and outputs of the each stage in a product's life cycle. These data will result in the environmental aspects identification.

Environmental aspects are elements of the activities, products or services of an organization that can interact with the environment. According to ISO14001, there are three main environmental aspect categories:

- Aspects related to product material.
- Aspects related to product use.
- Aspects related to the transport.

3.1.1.1. Environmental aspect in related to product materials

It includes the materials of the product components, as well as packaging and auxiliary materials that are used during the life cycle of the product. Material production processes, generated waste, energy consumption and material transport should be taken into account.

3.1.1.2. Environmental aspect in product use

In this category, all the useful life of the product is analysed. Consumables consumption and energy consumption must to be known during this time period. Thus, next information has to be collected [13]:

- Energy and consumables consumption during the useful life of the product.

However, it is not enough with this information, a life cycle view has to be applied to both energy and consumables' use. This requires information about:

- Consumables and energy sources: Type of process, as well as energy demand, of the process to obtain consumables and energy for the using phase.
- Waste generated in the consumables and energy production process.
- Consumables and energy transport from the source.
- Consumables disposal.

The different stages are described in Figure 22:

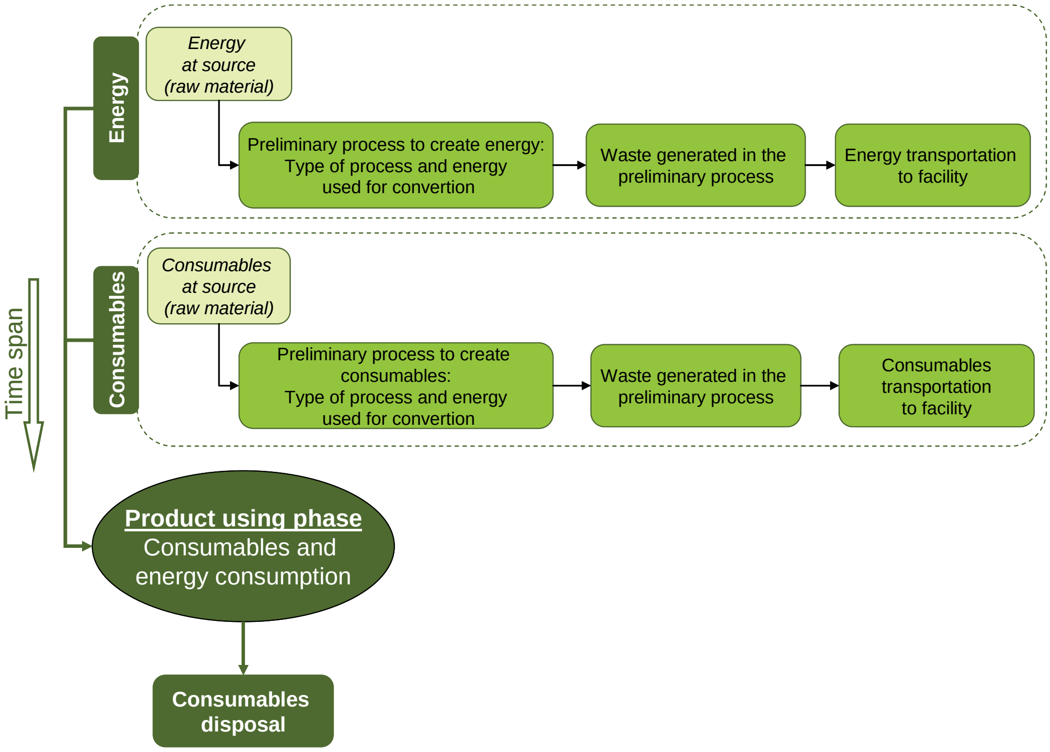


Figure 22: Different stages for an accurate aspect analysis.

3.1.1.3. Environmental aspect in related to transport

This category includes the transport of the product once it is manufactured, for its distribution and sale. Different purchases, % of product sent to each destination, average km and type of transport are factors that can vary the results.

In short, typical environmental aspects that can be related to the stages are mentioned in Figure 22 are listed below:

- Material consumption.
- Use of toxic substances.
- Energy consumption.
- Water consumption.
- Air emissions.
- Liquid waste.
- Solid waste (hazardous an non-hazardous).
- Noise.
- Smell.

3.1.2. Impact assessment: Evaluation and prioritisation

Once the aspects are known, they have to be converted into impacts. For instance, which will be the impact of the material consumption if 1 kg of aluminium is wanted. There are two ways to evaluate environmental impacts:

a) Without Ecoindicators

This is a qualitative or semiquantitative method, environmental aspects are evaluated with established principles, such as magnitude, toxicity or flammability. A matrix is generally used.

b) With Ecoindicators

It is a qualitative method. The aim of the Ecoindicator is to quantify the unitary impacts of the environmental aspects. An important advantage of this method is that there is no need for an expert person on environmental issues, although the experience always facilitates the decision making.

3.1.2.1. Ecoindicator ‘99

As mentioned before, the Ecoindicator is a qualitative tool, a number that shows the unitary environmental impact of different materials or activities. This is the method that has been selected in the environmental impact analysis.

There are five main categories for Ecoindicator ‘99:

- Materials.
- Processes.
- Transport.
- Use.
- Disposal.

3.1.2.1.1. Material ecoindicator

The ecoindicator includes all processes from the raw material extraction until gross material production. For instance, for plastic materials, all the processes are integrated, from the extraction of the oil up to the production of the granules.

3.1.2.1.2. Process ecoindicator

Process ecoindicators take into account energy needed and emissions during the process.

3.1.2.1.3. Transport ecoindicator

The ecoindicator is measured multiplying the carried weight and the km covered. It is based on the fuel consumption and its impacts.

3.1.2.1.4. Use ecoindicator

Use ecoindicators describe the energy consumption. During product's use phase. The ecoindicator consists of fuel extraction and production, as well as energy conversion to obtain electricity.

3.1.2.1.5. Disposal ecoindicator

Different disposal methods can be found within this category:

- Household waste.
- Municipal waste.
- Incineration.
- Landfill disposal.
- Recycling.

EcoScan in one of the various life cycle assessment software on the market, and has been used for the environmental analysis in chapter 3.3. This software has organized its ecoindicator'99 database on these mentioned five categories The ecoindicator'99 database of EcoScan life cycle assessment analysis software is included in Annex 2.

The values of the ecoindicator are taken from different environmental studies (Annex 1). An ecoindicator is measured in different ways: for instance, milipoints/kg is used for materials and milipoints/km*ton for transport.

Finally, the general way to express environmental aspects is:

Aspect evaluation = Quantity x Ecoindicator

3.2. Environmental aspect identification in the using phase of a machine tools

Previous chapters have highlighted the importance of the using phase of machine tools due to the fact that this phase is far longer than the others.

According to the material balance diagram in Figure 11, environmental aspects for the using phase has been divided in eight groups:

a) Filters
b) Lubricant oil
c) Cutting tools
d) Cutting fluid
e) Metal chips
f) Sludge
g) Air emissions
h) Energy and resource consumption

Filters, oil, tools and cutting fluids are included both as material consumption and waste aspects. With regards to waste streams, cutting fluids and metal chips are the main ones.

3.2.1. Filter

They are generally resin impregnated cellulose or resin impregnated synthetic fibbers. They mainly remove tramp oils, metal chips or other particles from the cutting fluid. Filter handling is dictated by how much metalworking fluid they contain [14].

3.2.2. Lubricating oil

Tramp oil sources are: lubricant oils, hydraulic fluid, way oils, tapping oils, gear box oils, etc. Tramp oils are a major cause of premature fluid failure, as well as contributing to the formation of oil mist and smoke on the workplace. Tramp oil is thoroughly separated from the cutting fluid.

3.2.3. Cutting tools

Today, most metal cutting is done using carbide tools. A large portion of these carbide tools are sold as indexable inserts, cutting inserts that are attached to specially designed tool holders. Once all the cutting edges of the indexable inserts have been used, the inserts is typically discharged, although they can be regrided as well.

There are many types of tool materials for different application areas, including ultra-hard tool materials such as diamond and cubic boron nitride, ceramics and high speed steel.

Besides, the more demanding cutting environment calls for coated tools. Therefore, cemented carbide tools are often used. CDV (chemical vapour deposition) and PVD (physical vapour deposition) techniques can be used.

However, it is stated that the direct environmental impact of tooling is limited due to their relatively long life.

3.2.4. Cutting fluids

Cutting fluids have two main properties: to cool and to lubricate the contact area between the tool and the part. This allows to extend the tool life, operate at higher machine tool speeds and feeds, enhance part quality, flush chips or swarf from the cut zone and temporary protect against the corrosion.

The most popular type of cutting fluid is the soluble oil. This is a combination of oil, emulsifiers, additives and a high percentage of water.

The oil from the cutting fluids is typically either a naphthenic or paraffinic oil. Common emulsifiers, which help to suspend the oil droplets in water, are sodium sulfonate, nonylphenol ethoxylates, PEG esters, and alkanolamides. Additives are used to limit corrosion (calcium sulfonate, alkanoamides, and blown waxes), control acidity (amines), control microbial growth (biocides such as formaldehyde condensates), improve lubricity, and prevent foaming. Additionally, EP additives, such as chlorine, phosphorus or sulphur compounds are used for heavy-duty operations.

Currently, disposal of spent metalworking fluid is becoming more controlled and costly. Consequently, it makes sense to recycle the fluid on-site, so it can be used once and again. A individual machine tool with internal cutting fluid system consist of a sump for fluid storage, a pump, delivery piping, a spent fluid collection and return system, and a filter to remove pollutants.

Impacts in the waterstream associated with cutting fluid disposal are listed below:

- Hazardous chemical compounds
- Hazardous metal carry-off (workpiece material)
- BOD
- Nutrient loading
- FOG

Spent cutting fluid can become hazardous when EP additives, specially chlorine compounds (most common chlorinated paraffins), are added. Besides, if working with metals other than carbon steel, there is a possibility that heavy metals (cadmium, copper, chromium, lead, mercury, nickel, silver, zinc) are 'pick up' by the fluid.

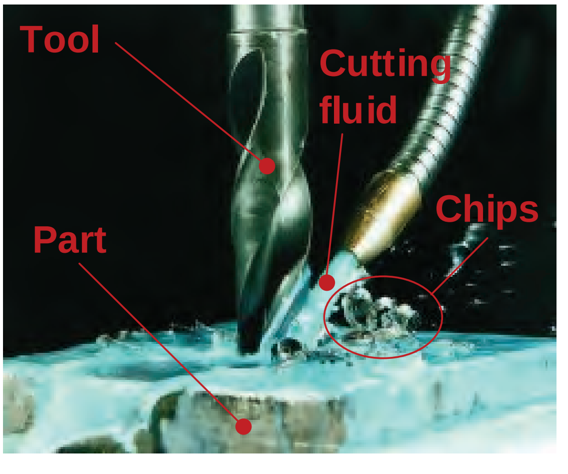


Figure 23: Picture of the cutting-contact area. The chips are removed by the cutting fluid.

Cutting fluids are also related to health problems: Workers in machining operations are continually exposed to cutting fluids. A fluid must be relatively non-toxic, non-flammable and non-misting to minimize health and safety risks. Dermatitis and respiratory problems are the most frequent health problems due to cutting fluids. Dermatitis usually comes from direct contact with the fluid, whereas respiratory problems are due to the oil mist generated in the work environment. [16].

Cutting fluids are also called ‘flood cooling’ since high amounts of fluid is used while machining (see Figure 19 or Figure 23). Some alternatives to flood cooling has been investigated and are becoming more popular. These are:

- MQL cooling: minimal quantities of lubrication. The aim is to keep the cutting fluid beneficial properties while applying only the minimal quantity.
- Dry machining: Machining without the use of any cutting fluid. However, friction and adhesion between the tool and the workpiece will be higher.
- Vegetable based oils, such as soybean oil: test are being conducted to compare vegetable oil performance in machining with mineral oils.

3.2.5. Metal chips

The generation of spent cutting fluids and metal chips are the two major waste streams. The EPA specifically exempts recycled metal from hazardous waste. The key pollution prevention issue in recycling metal chips is separating the metalworking fluids from the chips.

3.2.6. Sludge

If the sump sludge is found non-hazardous, it may be possible to dispose it at a landfill following approval from local landfill authorities. Otherwise, it must be managed and disposed as a hazardous waste.

3.2.7. Air emissions

Evaporating cutting fluids, fluid mist and smoke are generated in machining. However, they are not considered environmental impacts but health problems. There are actually oil mist collectors that avoid this problem

3.2.8. Energy and resource consumption

Energy consumption is high and the effects will be revealed in significantly high environmental impacts.

In the next chapter a LCA analysis for a real machine tool will be conducted. Aspects described above will be taken into account, however the study will consider not only the using phase but all the stages of the machine life.

3.3. LCA example of a machine tool: FS-8000 Milling Machine

For a real LCA analysis, the FS-8000 Milling Machine has been chosen. Its principal characteristics are listed in Table 4. For more specific information, this machine is described in the homepage of the Soraluze company [26].

Configuration	Unit	Specifications
Longitudinal traverse X-axis	mm	8.000
Vertical traverse Y-axis	mm	2.000 (2.400 - 2.800)
Cross traverse Z-axis	mm	1.250 (1.500)
Automatic indexing head	5º x 5º	Standard
Spindle power	kW	30 (37)
Spindle speed range	rpm	3.000 (4.000 / 5.000 / 6.000)
Digital CNC with TFT		Flat Screen Heidenhain iTNC 530
Coolant System		Standard

Table 4: Milling machine specifications

Figure 24: FS-8000 Milling Machine

The life cycle of machine tools in general has been divided into 4 main groups, as shown in Figure 25:

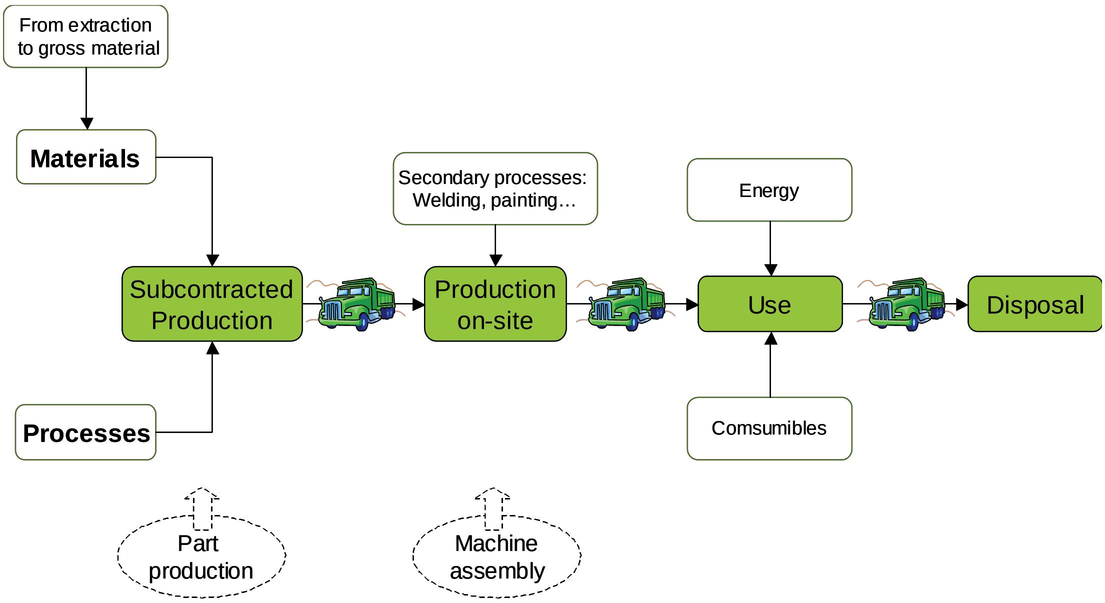


Figure 25: Life cycle view for a machine tools.

1. Subcontracted production:

Most of the parts of the machine are made by subcontracted companies, whereas the production on-site is more focused on the assembly. Therefore, it is assumed that these subcontracted companies will purchase the materials themselves to manufacture the parts

It should be underlined that LCA softwares, such EcoScan or SimaPro, have collected more information in the materials category than in the process category. Ecoindicators for materials are much more detailed than process ecoindicator. Actually, experience shows that mechanical processing contributes relatively little to the environmental load over the lifecycle [13].

2. Production on-site:

Assembly and finishing operations will be carried out on-site. They mainly consist of joining (welding) and superficial treatments (painting).

3. Use:

During the use of the product, there will be consumables and energy consumption.

4. Disposal:

Both machine materials and spent consumables has to be disposed. Each component will have a different disposal method.

Besides, these four main groups are linked by the transport step.

3.3.1. LCA inventory

In order to obtain the LCA the environmental impact of an aspect, it is not enough to list all the components and processes associated to a certain product. It is also necessary to quantify weights acquired in each component or process.

For data collection, Soraluze milling machine manufacturer has been the main source of information. Some data has been already collected in a previous report [17].

3.3.1.1. General assumptions

Next assumptions define the using phase of the machine. Machine tools can last for an average of 15 years, which makes important to identify carefully the machine's performance:

- Planned working hours: 60000 hours (15 years).
- Unplanned downtime: 2% (Maintenance related to failure).
- Planned downtime: 2% (Scheduled maintenance and machine verification).
- Changeover losses: 31% (Cutting tools change, part load/unload, machine start up and set up).
- Effective asset utilisation: 65%.

According to these assumptions, 4% of the total time spent on maintenance activities, 2400 hours in total. Part of this time is related to failure and the rest to preventive maintenance. These activities are not taken into account in the study, however, they are important.

Maintenance due to failure may not have a significant environmental impact. This impact is mainly related to spare parts and logistic issues. On the other hand, the scheduled maintenance is more important. A correct preventive maintenance has beneficial effects, for instance: consumables can last longer, mainly cutting oils; avoiding the wear of the parts in the energy chain could decrease electricity losses; proper tool and cutting oil condition decreases the thermal shock and less oil mist is generated.

3.3.1.1.1. Functional unit

Since the aim of the analysis is to study the environmental impact during its life, the functional unit will be 15 years of work or 60000 hours.

3.3.1.2. Production inventory

3.3.1.2.1. Materials

First, material data has been collected. Currently machine tools are basically made of cast iron, welded steel and a few aluminium alloys. Materials and weights of the different machine parts are summarized in Table 5.

The material category called ‘Others’ is associated to the materials that are unknown. This category may include cables and commercial components, especially from the electrical unit. It is stated that between 15% and 25% of the total weight of a machine is related to commercial components. Since the data in this category is unknown, it will not be considered for the analysis. It can be assumed that this category is divided into several materials that individually may be insignificant.

MATERIAL	Weight kg	%
GG30 (gray cast)	26770	59,0
F-1110	5150	11,3
F-1120	4500	9,9
F-1310 (low alloy steel)	900	2,0
Synthetic rubber	150	0,3
F-1140	110	0,2
F-1550 (low alloy steel)	80	0,2
Painting	75	0,2
25CrMo4	50	0,1
Silicate(water glass)	15	0,03
Methacrylate	20	0,04
Others	7564	16,7
Machine tool	*45384*	*100*

Table 5: Material declaration.

3.3.1.2.2. Production processes

The processes are not considered since as mentioned previously, it is stated that they contribute relatively little. Besides, it is complicated to collect the required data for process impact estimation.

3.3.1.3. Using phase inventory

3.3.1.3.1. Utilities

The milling machine needs both electricity and air supply (Table 6). Electricity consumption is calculated by the real power and working time (eq. (25).

$$Consumption(kWh) = \mathrm{Re}al\_Power(kW) * Working\_Hours(h) \qquad \textbf{(25)}$$

If the working hours are the 65% of the total time, the real power will be 27.8kW:

$$\mathrm{Re}al\_Power(kW) = \frac{1088400kWh}{60000h \times 65\%} = 27.8kW < 30kW$$

According to the machine's technical data in Table 4, the nominal power of the spindle of the machine is 30kW. The spindle is the main motor of the machine, and the power reference of the machine is given by it. The real power and the nominal one are similar, so 1088400kWh is considered an appropriate estimation. This electricity consumption has been divided into x/y/z modules, head or spindle, tool changer, coolant system and hydraulics&pneumatics.

On the other hand, 180000m^3 of compressed air is needed. Compressed air itself does not generate impacts; however, electricity is needed to convert air into compressed air. So, in order to apply life cycle view to the analysis, the electricity required to generate compresses air has to be taken into account.

This example will assume that the milling machine will have an individual air compressor that will not be shared with other machines. The consumption of compressed air in l/min will be:

$$180000m^3 / 15years \times \frac{1000l}{m^3} \times \frac{15years}{60000h \times 65\%} \times \frac{1h}{60\min} = 76.8\ l/\min$$

76.8l/min flow is a rather small compressor. After looking for air compressors in internet, small compressor with flows between 100-200 l/min have an average power of 1.1-1.5 kW. For this analysis, the BL20/90 Piston compressor has been chosen [25], with 200l/min and 1.5 kW

Finally, the total power consumed by the compressor will be:

$$1.5kW \times 60000h \times 65\% = 58500kWh$$

Utility		
Electricity	1088400	kWh
Compressed air	180000	m3
Compressed air	*58500*	*kWh*

Table 6: Utilities declaration.

3.3.1.3.2. Consumables

Cutting tools, lubricant oil and water are computed as consumables. This milling machine has a standard coolant system that does not include filters for coolant filtration.

The milling machine consumes hydraulic oil, lubricant, grease and cutting fluid (Table 7). Nevertheless, these four consumables are oil based and will be grouped with the same name, lubricant oil, and same ecoindicator. This ecoindicator was selected from a base oils and lubricant report [18]. In addition to this, the cutting fluid is mixed with demineralised water, with 96% of water and 4% of oil.

Cutting tools are made up of coated tungsten carbide inserts, so tungsten material is used as ecoindicator

The oily consumables on Table 7, with a density of 0.88 kg/cm^3, are grouped and converted into kg.

Consumable-oil	Units	
Cutting oil	1400	liters
Hydraulic	825	liters
Lubrification	1500	liters
Grease	30	kg

Table 7: Oily consumables.

Finally, consumables are listed on Table 8:

Consumable	Units	
Tungsten tools	3726	kg
Lubricant oil	3308	kg
Water	35000	liters

Table 8: Consumables declaration.

3.3.1.4. Disposal inventory

The machine tool is easily disassembled and grouped into different materials. Up to 82'7% of the machine is made by metallic materials. This study assumes that part of this metallic material will be recycled as scrap, a small percentage of grey cast will be reutilised, and the rest will be sent to landfill.

EcoScan provides different disposal alternatives depending on the material sent to disposal treatment but there was not an appropriate solution for oil waste. Lubricant oil, as well as the water mixed with oil for cutting fluid, has been considered hazardous waste, and is sent to a special waste incinerator, for which SimaPro data has been used. Indeed, it is not the only ecoindicator that has been taken from the SimaPro software. Annex 4 lists all the ecoindicators that has been added to EcoScan database.

On the other hand, painting and wood are sent to inert waste landfill. Metal chips are handled as scrap and recycled and are not included in the analysis.

Table 9 describes the disposal methods for different materials of the machine:

MATERIAL	Weight kg	Disposal method
GG30 (65%)	17400,5	Recycling ferro metals
GG30 (35%)	9369,5	Reutilized
F-1110	5150	Recycling ferro metals
F-1120	4500	Recycling ferro metals
F-1310	900	Recycling ferro metals
Synthetic rubber	150	Landfill PE
F-1140	110	Landfill steel
F-1550	80	Landfill steel
Painting	75	Waste(inert) to Landfill, ETH_ESU 96 System processes
25CrMo4	50	Landfill steel
Silicate	15	Glass landfill
Methacrylate	20	Glass landfill
Wood	4000	Waste(inert) to Landfill, ETH_ESU 96 System processes
PP	25	Landfill PP
HDPE	57	Landfill PE
Tungsten cutting tools	3726	Landfill steel
Lubricant + water	38308	Waste oil to special waste incinerator ETH_ESU 96 System processes

Table 9: End of life declaration

3.3.1.5. Transport inventory

According to collected data, the product will travel a distance of 3000 km in a 24ton trailer. It is assumed that this distance only covers the transport from on-site production facilities to the place where it will be used. Apart from this, the transport from subcontracted production to on-site production facilities and from use to disposal facilities have been added in Table 10:

Departure	Arrival	Km	Transport type	Transported kg
Subcontracted procuction site	On-site production	30	Trailer 28ton	41902
On-site production	Use site	3000	Trailer 28ton	41902
Use site	Disposal facilities	30	Trailer 28ton	41902

Table 10: Transport declaration

A trailer of 28ton has been selected since the ecoindicator for 24 ton is not available. Besides, 41902 kg represents the machine tool weight without unknown materials, plus packaging materials.

3.3.1.5.1. Packaging

Packaging is divided into three elements: a wooden drawer made if pine, a polypropylene awning and a HDPE flat bag.

Material	kg
Wood	4000
PP	25
HDPE	57

Table 11: Packaging materials declaration

3.3.2. Analysis tool: EcoScan LCA software

EcoScan life is a software tool for a fast and easy analysis of the environmental impact of products or product concepts. The software applies the Life Cycle Thinking, and different product stages, like production, usage and disposal can be defined.

3.3.2.1. Application

EcoScan software has been developed to simplify the sustainable product development. The tool is also very suited for product benchmarking, product focused on environmental protection or choices in the field of sustainable implementation. *EcoScan life* is applicable to all types of products.

3.3.2.2. Strong features

EcoScan allows the fast understanding of its features and LCA thinking can be applied without extensive calculations or studies.

The software includes Eco Indicator 95 and ‘99 databases. Besides, it is easy to customize a database, by adding existing or new data. The communication is going smoothly by “drag and drop” system that allows to choose easily the material, process, transport, etc. data.

It provides different product stages. Production, use and disposal stages are included by default, whilst other stages such as transport can also be created.

In addition, automatic disposal mode is available, which means that materials in production or use phase will be linked to a specific disposal method.

Finally, bar or pie charts show the environmental impact of the product, and can represent both the overall impact and the impact divided in stages. A proper analysis of the results leads to the identification of bottlenecks and priorities.

3.3.2.3. EcoScan vs. SimaPro

SimaPro software is a well-know LCA analysis tool. These are some differences with EcoScan software:

SimaPro users require a higher knowledge of the LCA methodology in order to achieve optimal results, while EcoScan is easier to handle.

Furthermore, SimaPro offers a wider data inventory based on different studies. EcoScan’s data inventory can be checked in Annex 2. Actually, SimaPro includes this database and has added some more ecoindicators.

Last but not least, SimaPro gives the possibility to evaluate various categories within environmental impacts, resource depletion and health impacts. Examples of different impact categories are climate change, ozone layer depletion, acidification, eutrofication or fossil fuels depletion. These different impacts categories lead to a more accurate analysis. Meanwhile, EcoScan does not have impact categories; the results in EcoScan are evaluated in overall impact or milipoints (mPts), applying *Quantity*Ecoindicator* simple formula.

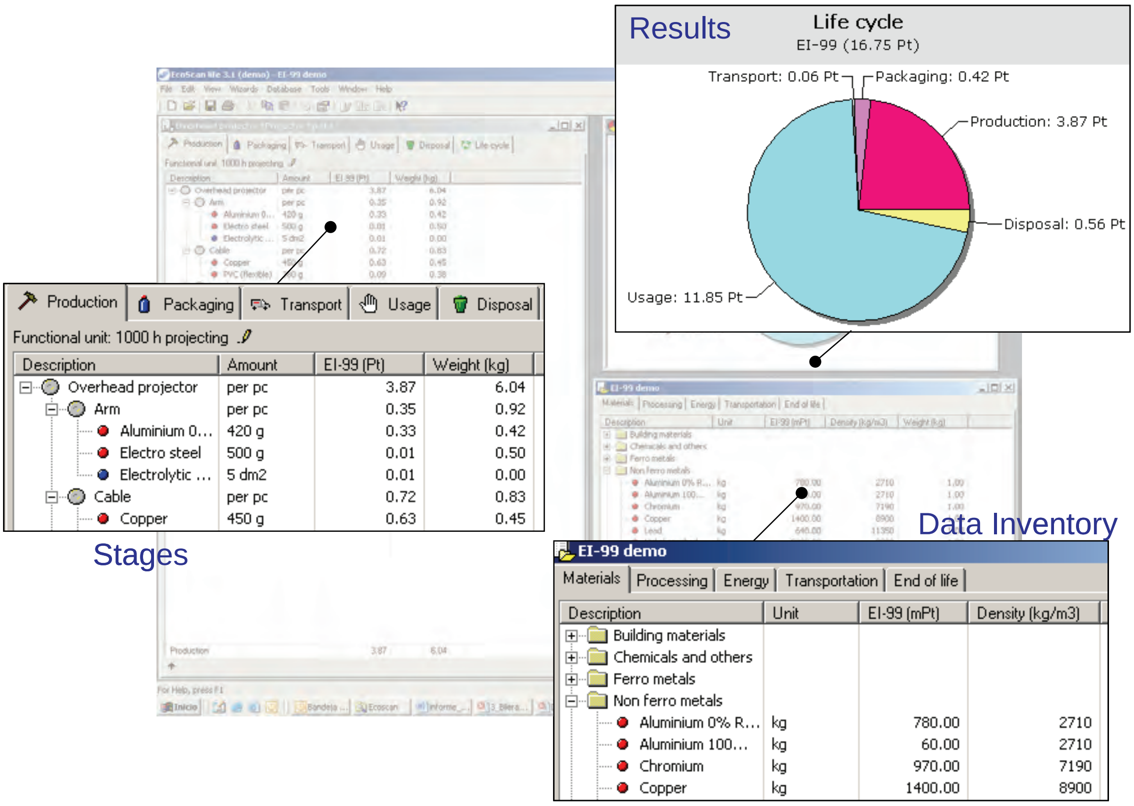


Figure 26: EcoScan interface

3.3.3. Results of the FS-8000 milling machine LCA analysis

The overall impact of the machine tool is 42949031.34 mPts. However, this figure is not helpful because there is no other machine analysis to compare with. The evaluation will focus on the influence of different phases and variables within the milling machine.

EcoScan provides pie and bar charts in order to evaluate the results. The pie diagram of the Chart 1 shows the distribution of the four main stages: Production, use, transport and disposal.

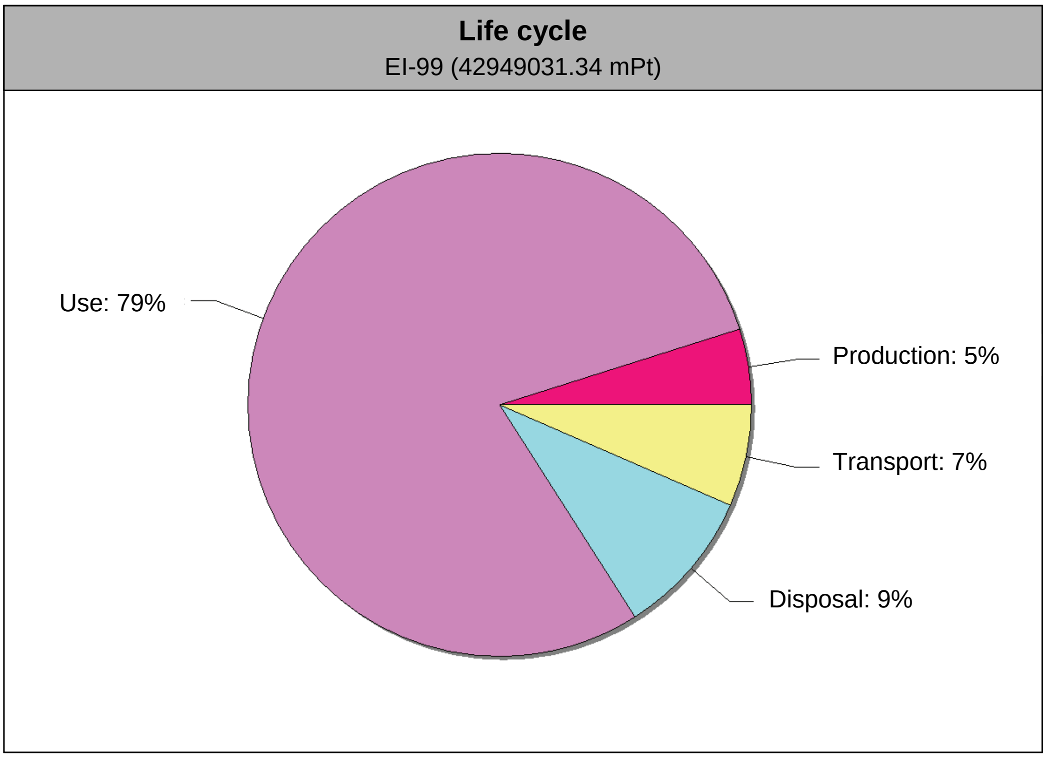


Chart 1: Life cycle view of the FS-8000 Milling Machine. Production, use, Transport and disposal stages

The use stage is by far the most important stage, with up to 79% of the total impact. It is followed by the disposal stage, with 9%, the transport with 7% and the production phase with 5%. The high contribution of the use stage is not surprising; this report has already explained the importance of this stage. On the other hand, the transport stage, which in fact is a short stage, has a relevant influence, mainly from petrol consumption. When it comes to production, only material consumption has been studied. The 5% of the impact of this stage comes from the high amounts of materials, around 40 ton in total.

Next, Chart 2 illustrates the breakdown of the use stage. Electricity consumption with 83% has the biggest impact, as it was expected. Tungsten cutting tool inserts are second with a significant 10%. Last, lubricant oils contribute slightly with a 3%.

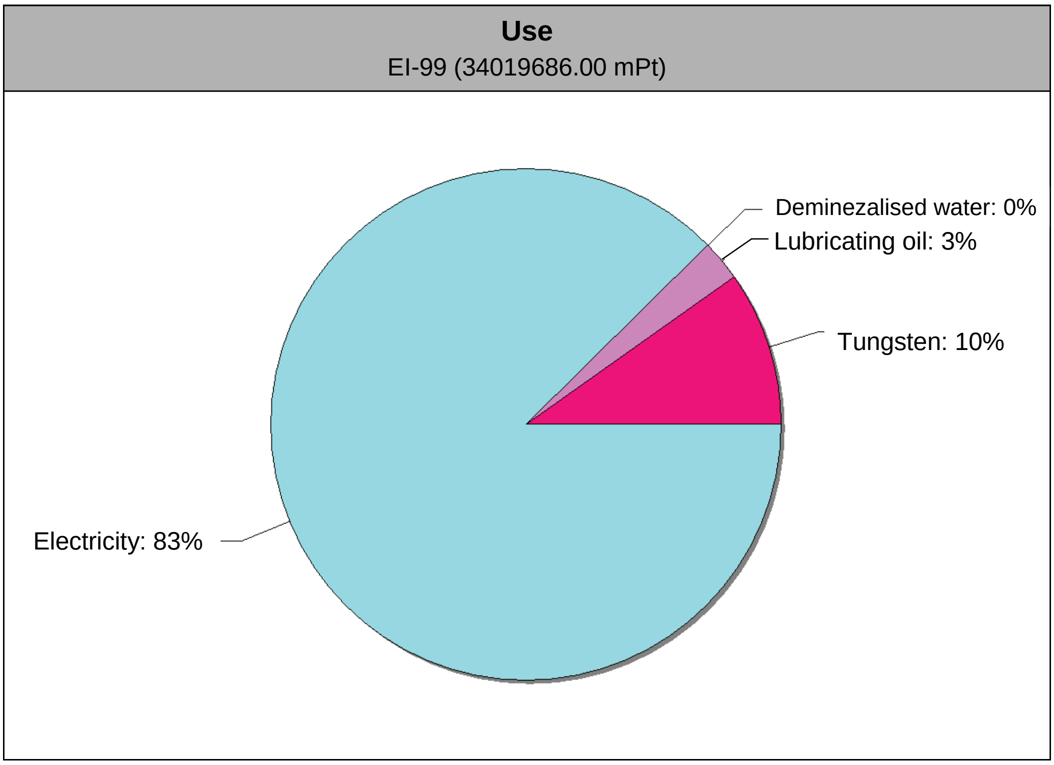


Chart 2: Variables at the use phase.

In the production pie chart (Chart 3), grey cast and steel, have the higher contribution, with 42% and 41% respectively. This is due to the fact that the machine is mainly built with these materials. These materials are not critical for their own but they rather stand out on this chart due to their high weight in the machine. Packaging materials (wood and plastics) are the third parameter with the biggest impact, 9%, specially the 4000 kg of wood.

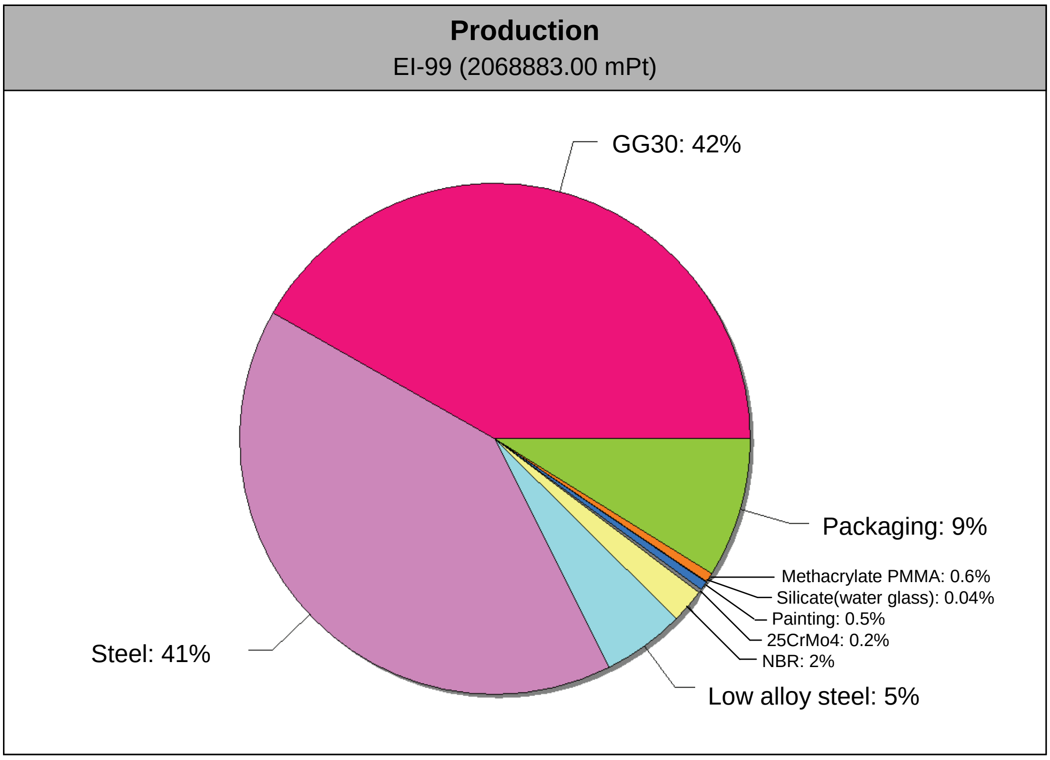


Chart 3: Variables at the production stage.

Last, disposal scenario has been analysed in Chart 4. There are two major issues in disposal: First, the impact of oil disposal (grease, hydraulic, lubricant and cutting fluids), which are considered hazardous waste and have to be incinerated. Second, the positive influence or avoided impact of recycling of metallic materials, which decreases the overall disposal impact by approximately one third.

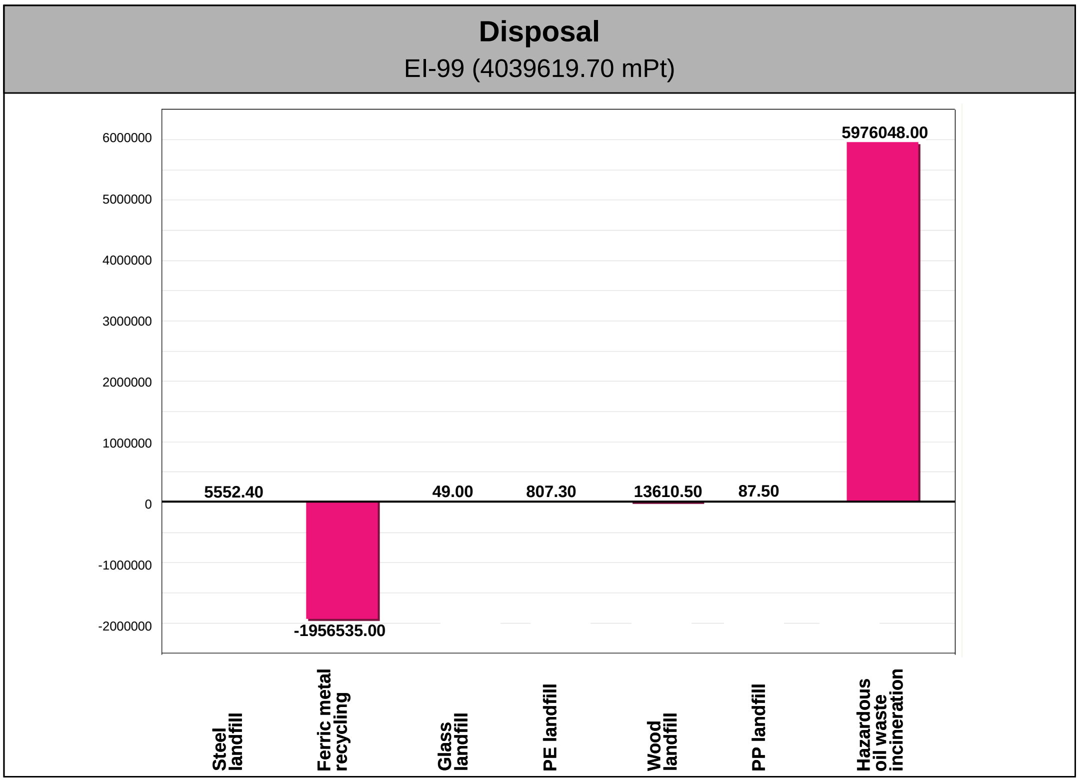


Chart 4: Disposal scenario with negative and positive impacts.

EcoScan allows to compare elements on the same stage with these charts, but the general impact distribution per element cannot be viewed. Table 12 has gathered the main aspects from each stage.

		Impact in mPts	Impact %
Production	Steel	839360 mPts	**1,95%**
	GG30	864671 mPts	**2,01%**
Use	Electricity (total)	29819400 mPts	**69,43%**
	Cutting tools(tungsten)	3316140 mPts	**7,72%**
	Lubricant oil	883236 mPts	**2,06%**
Transport	Truck 28t	2820843 mPts	**6,57%**
Packaging	Wood	183060 mPts	**0,43%**
Disposal	oil incineration	5976048 mPts	**13,91%**
	Metal recycling	-1956535 mPts	**-4,56%**
Rest of parameters		202809 mPts	**0,47%**
TOTAL		**42949031,34 mPts**	**100%**

Table 12: Distribution of the main environmental aspects of the machine

Table 12 corroborates that electricity consumption is the main impact source, with 69.4%. Oil waste incineration (13.9%), cutting tool tungsten inserts (7.7%) and transport by truck (6.6%) have considerable impacts as well. The avoided impact of the metal recycling process is around 4.5% since around 26 ton are recycled.

In a previous chapter, the idle power consumption of a machine tool has been calculated in a example, around 2.26% of the total power. If this figure is evaluated as environmental burden, it would be equivalent to 640000 mpts, and the total burden would be 1.5% higher than what it is now. This increase is quite significant because the weight of the electricity burden is high. This concept is better evaluated in the sensitivity analysis.

3.4. Uncertainty

To make rational decisions, there is a need to understanding the uncertainty involved in the information and knowledge on which decisions are based. It is therefore necessary to recognize that there are two types of uncertainty: *aleatory uncertainty* and *epistemic uncertainty [23].*

Strictly, uncertainty (*epistemic uncertainty*) arises due to lack of knowledge about the true value of a quantity, whilst variability (*aleatory uncertainty*) is attributable to the natural heterogeneity of values. However, they are usually known as just uncertainty.

The reliability of life cycle assessment is affected, for instance, by the dependence on data from different countries, different unit operations or different sources. Thus, there is a need for improving techniques for sensitivity and uncertainty analysis.

3.4.1. Uncertainty models

Variability is best represented in stochastic terms. A typical tool to deal with variability is the Monte Carlo simulation. On the other hand, epistemic uncertainty is generally best represented in terms of intervals. There are several analysis alternatives, such as Convex sets, Possibility theory, Fuzzy set theory, Dempster-Shafer evidence theory, Probability bounds analysis, Interval analysis and Information gap decision theory [24]. Therefore, since a LCA analysis has both types of uncertainty, the question is how to compute them and compare results appropriately.

Some researches suggest representing all uncertainty using probability density functions, even if such an approximation may lead to conclusions that are overly confident [23].

3.4.1.1. Uncertainty problems in LCA

The uncertainty problem in LCA can be divided in three sub-problems:

1. Assessing errors in input data.
2. Assessing the propagation of errors in the calculation.
3. Assessing errors in the calculation’s outcome, interpreting outcomes.

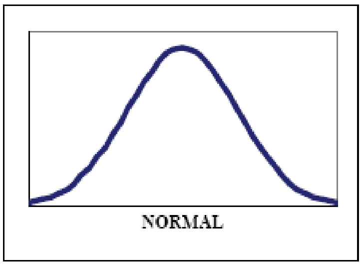
Monte Carlo simulation is a useful tool for assessing the model propagation errors, but cannot correct input uncertainties and does not tell what to do with the outcome uncertainty it calculates.

3.4.1.2. Monte Carlo simulation

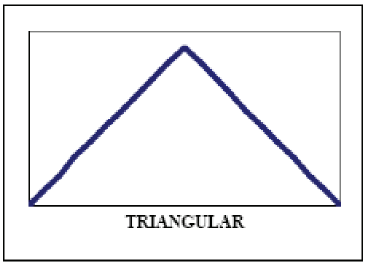
The Monte Carlo simulation is a widely used probability analysis. This tool uses a simple procedure: It basically randomly varies input data value according to a given probability distribution, runs the calculation and stores the output. This procedure must be repeated often enough (typically 10000 times) in order to be sure to obtain input values that adequately represent the selected probability distribution.

Because of the repetition of algorithms and the large number of calculations involved, Monte Carlo is a method suited to calculation using a computer.

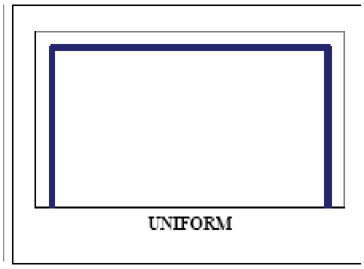
As mentioned before, for each uncertain variable, possible values are defined with a probability distribution. The type of distribution selected is based on the conditions surrounding that variable. Probability distribution types include:



Normal probability distribution



Triangular probability distribution



Uniform probability distribution

Normal probability distribution for a parameter is the most accurate one. The distribution is defined by the mean and standard deviation values. On the other hand, uniform distribution is used when extreme values of the parameter are know but not the distribution, and consequently all the values are equally probable. Finally, triangular distribution can be seen as a rough approximation of a probability distribution.

Currently, some LCA analysis tools, for instance GaBi software, as well as the latest SimaPro version (SimaPro 7), include the Monte Carlo simulation option.

3.4.1.2.1. Example with Monte Carlo

There are various studies about quantifying uncertainty in life cycle assessment. One example is a municipal waste management analysis [22]. The aim of this study was to decide which of the two alternative, incineration or landfill, was the most appropriate for waste treatment. To further simplify the case, only global warming potential(GWP) was considered within the total environmental burden. Next, the distribution of the inventory parameters used in the Monte Carlo simulation were based on expert judgement, intergovernmental panel on climate change guideline as well as on statistic data. Other parameters that tend to small variations were assumed to be uniformly distributed.

This study found out that, while without an uncertainty study incineration was clearly the best option, with an uncertainty study the ranges of global warming potential values for both treatments were overlapping. This is an example of how an uncertainty study can uncover results that are not expected.

3.4.1.3. Uncertainty on the FS-8000 milling machine LCA analysis

The main problem of the FS-8000 milling machine LCA analysis is the uncertainty in the input data. On one hand there is the quantity input data error. One example is to ignore the idle power consumption during the use phase, as explained before. Depending on the environmental impact capacity of the variable and its sensitivity, it can influence the results. On the other side, there are the errors given by the ecoindicator. EcoScan provides some ecoindicators, and if the parameter is not defined in the EcoScan database, some new ecoindicators has to be found, for instance in SimaPro software. The uncertainty can appear in two ways: first, the ecoindicator has already some uncertainty due to previous assumptions, and next, the chosen ecoindicator may not be the most appropriate one for the analysis.

For instance, the ecoindicator value for the electricity can vary depending on the country. For the LCA analysis, Electricity form grid, low voltage, mix in Europe (UCTPE) has been chosen, which has an impacts of 26 mPts per kWh. However, if low voltage electricity in France is chosen, the ecoindicator will be 8.9 mPts per kWh, and for Great Britain, 33 mPts (see Annex 2). This difference is mainly based on primary electricity production on each country. In France, around 84% comes from nuclear power plants and 2% from coal and petrol power plant. On the other hand, In Great Britain, only about 9,4% comes from nuclear power plants and around 50% from coal and petrol power plant [28]. Choosing one ecoindicator or the other for the electricity parameter will vary the results. However, due to the high consumption on the use phase, the electricity parameter will continue being the most important environmental impact.

In short, the milling machine LCA analysis assumes that there will be some uncertainty. Furthermore, a sensitivity model will identify the most sensitive variables, and thus data for these variables should be carefully collected.

3.4.2. Sensitivity models

While uncertainty analysis identifies and quantifies the uncertainty introduced into the results, sensitivity analysis evaluates the influence that one parameter has on the value of another. It can be carried out to choose relevant parameters

One technique is the Tornado diagrams. The model runs with low and high values for each parameter whereas all the others are held constant. The results are represented in laying bars graphs, where the top bar is the most sensitive parameter and the bottom bar is the least. The base values are marked with dashed lines.

A Tornado diagram applied to the previous waste treatment example could look as follows (Figure 27), where the contribution of each parameter’s uncertainty to the overall variance of global warming potential is measured:

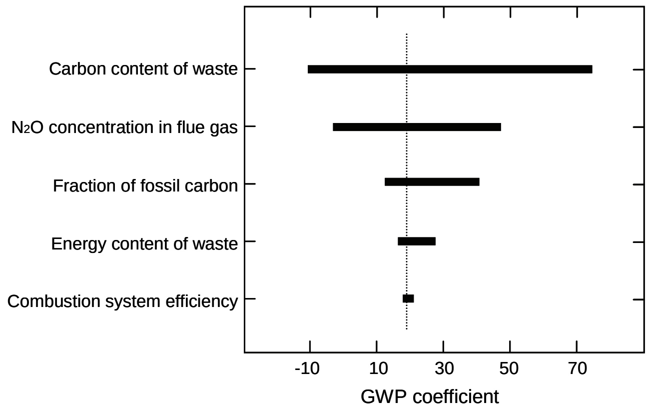


Figure 27: Tornado diagram example

According to the Figure 27, carbon content of waste parameter has the largest influence, followed by N_2O concentration. Consequently, data for these parameters can be collected more carefully in order to obtain more accurate results.

3.4.3. Sensitivity study of FS-8000 milling machine

A sensitivity study has been conducted for the milling machine examined in chapter 3.3 in order to highlight the relevant parameters. The previous LCA analysis has already identified the parameters with high environmental impacts; nevertheless, the aim of the sensitivity analysis will be to check if there are significant changes on the overall environmental impacts if the values of the parameters are varied. If so, the list of the variables with the main environmental impact identified in the LCA could change.

The study will take the parameter values applied in the LCA and vary then ±10%. The initial and new values are shown in Table 13:

Variable limits							
Variables		Initial value		- 10%		+ 10%	
Production	Steel	9760	kg	8784	kg	10736	kg
	GG30	26770	kg	24093	kg	29447	kg
Use	Electricity (total)	1146900	kWh	1032210	kWh	1261590	kWh
	Cutting tools(tungsten)	3726	kg	3353,4	kg	4098,6	kg
	Lubricant oil	3308	kg	2977,2	kg	3638,8	kg
Transport	Truck 28t	128220	tkm	115398	tkm	141042	tkm

Table 13: Initial values, -10% values and +10% values of the main variables.

Then, the new value of one of the parameter is inserted in the EcoScan software, while the others are held constant. The results of the overall environmental impacts for the new values in EcoScan are collected in Table 14:

Total mPts of the machine life cycle			
Variable parameter		Total impact in mPts	
		- 10%	+ 10%
Production	Steel	42933415,34 mPts	42964647,34 mPts
	GG30	43049954,24 mPts	42848108,44 mPts
Use	Electricity (total)	39967091,34 mPts	45930971,34 mPts
	Cutting tools(tungsten)	42616895,70 mPts	43281166,98 mPts
	Lubricant oil	42263102,94 mPts	43634959,74 mPts
Transport	Truck 28t	42666944,70 mPts	43231112,00 mPts

Table 14: Variation of the overall impact applying ±10% to the variables.

It should be underlined that not all the parameters have a linear influence on the results. For instance, if electricity consumption decreases by 1000 mPts, the overall result will also decrease 1000 mPts. On the other hand, if less steel is used in production and its impact is reduced by 1000 mPts, the avoided impact of metallic material recycling will also change, and thus the overall impact will be different to a variation of 1000 mPts. The sensitivity analysis takes into account these correlations for an accurate evaluation.

The results of the sensitivity analysis are illustrated in a Tornado diagram in Figure 28. Electricity consumption keeps been the most important parameter, however, lubricant oil, with only a 2.1% of the total impact (Table 12) is in the second place. This is due to the fact that oil waste incineration has a rather big influence on the overall impact, and a variation of 10% on cutting oil is directly related to oil disposal. Cutting tools and transport do not have a big sensitivity to variations, they concur with the classification on Table 12. Another interesting fact that can be seen on the tornado diagram is that the material GG30 is more susceptible to variations than the steel, even though their weight in the overall environmental impact is the same, 2%. Actually, GG30 mass on the machine is almost three times bigger than steel, but it has also a smaller ecoindicator so at the end their impacts are similar. However, the avoided impact of metal recycling is what makes them different in the tornado diagram; A 10% variation on GG30 mass has also three times more positive influence in recycling than the steel.

In general, this sensitivity analysis verifies the results obtained on the LCA analysis, but on the other hand it has found out some interesting conclusions that can be helpful to get a better knowledge of the environmental burdens of the machine tool.

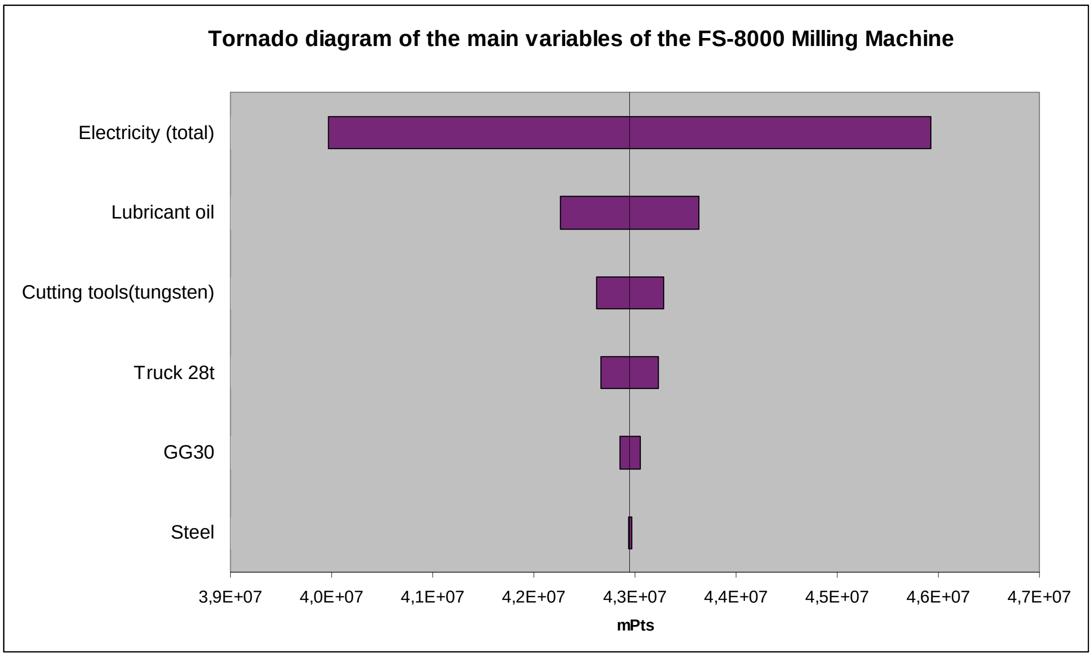


Figure 28: Tornado diagram for the FS-8000 Milling Machine

4. THE MACHINE TOOLS OF THE FUTURE

Although there has been some researches about environmental issues on the machine tool area, the truth is that it is still quite undeveloped. Electric&Electronics category, for instance, is much more developed, because they have more strict regulations. One example is the WEEE regulations about the end of life of Electric&Electronics plastic waste.

However, the machining sector has to make progress. Therefore, there are currently many research studies that are working on the machine tool development, not only in performance areas but also in more environmental conscious machining. These studies are trying to first define and then evolve into the machines of the future.

The integrated project NEXT (Next generation production systems) aims at committing the main players at European production equipment industry to new frontiers in diverse fields [20]. The main objectives relate to:

- The green machines: Innovation forward in environmentally friendly production machines. The aim is to get machines that consider environmental aspects through their entire life-cycle:
    - Use of recycled materials for machine elements (>50%).
    - Reduction of energy consumption (>25%) at machine use.
    - Zero waste produced.
    - Dismantling and recycling 100% machines.
    - Non pollutant alternative processes.
    - Reduction of machine volume.
    - Reduction of noise emission.
    - Reduction of logistic area for maintenance/spare parts allocation.
- The user centric autonomous machine: Breakthrough in usability and machine autonomy.
- The manufacturing breakthrough: Big leap in performance and innovative processing methods.
- New business paradigm for machinery: A breakthrough to create value for the production.
- New contents for training, marketing and dissemination around production: New content for training, marketing strategies, socio-economics aspects.

Other studies, such as the CENIT of Machine tools, are dealing with eco-machines or e-machines [21], where the main goals are:

- Reduction of the weight of the structural elements by the use of lighter materials. Currently machine tools are basically made of cast iron, welded steel and a few aluminium alloys. There is already a cluster working on this called “Lightstruct” (Light Structures Machine Tools). Besides, materials used in machine tools should also increase damping properties in order to absorb the impacts.

- Use of ecologic lubricants and refrigerants, which will be biodegradable and non toxic.
- Energy optimisation:
    - Focusing on auxiliary systems, such as hydraulic systems, pumps… These systems are usually working even though the main machine is switched of or when these systems are not needed. An efficient management of these auxiliary machinery could save 10% of the total consumption.
    - Energy demand management:
    - Energy recovery.

5. CONCLUSIONS

This report has studied the machine tools focusing on two issues of high importance in the market: costs and environmental impacts.

Machine tools are essential for the manufacturing sector, and several researches are being conducted to improve their performance, decrease costs, and most recently, to diminish environmental impacts. Nevertheless, the environmental thinking is still a relatively new perspective for machine tools.

The first fundamental fact is that machine tools have a long useful life, around 15 years, and that almost during all that time the machines are running. This is the reason why the use phase is the most important stage, and thus a special attention has to be paid to it.

For the cost analysis model of the machine, only the use phase has been studied. Equations has been developed for several parameters, grouped into energy, consumables, resources, waste disposal, space and labour costs. These equations will help to estimate the costs of the machine during its use phase. The purpose of this cost estimation is to avoid the iceberg effect, the hidden costs that are ignored when only acquisition costs are considered when buying a machine.

Within using phase costs, previous studies have stressed on the importance of energy consumption costs. Consequently, and accurate energy analysis model has been proposed. This model makes an estimation, not only of the uptime energy needs, but also of the energy from auxiliary machinery and stand-by situations, which can increase, sometimes slightly and considerably, the electricity invoice.

In short, this energy analysis model has three strong points:

- Electricity consumption is often roughly estimated. The model takes into account that the power consumption is not constant, and a more accurate estimation is achieved.
- The model does not ignore the idle power. Currently more and more auxiliary equipment is been used, which may increase the idle power consumption.
- It allows to conduct a thorough analysis about where and how the electricity is consumed. This is an important fact when energy optimisation measures wants to be implemented.

It has an important weakness as well: it is a time consuming approach.

The cost model has not been tested with a real example, since onsite data collection from a real machine is needed for that. However, the model aims to be helpful for future cost accurate estimations.

The environmental impact analysis of the machine tool has provide more information since a real example has been conducted. Following the LCA methodology, the environmental analysis has been divided into production, use, transport and disposal stages. For the same reason explained in cost analysis, the use phase of the machine was expected to have the higher environmental burden. Therefore, resources and consumables for this stage has been carefully studied: cutting tools, cutting fluids, metal chips, filters, lubricant oil, sludge, energy consumption and air emissions. Cutting fluids and metal chips are the two main waste streams. Besides, cutting fluids can become hazardous waste and has to be handled carefully.

After the theoretical approach to the environmental impacts, the FS-8000 Milling machine has been chosen for the real example, and the analysis has been conducted with the EcoScan LCA software. This software is not as complete as SimaPro, but is fast and easy to use. Some interesting information has been collected from the LCA analysis:

- As it was expected, the use phase of the machine has the biggest environmental burden, with a 79% of the total; meanwhile, disposal, transport and production stages have similar impacts.
- Within the use phase, almost 70% of the overall impact is generated by the electricity consumption. In order to avoid or decrease this situation, energy efficiency measures for the machine tools should be implemented.
- Oil waste incineration has also a significant influence, since oil is treated as hazardous waste. The impact could be reduced by using oil without hazardous components. Besides, some new approaches such as dry machining or vegetal based oils could help to decrease these impacts.
- The material used for cutting tools, tungsten, accounts for the 7.7% of the total impact. Tool insert could be regrided and used again, and thus the impact could be diminished.
- Transport is also an interesting aspect. This milling machine is supposed to be carried by truck across Europe for about 3000 km. This transport process, which can be done in a few days, has an impact of 6.6% of the total. It is surprising how a secondary activity such as transport can have such a big impact in the machine tool life. This can be caused by the heaviness of the transported element. A decrease on the machine weight as well as on the volume will diminish environmental impacts related to transport.

Some of the results were expected, particularly the high burden of the electricity consumption. Nevertheless, 70% of the overall environmental impact for the electricity consumption is surprisingly high. Besides, even though the importance of the electricity consumption is known, environmental researches are more focusing on cutting oils. Cutting oil disposal legislation has become more stringent, especially for hazardous oils, which has raised the disposal costs as well as the environmental concern. This could be the reason why vegetal based oils and low quantity lubricant application are being investigated. On the other hand, electricity does not generate a waste after use, so the impacts related to the electricity consumption are “hidden”, they are associated with the electricity production. Therefore the environmental concern about electricity consumption may be lower.

This report considers that even though it is important to improve the environmental performance of consumables and other aspects of the machine, the first objective should be to decrease drastically the electricity consumption of the machine during its operational life.

The LCA analysis of the machine tools has provided a ranking of the most significant environmental burden sources. On the other hand, the objective of the sensitivity study has been to study the variability of the aspects that generate impacts, and to check if the are changes in the ranking compared to the analysis in EcoScan. The sensitivity study confirms once more that the electricity consumption is the main aspect to take into account. Nevertheless, the lubricant oil and the GG30 material parameters have revealed that correlations that are hidden in a simple environmental impact analysis can emerge in a sensitivity analysis. In this case, lubricant oil is a sensitive variable not because the raw material itself but because the disposal method. The GG30 material is sensitive as well because it is the main component on weight of the machine and a large fraction is recycled. In conclusion, this report recommends that a LCA analysis should go together with a sensitivity analysis for more accurate results interpretation.

The LCA analysis of the FS-8000 milling machine is based on various assumptions: No filters and metal chips are considered, the oil is hazardous and manufacturing processes are not measured. Furthermore, the choice of the correct ecoindicator for each parameter can be a key issue for the analysis. For instance, the ecoindicator for the electricity varies significantly depending on the European country this electricity is consumed. Also, there is not a specific ecoindicator for some parameters, such as for spent cutting oil disposal, so some suppositions have to be made.

Therefore, the LCA analysis of the real milling machine can be considered as a preliminary study. This study, along with the sensitivity study, underlines the parameters has to be collected carefully for a further analysis.

Another important assumption for both cost and environmental analysis is that maintenance cost is not taken into account. Several researches are interested on maintenance activities for cost estimation. Words such as reliability (reducing failures over a time interval) or maintainability (deals with the duration of maintenance downtime) are well known. Increasing the reliability of the machine, and thus the effectiveness, is an important issue and it is integrated in the LCC thinking. Maintenance costs include machine downtime, spare parts and labour costs.

Although it seems that maintenance is more related to cost issues, it has also consequences on environmental issues. A preventive maintenance has beneficial effects such as extending the cutting fluid life or decreasing the energy consumption by the correct operation of the machine.

Briefly, even though maintenance activities are not analysed on this report, it is worth taking them into account for further cost and environmental impact studies.

Finally, two current researches have been presented. Both are investigating machine tools of the future. With regards to environmental issues, their main goals are to increase energy optimisation, create non pollutant process and decrease the use of raw materials. However, it should be highlighted that all these environmental improvements have to be economically feasible if they want to be implemented.

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ANNEXES

Annex 1

Notes taken from “Eco-indicator ‘99, Manual for designers. A damage oriented method for life cycle impacts assessment” [15].

Notes on the process data

The last column of the indicator list contains a code, referring to the origin of the process data, like the emissions, extracted resources and land-uses. In Chapter 5 of the Manual for Designers we refer to this as the data collected under "Step 1".

Below the data sources are briefly described. In all cases the data has been entered into LCA software (SimaPro) and then evaluated with the Eco-indicator 99 methodology.

1 By far most data have been taken directly from the ESU-ETH database Ökoinventare für Energiesystemen (Environmental data on energy systems), the third edition, produced by ETH in Zurich. This very comprehensive database includes capital goods (i.e. concrete for hydroelectric dams and copper for the distribution of electricity) and items like exploration drilling (exploration drilling) for energy systems. Also for transport, capital goods and infrastructure (maintenance and construction of roads, railways and harbours) are included. For material production capital goods are not included. Finally it is important to note that land-use is taken into account in all processes.

2 The Swiss ministry of Environment (BUWAL) has developed a database on packaging materials with the above-mentioned ESU-ETH database as the starting point. However, in this database all capital goods are left out. For the Eco-indicator 99 project we used the data on waste disposal and a few specific packaging materials. For disposal data we made a number of recalculations to include the "positive" effects form reusing material (recycling) or energy (waste incineration). Next to this we used the [OECD 1997] compendium to generate waste scenarios for municipal and household waste for Europe. An important difference with the Eco-indicator 95 is that now we use European in stead of Dutch scenario data. [BUWAL 250-1998]

3 The European Plastics industry (APME) has collected state of the art data for average environmental load for many plastics. As far as possible we used the ESU-ETH version (see 1), as this combines the APME data with much better detailed energy and transport data. The data marked with a 3 are thus the original data, but as they use rather simplified energy and transport data, they can deviate approximately 10 % from the other indicators [APME/PWMI]

4 Processing data has mostly been taken form the Eco-indicator 95 project. In virtually all cases only the primary energy consumption has been taken into account. Material loss and additional materials as lubricants are not included. It should be noted that the energy consumption of a process is very much determined by the type of equipment, the geometry of a product and the scale of operation. Therefore we suggest to take these indicators only as a rough estimate and to calculate more specific data by determining the exact energy consumption in a particular case and to use the indicator for electricity consumption to find a better value. Experience shows that mechanical processing contributes relatively little to the environmental load over the lifecycle. This means the crude nature of the data does not really have to be a big problem. [Kemna 1982]

5 Data on alkyd paint production have been added on the basis of a somewhat older study of AKZO.

6 The KLM environmental annual report was the basis for the data on air transport. This data includes the handling of planes on the ground. [KLM 1999]

7 Data for recycling of plastics are taken from an extensive study of the Centre of Energy Conservation and Clean Technology [CE 1994]

Annex 2

Ecoindicator '99 inventory for EcoScan software:

Production of ferro metals (in millipoints per kg)

	Indicator	Description	
Cast iron	240	Casting iron with > 2% carbon compound	1
Converter steel	94	Block material containing only primary steel	1
Electro steel	24	Block material containing only secondary scrap	1
Steel	86	Block material containing 80% primary iron, 20% scrap	1
Steel high alloy	910	Block material containing 71% primary iron, 16% Cr, 13% Ni	1
Steel low alloy	110	Block material containing 93% primary iron, 5% scrap, 1% alloy metals	1

Production of non ferro metals (in millipoints per kg)

	Indicator	Description	
Aluminium 100% Rec.	60	Block containing only secondary material	1
Aluminium 0% Rec.	780	Block containing only primary material	1
Chromium	970	Block, containing only primary material	1
Copper	1400	Block, containing only primary material	1
Lead	640	Block, containing 50% secondary lead	1
Nickel enriched	5200	Block, containing only primary material	1
Palladium enriched	4600000	Block, containing only primary material	1
Platinum	7000000	Block, containing only primary material	1
Rhodium enriched	12000000	Block, containing only primary material	1
Zinc	3200	Block, containing only primary material (plating quality)	1

Processing of metals (in millipoints)

	Indicator	Description	
Bending–aluminium	0.000047	one sheet of 1mm over width of 1 metre; bending 900	4
Bending–steel	0.00008	one sheet of 1mm over width of 1 metre; bending 900	4
Bending–RVS	0.00011	one sheet of 1mm over width of 1 metre; bending 900	4
Brazing	4000	per kg brazing, including brazing material (45% silver, 27% copper, 25% tin)	1
Cold roll into sheet	18	per thickness reduction of 1 mm of 1 m2 plate	4
Electrolytic Chromium plating	1100	per m2, 1 _m thick, double sided; data fairly unreliable	4
Electrolytic galvanising	130	per m2, 2.5 _m thick, double sided; data fairly unreliable	4
Extrusion – aluminium	72	per kg	4
Milling, turning, drilling	800	per dm3 removed material, without production of lost material	4
Pressing	23	per kg deformed metal. Do not include non-deformed parts!	4
Spot welding–aluminium	2.7	per weld of 7 mm diameter, sheet thickness 2 mm	4
Shearing/stamping–aluminium	0.000036	per mm2 cutting surface	4
Shearing/stampin–steel	0.00006	per mm2 cutting surface	4
Shearing/stamping–RVS	0.000086	per mm2 cutting surface	4
Sheet production	30	per kg production of sheet out of block material	4
Band zinc coating	4300	(Sendzimir zink coating) per m2, 20-45 _m thick, including zinc	1
Hot galvanising	3300	per m2, 100 _m thick, including zinc	1
Zinc coating (conversion um)	49	per m2, 1 extra _m thickness, including zinc	1

Production of plastic granulate (in millipoints per kg)

	Indicator	Description	
ABS	400		3
HDPE	330		1
LDPE	360		1
PA 6.6	630		3
PC	510		1
PET	380		3
PET bottle grade	390	used for bottles	3
PP	330		3
PS (GPPS)	370	general purposes	3
PS (HIPS)	360	high impact	1
PS (EPS)	360	expandable	3
PUR energy absorbing	490		3
PUR flexible block foam	480	for furniture, bedding, clothing	3
PUR hardfoam	420	used in white goods, insulation, construction material	1
PUR semi rigid foam	480		3
PVC high impact	280	Without metal stabilizer (Pb or Ba) and without plasticizer (see under Chemicals)	1
PVC (rigid)	270	rigid PVC with 10% plasticizers (crude estimate)	1*
PVC (flexible)	240	Flexible PVC with 50% plasticizers (crude estimate)	1*
PVDC	440	for thin coatings	3

Processing of plastics (in millipoints)

	Indicator	Description	
Blow foil extrusion PE	2.1	per kg PE granulate, but without production of PE. Foil to be used for bags	2
Calandering PVC foil	3.7	per kg PVC granulate, but without production of PVC	2
Injection moulding – 1	21	per kg PE, PP, PS, ABS, without production of material	4
Injection moulding – 2	44	per kg PVC, PC, without production of material	4
Milling,turning,drilling	6.4	per dm3 machined material, without production of lost material	4
Pressure forming	6.4	per kg	4
React.Inj.Moulding-PUR	12	per kg, without production of PUR and possible other components	4
Ultrasonic welding	0.098	per m welded length	4
Vacuum-forming	9.1	per kg material, but without production of material	4

Production of rubbers (in millipoints per kg)

	Indicator	Description	
EPDM rubber	360	Vulcanised with 44% carbon, including moulding	1

Production of packaging materials (in millipoints per kg)

	Indicator	Description	
Packaging carton	69	CO_2 absorption in growth stage disregarded	1
Paper	96	Containing 65% waste paper, CO_2 absorption in growth stage disregarded	1
Glass (brown)	50	Packaging glass containing 61% recycled glass	2
Glass (green)	51	Packaging glass containing 99% recycled glass	2
Glass (white)	58	Packaging glass containing 55% recycled glass	2

Production of chemicals and others (in millipoints per kg)

	Indicator	Description	
Ammonia	160	NH_3	1
Argon	7.8	Inert gas, used in light bulbs, welding of reactive metals like aluminium	1
Bentonite	13	Used in cat litter, porcelain etc.	1
Carbon black	180	Used for colouring and as filler	1
Chemicals inorganic	53	Average value for production of inorganic chemicals	1
Chemicals organic	99	Average value for production of organic chemicals	1
Chlorine	38	Cl_2. Produced with diaphragm production process (modern technology)	1
Dimethyl p-phthalate	190	Used as plasticizer for softening PVC	1
Ethylene oxide/glycol	330	Used as industrial solvent and cleaning agent	1
Fuel oil	180	Production of fuel only. Combustion excluded!	1
Fuel petrol unleaded	210	Production of fuel only. Combustion excluded!	1
Fuel diesel	180	Production of fuel only. Combustion excluded!	1
H_2	830	Hydrogen gas. Used for reduction processes	1
H_2SO_4	22	Sulphuric acid. Used for cleaning and staining	1
HCl	39	Hydrochloric acid, used for processing of metals and cleaning	1
HF	140	Fluoric acid	1
N_2	12	Nitrogen gas. Used as an inert atmosphere	1
NaCl	6.6	Sodium chloride	1
NaOH	38	Caustic soda	1
Nitric acid	55	HNO_3. Used for staining metals	1
O_2	12	Oxygen gas.	1
Phosphoric acid	99	H_3PO_4. Used in preparation of fertiliser	1
Propylene glycol	200	Used as an anti-freeze, and as solvent	1
R134a (coolant)	150	Production of R134a only! Emission of 1 kg R134a to air gives 7300 mPt	1
R22 (coolant)	240	Production of R22 only! Emission of 1 kg R22 to air gives 8400 mPt	1
Silicate (waterglass)	60	Used in the manufacture of silica gel, detergent manufacture and metal cleaning	1
Soda	45	Na_2CO_3. Used in detergents	1
Ureum	130	Used in fertilisers	1
Water decarbonized	0.0026	Processing only; effects on groundwater table (if any) disregarded	1
Water demineralized	0.026	Processing only; effects on groundwater table (if any) disregarded	1
Zeolite	160	Used for absorption processes and in detergents	1

Production of building material (in millipoints per kg)

	Indicator	Description	
Alkyd varnish	520	Production + emissions during use of varnish, containing 55% solvents	5
Cement	20	Portland cement	1
Ceramics	28	Bricks etc.	1
Concrete not reinforced	3.8	Concrete with a density of 2200 kg/m3	1
Float glass coated	51	Used for windows, Tin, Silver and Nickel coating (77 g/m2)	1
Float glass uncoated	49	Used for windows	1
Gypsum	9.9	Selenite. Used as filler.	1
Gravel	0.84	Extraction and transport	1
Lime (burnt)	28	CaO. Used for production of cement and concrete. Can also be used as strong base	1
Lime (hydrated)	21	Ca(OH)2. Used for production of mortar	1
Mineral wool	61	Used for insulation	1
Massive building	1500	Rough estimate of a (concrete) building per m3 volume (capital goods)	1
Metal construction building	4300	Rough estimate of a building per m3 volume (capital goods)	1
Sand	0.82	Extraction and transport	1
Wood board	39	European wood (FSC criteria); CO2 absorption in growth stage disregarded	1*
Wood massive	6.6	European wood (FSC criteria); CO2 absorption in growth stage disregarded	1*
Land-use	45	Occupation as urban land per m2 yr	*

Heat (in millipoints per MJ)

	Indicator	Description	
		Including fuel production	
Heat coal briquette (stove)	4.6	Combustion of coal in a 5-15 kW furnace	1
Heat coal (industrial furnace)	4.2	Combustion of coal in a industrial furnace (1-10MW)	1
Heat lignite briquet	3.2	Combustion of lignite in a 5-15kW furnace	1
Heat gas (boiler)	5.4	Combustion of gas in an atmospheric boiler (<100kW) with low NOx	1
Heat gas (industrial furnace)	5.3	Combustion of gas in an industrial furnace (>100kW) with low NOx	1
Heat oil (boiler)	5.6	Combustion of oil in a 10kW furnace	1
Heat oil (industrial furnace)	11	Combustion of oil in an industrial furnace	1
Heat wood	1.6	Combustion of wood; CO2 absorption and emission disregarded	1*

Solar energy (in millipoints per kWh)

	Indicator	Description	
Electricity facade m-Si	9.7	Small installation (3kWp) with monocrystaline cells, used on building facade	1
Electricity facade p-Si	14	Small installation (3kWp) with polycrystaline cells, used on building facade	1
Electricity roof m-Si	7.2	Small installation (3kWp) with monocrystaline cells, used on building roof	1
Electricity roof p-Si	10	Small installation (3kWp) with polycrystaline cells, used on building roof	1

Electricity (in millipoints per kWh)

	Indicator	Description	
		Including fuel production	
Electr. HV Europe (UCPTE)	22	High voltage (> 24 kVolt)	1
Electr. MV Europe (UCPTE)	22	Medium voltage (1 kV – 24 kVolt)	1
Electr. LV Europe (UCPTE)	26	Low voltage (< 1000Volt)	1
Electricity LV Austria	18	Low voltage (< 1000Volt)	1
Electricity LV Belgium	22	Low voltage (< 1000Volt)	1
Electricity LV Switzerland	8.4	Low voltage (< 1000Volt)	1
Electricity LV Great Britain	33	Low voltage (< 1000Volt)	1
Electricity LV France	8.9	Low voltage (< 1000Volt)	1
Electricity LV Greece	61	Low voltage (< 1000Volt)	1
Electricity LV Italy	47	Low voltage (< 1000Volt)	1
Electricity LV the Netherlands	37	Low voltage (< 1000Volt)	1
Electricity LV Portugal	46	Low voltage (< 1000Volt)	1

Transport (in millipoints per tkm)

	Indicator	Description	
		Including fuel production	
Delivery van <3.5t	140	Road transport with 30% load, 33% petrol unleaded, 38% petrol leaded, 29% diesel (38% without catalyst) (European average including return)	1
Truck 16t	34	Road transport with 40% load (European average including return)	1
Truck 28t	22	Road transport with 40% load (European average including return)	1
Truck 28t (volume)	8	Road transport per m3km. Use when volume in stead of load is limiting factor	1*
Truck 40t	15	Road transport with 50% load (European average including return)	1
Passenger car W-Europe	29	Road transport per km	1
Rail transport	3.9	Rail transport, 20% diesel and 80% electric trains	1
Tanker inland	5	Water transport with 65% load (European average including return)	1
Tanker oceanic	0.8	Water transport with 54% load (European average including return)	1
Freighter inland	5.1	Water transport with 70% load (European average including return)	1
Freighter oceanic	1.1	Water transport with 70% load (European average including return)	1
Average air transport	78	Air transport with 78% load (Average of all flights)	6
Continental air transport	120	Air transport in a Boeing 737 with 62% load (Average of all flights)	6
Intercontinental air transport	80	Air transport in a Boeing 747 with 78% load (Average of all flights)	6
Intercontinental air transport	72	Air transport in a Boeing 767 or MD 11 with 71% load (Average of all flights)	6

Recycling of waste (in millipoints per kg)

	Indicator			Description	
	Total	Process	Avoided product	Environmental load of the recycling process and the avoided product differs from case to case. The values are an example for recycling of primary material.	
Recycling PE	-240	86	-330	if not mixed with other plastics	7*
Recycling PP	-210	86	-300	if not mixed with other plastics	7*
Recycling PS	-240	86	-330	if not mixed with other plastics	7*
Recycling PVC	-170	86	-250	if not mixed with other plastics	7*
Recycling Paper	-1,2	32	-33	Recycling avoids virgin paper production	2*
Recycling Cardboard	-8,3	41	-50	Recycling avoids virgin cardboard production	2*
Recycling Glass	-15	51	-66	Recycling avoids virgin glass production	2*
Recycling Aluminium	-720	60	-780	Recycling avoids primary aluminium.	1*
Recycling Ferro metals	-70	24	-94	Recycling avoids primary steel production	1*

Waste treatment (in millipoints per kg)

	Indicator	Description	
Incineration		Incineration in a waste incineration plant in Europe. Average scenario for energy recovery. 22% of municipal waste in Europe is incinerated	
Incineration PE	-19	Indicator can be used for both HDPE and LDPE	2*
Incineration PP	-13		2*
Incineration PUR	2,8	Indicator can be used for all types of PUR	2*
Incineration PET	-6,3		2*
Incineration PS	-5,3	Relatively low energy yield, can also be used for ABS, HIPS, GPPS, EPS	2*
Incineration Nylon	1,1	Relatively low energy yield	2*
Incineration PVC	37	Relatively low energy yield	2*
Incineration PVDC	66	Relatively low energy yield	2*
Incineration Paper	-12	High energy yield CO2 emission disregarded	2*
Incineration Cardboard	-12	High energy yield CO2 emission disregarded	2*
Incineration Steel	-32	40% magnetic separation for recycling, avoiding crude iron (European average)	2*
Incineration Aluminium	-110	15% magnetic separation for recycling, avoiding primary aluminium	2*
Incineration Glass	5,1	Almost inert material, indicator can be used for other inert materials	2
Landfill		Controlled landfill site. 78% of municipal waste in Europe is landfilled	
Landfill PE	3,9		2
Landfill PP	3,5		2
Landfill PET	3,1		2
Landfill PS	4,1	Indicator can also be used for landfill of ABS	2
Landfill EPS foam	7,4	PS foam, 40 kg/m3, large volume	2*
Landfill foam 20kg/m3	9,7	Landfill of foam like PUR with 20kg/m3	2*
Landfill foam 100kg/m3	4,3	Landfill of foam like PUR with 100kg/m3	2*
Landfill Nylon	3,6		2*
Landfill PVC	2,8	Excluding leaching of metal stabilizer	2

Landfill PVDC	2,2		2
Landfill Paper	4,3	CO_2 and methane emission disregarded	2
Landfill Cardboard	4,2	CO_2 and methane emission disregarded	2
Landfill Glass	1,4	Almost inert material, indicator can also be used for other inert materials	2
Landfill Steel	1,4	Almost inert material on landfill, indicator can be used for ferro metals	2
Landfill Aluminium	1,4	Almost inert material on landfill, indicator is valid for primary and recycled alu.	2
Landfill of 1 m^3 volume	140	Landfill of volume per m^3, use for voluminous waste, like foam and products	*
Municipal waste		In Europe, 22% of municipal waste is incinerated, 78% is landfilled. Indicator is not valid for voluminous waste and secondary materials	
Municipal waste PE	-1,1		2*
Municipal waste PP	-0,13		2*
Municipal waste PET	1		2*
Municipal waste PS	2	Not valid for foam products	2*
Municipal waste Nylon	3,1		2*
Municipal waste PVC	10		2*
Municipal waste PVDC	16		2*
Municipal waste Paper	0,71		2*
Municipal waste Cardboard	0,64		2*
Municipal waste ECCS steel	-5,9	Valid for primary steel only!	2*
Municipal waste Aluminium	-23	Valid for primary aluminium only!	2*
Municipal waste Glass	2,2		2*
Household waste		Separation by consumers of waste for recycling (average European scenario)	
Paper	-0,13	44% separation by consumers	2*
Cardboard	-3,3	44% separation by consumers	2*
Glass	-6,9	52% separation by consumers	2*

Annex 3

Ecoindicators from SimaPro that has been added to the EcoScan software.

	Complete name	Ecoindicator	Library
25CrMo4	25CrMo4 I	78,4 mpts	Idemat 2001
GG30	GG35 I	32.3 mpts	Idemat 2001
Methracrylate PMMA	PMMA sheet A	632 mpts	Industry data
NBR	NBR I	298 mpts	Idemat 2001
Silicate (water glass)	Silicate(waterglass) ETH T	58.8 mpts	ETH-ESU 96
Tungsten	Tungsten I	890 mpts	Idemat 2001
Hazardous oil waste incineration	Waste oil to special waste incinerator S	156 mpts	ETH-ESU 96 System processes.
Disposal landfill for inert materials.	Disposal, Wood, untreated, 20% water, to sanitary landfill.	3.34 mpts	Ecoinvent unit process.

Annex 4

Cost activities for acquisition, ownership and disposal phases in Prolima project:

- 1.1. Concept and definition
  - 1.1.1. Market research
  - 1.1.2. Project management
  - 1.1.3. Product concept and design analysis
  - 1.1.4. Preparation of a requirement specification of the product
- 1.2. Design and development
  - 1.2.1. Project management
  - 1.2.2. Design engineering, including reliability, maintainability and environmental protection activities
  - 1.2.3. Design documentation
  - 1.2.4. Prototype fabrication
  - 1.2.5. Software development
  - 1.2.6. Testing and evaluation
  - 1.2.7. Producibility engineering and planning
  - 1.2.8. Vendor selection
  - 1.2.9. Demonstration and validation
  - 1.2.10. Quality management
- 1.3. Manufacturing
  - 1.3.1. Industrial Engineering and operations analysis
  - 1.3.2. Construction of facilities
  - 1.3.3. Documenting
  - 1.3.4. Software making
  - 1.3.5. Type-approval testing (qualification testing)
  - 1.3.6. Production management and engineering
  - 1.3.7. Facility maintenance
  - 1.3.8. Fabrication
  - 1.3.9. Assembly
  - 1.3.10. Set up
  - 1.3.11. Testing
  - 1.3.12. Quality control and inspection
  - 1.3.13. Storage
- 1.4. Installation
  - 1.4.1. Packaging
  - 1.4.2. Shipping
  - 1.4.3. Transportation
  - 1.4.4. Installation at customer's
  - 1.4.5. Training
- 2.1. Operation
  - 2.1.1. Training
  - 2.1.2. Operating
  - 2.1.3. Waste Handling
  - 2.1.4. Upgrading
- 2.2. Maintenance
  - 2.2.1. Maintenance training
  - 2.2.2. Preventive maintenance
  - 2.2.3. Corrective maintenance
- 3.1. System shutdown
- 3.2. Decommissioning
- 3.3. Disassembly
- 3.4. Removal
- 3.5. Recycling
- 3.6. Safe disposal

Types of cost in use phase, Prolima project:

1. Labour: it refers to the personnel costs to carry out an activity.
    1.1. Operator
    1.2. Specialist
2. Material: it refers to the cost of the material consumed when carrying out an activity. there are a few different types of material costs that can be classified as follows:
    2.1. Tooling: it refers to the cost of the equipment required to carry out an activity to build or operate a machine tool.
        2.1.1. Fixtures
        2.1.2. Tools for maintenance
        2.1.3. Production tooling
        2.1.4. Special Support equipment
        2.1.5. Test equipment
        2.1.6. Tools for operation
            2.1.6.1. Grinding tool
            2.1.6.2. Cutting tools
            2.1.6.3. Moulds
    2.2. Utilities: it refers to the energy and fluids required to activate the different systems installed in the machine tool.
        2.2.1. Electricity
        2.2.2. Petrol
        2.2.3. Gas
        2.2.4. Steam
        2.2.5. Water
        2.2.6. Air
        2.2.7. Hydraulic Oil
    2.3. Consumables: it refers to the materials consumed while the machine tool is operating.
        2.3.1. Coolant
        2.3.2. Lubricants
        2.3.3. Filters
        2.3.4. Spare parts
    2.4. Waste materials: it refers to the cost of the materials resulting from the operation of the machine tool.
        2.4.1. Used Filters
        2.4.2. Sludge
        2.4.3. Used Coolant
3. Space: the cost of the floor space used by the machine when operating at the customer’s site.
4. Administration: administration cost of any activity.
5. Warranty: costs of an extension of the warranty period.
6. Consequential costs: costs derived from the unscheduled stop of the machine.
    6.1. Warranty costs
    6.2. Liability costs
    6.3. Costs due to loss of revenue
    6.4. Costs for providing an alternative service
    6.5. Loss of image, reputation, prestige

Annex 5

Nomenclature of the variables from the equations.

functional_unit	Functional unit of the analysis [hour]
$(Water)_{CF}$	Water consumption for cutting fluid product[litre]
Water_Cost	Cost of the water used in cutting fluids for the functional unit [Euro]
%Water	Percentage of water in the cutting fluid [%]
CF_Capacity	Capacity of the cutting fluid cooling system [litre]
%Losses	Percentage of cutting fluid lost during working life [%]
Meantime_between_change	Meantime between cutting fluid removal [hour]
Tool_cost	Cost of the cutting tools for the functional unit [Euro]
Tool_life	Time the tool is operational before wearing out [hour]
Nºregrid	Number of times the tool is regrided and used again
CF_cost	Cost of the cutting fluis for the functional unit [Euro]
Nºmachines	Number of machines that share the same system.
Lubricant cost	Cost of the lubricant oil for the functional unit [Euro]
Discharge_rate	Lubricant quantity that is supplied to the lubricant system [litre]
Meantime_between_supply	Meantime between lubricant oil supply [hour]
Filter_Cost	Filter cost for the functional unit [Euro]
Meantime_between_F_change	Meantime between filter changes [hour]
NºFilters	Number of filters on the filtering system.
Nºspent_Filters	Number of spent filters for the functional unit.
Spent_filters_mass	Weight of total spent filters for the functional unit [kg]
Disposal_cost	Disposal cost per litre or kg for different wastes [Euro]
Spent_Filter_cost	Cost of total spent filter disposal for the functional unit [Euro]
Spent_CF	Spent cutting fluid quantity for the functional unit[litre]
Spent_CF_cost	Spent total cutting fluid disposal cost for the functional unit[Euro]
Sludge_cost	Cost for the total sludge disposal for the functional unit [Euro]
Sludge_mass	Sludge mass collected for the functional unit [kg]
Spent_Lubricant_cost	Cost for the total spent lubricant disposal for the functional unit [Euro]
Chip_mass	Metal chip mass that is removed from the part [kg]
Workpiece_volume	Volume of the part before machining [cm3]
Part_volume	Volume of the part after machining [cm3]
density	Density of the material of the part [kg/cm3]
Time_part	Time need for machining a part [hour]
Chip_cost	Cost for the total chip disposal for the functional unit [Euro]
Chip_processing_cost	Cost of chip recycling process [Euro/kg]
Recycled_chip_income	Profits from recycled metal chips [Euro/kg]
Spent_Tool_cost	Cost for the total tool disposal for the functional unit [Euro]
Machine_floor_cost	Cost of the total space taken up by the machine [Euro]
Machine_space	Space taken up by the machine [m2]
Auxiliary_space	Space taken up by the auxiliary equipment of the machine [m2]
Shared_auxiliary_space	Space taken up by the shared auxiliary equipment of the machine [m2]
Floor_cost	Cost of the factory floor [Euro/m2]
Labour cost	Total labour cost for the functional unit [Euro]
Worker cost	Hourly cost, per worker [Euro/hour]
NºWorkers	Number of workers that are working with the machine.
functional unit [T_1]	Operational time defined in the functional unit [hour]
functional unit [T_2]	Start-up time defined in the functional unit [hour]
functional unit [T_3]	Runtime defined in the functional unit [hour]
functional unit [T_4]	Cutting time defined in the functional unit [hour]

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