



Material Flow Analyses

Simulation Environmental analysis in the manufacturing
of textile products

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Material Flow Analysis - Simulation Environmental
analysis in the manufacturing of textile products

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Abstract

The growing concern about the environmental sustainability on production models have generated on the manufacturing sector a constant pressure based on the fact that natural resources are consumed, plus the production of wastes and effluents with large polluting potential.¹

Thus, there is a need for acting on current factory production models, to mitigate their impact on the environment, ensuring at the same time the economic feasibility of the processes involved.

In accordance to the previous paragraph, the present project has as its main objective the environmental analysis of a tailoring factory.

The tasks carried out, were as follows:

- Definition of Material Flow Analysis (MFA);
- Methodology used in MFA and its applicability;
- Computational tool employed: Umberto;
- Implementation of inventory and process layout;
- Analysis of simulation results;
- Identification of “hot spots” (points of the process that has higher impact on the process) to improve the inherent behaviour of the production process

To achieve the previously stated objectives, this project is subdivided in five sections.

The first section, introduction, is related to the explanation of what is material flow analysis and its benefits and a brief historical development. It also refers to the raw materials and processes involved in the textile manufacturing industry,

The second section, methodology, refers to the foundation of material flow analysis, its implementation in the chosen software and the methodology being both.

The third section explains detailed the case study of the project. In the fourth section the results are presented as well as the discussions. The fifth section refers to brief conclusions that were achieved in the project. The final section contains the work assessment.

Keywords: Material flow analysis, Umberto software, environmental modelling, simulation textile manufacturing

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Notation and Glossary

t	tons
yr	year
kg	kilogram
c	cross-section
ΔT	time gap
M	materials
E	energy
LO	living organisms
I	information
[M]	Adimensional mass
[T]	Adimensional time
[L]	Adimensional length
[TC]	transfer coefficient
X	Substance
$X_{O,i}$	output of material i
$X_{I,i}$	input of material i
m^3	cubic meter
kWh	kilowatt hour
kJ	kilojoule

List of Abbreviations

ATC	Agreement on textiles and clothing
A.S.T.M.	American Society for testing and materials
B.C.	Before Christ
MFA	Material Flow analysis
E.U.	European Union
IfEU	Institut für Energie und Umweltforschung Heidelberg
LCA	Life Cycle Analysis
WCDE	Worldwide Commission of Development of the Environment
WRI	World Resource Institute

*"There is a sufficiency in the world
for man's need but not for man's
greed."*

Mohandas K. Gandhi

*"If you don't know where you're
going how do you expect to get
there?"*

Popular quote

1 Introduction

The world population growth rate is close to 1.17% per annum². Thus, we should ask ourselves how long the Earth's natural resources will be sufficient to sustain this continuous increase (exponential) growth in population.

Previous studies³ have concluded that everything on Earth has limits and if not respected, a collapse is the unavoidable outcome. The dependence on non renewable natural resource (e.g. fossil fuels) is a main concern at present.

Technology, one of the dimensions of the present global change, has come in the past to the rescue several times, but the size of the present environmental issues makes difficult, if not impossible, its benefits for any case.

In 1987, the Brundtland report brought into the discourse a new concept: **sustainable development**, defined by the Worldwide Commission of Development of the Environment (WCDE) in 1987 as "*meeting the needs of present generation without compromising the ability of future generations to meet their own needs*"⁴.

Sustainable development can be understood as a rational and wise way of using natural resources, where the ideal would be drawn from nature only what can be reset. Materials that were removed should not return to nature as waste, but should be recycled and return as consumer goods. When this is not possible, the effluents should be dealt with in order to reduce the environmental impacts caused by the industrialization.⁵

Thus, this kind of thinking can be compared to the nature process itself, "When a living organism dies, it takes its place in the food chain. When a human artefact gets to the end of its life, it should go back into the material chain."⁶

As so, to meet the new environmental requirements, several methods and techniques were implemented in order to act in a preventive or corrective way on the environmental impacts. As so, the methodology of **Material Flow Analysis (MFA)** was developed so it could be applied as a sustainable development tool.

1.1 Material Flow Analysis

What is MFA?

“Material flow analysis (MFA) is a systematic assessment of the flows and stocks of materials within a system defined in space and time.”

Brunner and Rechberg, 2004

This methodology connects and analyzes every process since the raw material through the final product, with every pathways, intermediate processes and residues caused in the manufacture. All the results obtained can be controlled applying a material balance to all inputs, stocks and outputs of a process, since it respects the law of conservation of matter. This is the main distinct characteristic that makes this method attractive and as times goes by it has been applied more frequently as a decision support tool in resource, waste and environmental management.

One special characteristic of MFA is that it can be applied to case studies that include the environment and anthropogenic systems. An anthroposphere can be defined as a part of the biosphere that has been modified by the activities of humankind.⁷ Thus MFA serves as a linkage between the two systems, exchanging data as energy, space, information and socioeconomic issues, and all information that might be relevant to the case study.

It can be performed without considering these aspects, but often these factors are necessary to interpret and to obtain accurate results. Therefore MFA analyse is often completed with energy analysis (taking in count the law of energy conservation), economic analysis, urban planning and the linkage between them.

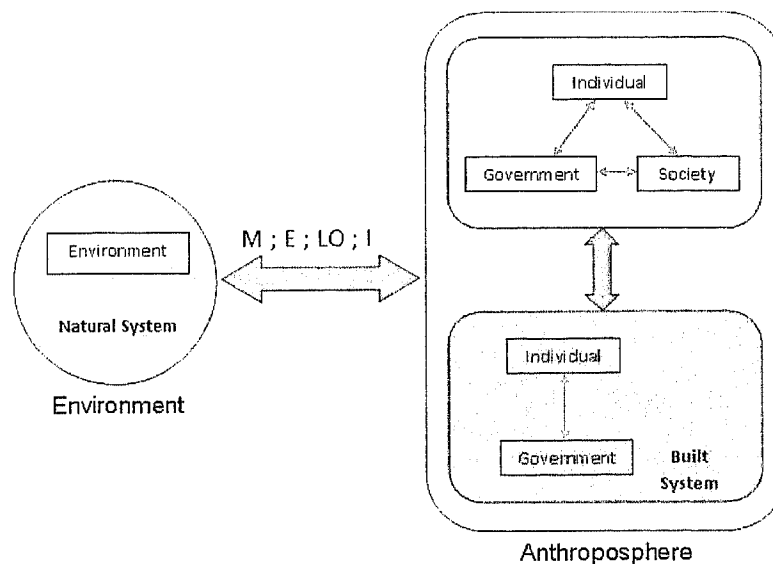


Figure 1-The two systems, Environment and Anthroposphere exchanging Materials (M), Energy (E), living organisms (LO) and Information (I)⁸

1.2 Historical development of MFA

The MFA methodology builds on the earlier concepts of material and energy balancing. But long before it was applied as a tool for managing resources, wastes and as environmental tool, the mass balance principle has been applied in several other fields, such as medicine, chemistry, economic between others. Greeks Philosophers were the first who postulated the law of conservation of matter (input equals output) more than 2000 years ago⁹. In the middle 1770s, Antoine Lavoisier (1743-1794) formulated what was called “Law of Lavoisier” or the “law of conservation of mass”, which was described as *“Neither man made experiments nor natural changes can create matter, thus it is a principle that in every process the amount of matter does not change”*. Even if it was an ancient knowledge, (the Greeks where the one who first applied it), Lavoisier was the first who provided experimental evidence for the confirmation¹⁰.

The concept of conservation of matter had been applied to different areas even before the concept of MFA had been developed. The chemical engineers applied it to analyze and balance the inputs and outputs of chemical reactions. In the economics area, Leontief introduced input-output tables in 1930, allowing then the basis of methods to solve economic problems, between several other examples.

The first MFA ever applied was in the area of medicine, by Doctor Santorio Santorio (1561-1636) and the objective was to measure the material metabolism of the human body. Santorio measured every input (food, drinks, etc) given to a subject, and measured every output's (sweat, feces). Santorio observed that the output weighed much less, witch by the law of conservation of matter wasn't possible. So Santorio formulated a hypothesis that an unknown fluid leaves the body during the night but didn't know neither what was neither how. What Santorio didn't take in count was the air breathed by the human body.

The first studies in the fields of resource conservation and environmental management were performed in the 1970s. The first two areas of application were the metabolism of cities and the analysis of pollutant pathways in watersheds regions or urban areas.

As said before, with the Brundtland report, MFA had developed and been applied in such a widespread area that it is probably the preferential tool in the study of the environment impact.

The first material flow accounts applied on a national level had been made at the beginning of 1990s for the country of Austria (studied by Steurer, 1992), and Japan (performed by the Environment Agency of Japan, 1992).

Since then, it has been a growing field with scientific interest. Major efforts have been made to harmonize the different methodological approaches developed, so that they can be as accurate as possible. The main objective is developing the methodology so it can be as rigorous and exact that can be applied generally with scientific feasibility. To assess this harmonization, the European Commission created the Concerted Action “ConAccount” (www.conaccount.net). Other important factor that contributed to this objective was guided by the World Resource Institute (WRI www.wri.org) when they brought together MFA experts to proceed a MFA analysis to four countries in a first study and later to five countries. In their first publication¹¹ material inputs of four industrial societies have been assessed and guidelines for resource input indicators have been defined.¹²

Thus MFA has been largely optimized and applied to several studies, and has been recognized as a tool that can be assessed in several different areas.

1.3 Application and objectives of MFA

“Constant variations of the prices, availability and quality of raw materials, as well as the characteristics of components and auxiliary materials necessary for production or functioning of services are a permanent challenge for the enterprise management as well as for public or private enterprises.

The differences between the estimated and effective costs are largely known, and have to be seen as an alarm symptom because they reveal a harmful management practice.”¹³

Several methods have been developed that allows quantification on the use of natural resources by the society. One of the most internationally recognized method as a tool for evaluating environmental policies is MFA. The principle concept beyond MFA is a simple model of the inter-relation between the economy and the environment, in which economy is an embedded subsystem of the environment.

Knowing the material flows related to the production system, finding the hot spots that are vulnerable and analyzing the viability of possible alternatives, identifying the elements on the system that can put in risk the legal conformity of the company and having a choice that can predict exactly the costs associated by other options, all of this factors are part of the system on the enterprise management orientated to the promotion of the efficiency, and to assess the high quality of the products and services produced, taking in count all the legal issues.

An MFA study can focus on a single process of the system, a single infra-structure or parts of them, but can also be applied to all the company, or incorporate outsiders such as suppliers or costumers. By applying a MFA study, the contributions of each process for all input or output material flows are known as well as its associated costs. It is a tool that supports the decisions on optimizing processes and it's energetic and materials efficiencies that allows the applicability of alternative technologies.

There are an endless potential on the MFA tool, some of the most frequently application are:

- Environmental management and engineering;
- Industrial Ecology study and the surrounding environmental impact
- Resource and waste management

Anthropogenic metabolism (relates to the environment that had been modified by human activities) such as:

- Unprecedented growth

- Linear urban materials flows
- Changes in amount and composition of wastes

By choosing which tool to apply to each study, the most important issue to take in count is what objectives it has to respond. As so, the main objectives that an MFA can respond by being applied are listed below:

Delineate a system which allow that the material flows and stocks are well defined and in uniform terms;

Reduce the complexity of the system as possible, while still guaranteeing a basis to choose and perform a rigorous decision;

Assess the relevant flows and stocks in quantitative terms, thereby applying the balance principle and revealing sensitiveness and uncertainties;

Present results about flows and stocks of a system in a reproducible, understandable and transparent way;

Use the results as a base for managing resources and wastes in such a way that minimizes its impact on the environment;

Early recognition for potentially harmful or beneficial accumulations and depletions of stocks, as well as for timely prediction of future environmental loadings;

The settings of priorities regarding measures of environmental protection, resource conservation and waste management (category the decisions by its importance, what's more important comes first);

The design of goods processes and systems that promotes environmental protection, resource conservation and waste management (green design, eco-design, design for recycling or disposal, etc...)

One of the disadvantages of MFA is that it quickly reaches the limits of capability on processing the data manually because it requires an infinite of cross in formations and an excellent documentation technique. Despite his recognized methodological value, it's applicability in practical investigation and in system management collides with the difficulties in applying the data obtained. Software was at the beginning applied to simplify the management of the environment data, but then was developed to enlarge its applicability to management systems of public and private entities, as well as investigation projects that applies this methodology.

1.4 Software and simulation

MFA actually is applied by implementing the data acquired from the case study in specific software that is available in the market that provides simulations of the system in study.

A simulation is a construction process of a model that is a real system and then conducting experiences on that model, with the objective of understanding and learning the behavior of the system and/or to evaluate operation strategies to reach the objectives that are stipulated. The objectives of the simulation models on MFA can be as example the evaluation on industry implementation, management and planning of the capability of production or production control, engineering and optimization of processes, evaluation of routes for material transport, evaluation and optimization on the ambient impacts, etc...

The principal advantages¹⁴ on simulation software are:

- Evaluation of real systems (with or without physical existence) complex and whit stochastic elements,
- Reduce of costs associated on the development on physical prototypes;
- Possibilities of analyzing different types of schemes or different procedures in the same model, or even quickly modified;
- Detailed evaluation of the simulation modulated;
- Identification of the variables with an major impact on the system performance;
- Dynamic visualization (2D or even 3D) of the system modulated

The principle disadvantages are:

- Elevated costs of equipment (hardware, peripheral systems, software...)
- Elevated time consumed on the development of the models;
- Necessity of specialized training;
- Difficulties on the interpretation of results (the simulation provides estimations of the system parameters)

As all tools, the simulation on MFA also has his methodology that can be resumed as:

- Definition on the objectives of the simulation study and frontiers;
- Acquisition and analyze of the data;
- Development of the simulation model;
- Experimentation;

- Analyse of the results

There are some requirements that software must possess in order to fulfill the objectives¹⁵ of MFA such as:

- The terminology be compatible or if possible the same as MFA;
- The methodology be compatible with the one applied by MFA, this is create material flow systems such as networks by assembling elements in a interactive way;
- The software has the capabilities of managing the data in different forms such as inputs, outputs, data storages and uncertainties.
- Be capable to do different types of calculations such as descriptions of the actual state of a model, simulating different scenarios, comparison between scenarios or simulating a dynamic behavior of a system as well as a static.

There are several options on software available in the market that can perform MFA. The most known and more reliable are Simbox®, Gabi® and Umberto®. Simbox® is the only software that was developed exclusively to apply MFA methodology, and its terminology thus it is limited.

Gabi® bases its calculation model on linear equation system, thus all the variables must be specified or else no calculations will be made.

The chosen software was Umberto® because it bases its calculation on Petri nets, they are done iteratively and if some variable isn't specified it will perform iterations to achieve a value that fits the system. Another major advantage is the possibility of displaying the results in Sankey diagrams. These are flowcharts in which the width of the arrow is proportional to the flow quantity. This is very suitable for visualizing quantity flows in a system and thus is an ideal supplement to the normal display of material flow networks. Other featured characteristic in Umberto® is cost accounting and cost allocation.

1.5 Textile Industry

This chapter has the intention to provide a brief description of the textile industry, its history, current status of global and European industry as well as a brief description on the process and raw materials.

1.5.1 History of Textile Industry

Since the earliest times that mankind manufactures textiles, in order to protect themselves from the aggressiveness of the surround environment (such as the cold weather or the season predators). The oldest known fibre material used by early humans was discovered in a cave in the Republic of Georgia with approximate 34 000 years old¹⁶. As so, the textile industry is one of the oldest in the world. At the beginning, it was only a domestic or a family industry, regarding only small quantities or only for local sellers, until 1500s, when was established the first factory system, where all the fabrication was man powered. It was only until the 18th century, marked in history has the industrial revolution, that were developed power machines for spinning and weaving, and only in 1769, when Richard Arkwright patented the spinning frame with variable speed rollers. Only then manual power was replaced by water power.¹⁷

1.5.2 State of textile industry

Until the decade of the sixties and seventies the textile sector where divided, and each continent dominated its own market. Since then, the textile had developed due the effects of increase competition from the new countries producers who joined the international market. First Asia in the sixties/seventies then China followed the same model in the eighties and more recently the Southeast Asia and India.

This caused alterations in the industry structure, such as a trend to relocation and regionalization of the manufacture and also an increase of the international trade market. As their cheaper and more abundantly but less qualified hand-labor (that results on even smaller salaries) the Asian market had a lower price on retails.

To have a equilibrium in the economy, in 1973 in Geneva was agreed a protocol that kept in force the agreement related to the international textile trade, named "*Multifibres Agreement*", which established quotes for limit the textile quantities exported by the countries, especially the Asian's, with the purpose to ensure the textile trade competitive for all involved.

In 1994, in Marrakech, was signed the “*Agreement on Textiles and Clothing*” (ATC) also known as the “*Marrakech Agreements*”, who’s main purpose was “*trade in textile and clothing products is no longer subject to quotas under a special regime outside normal WTO/GATT rules but is now governed by the general rules and disciplines embodied in the multilateral trading system*”¹⁸. This abolished the *Multifibres Agreement*, and all the limitation on import/exportation quotes. As result, from first January of 2005 occurred the complete liberalization in textile markets and all import quotas disappeared completely. This measure was taken to ensure a more competitive and contribute to a globalization of the markets. This opened the market worldwide, and the textile and clothing sector changed significantly due the competition between producers.

1.5.3 Textile Industry situation in Europe

One of the main characteristic of textile industry is that’s one of the longest and complicated industrial chains in manufacturing industry. This is due its fragmentation and heterogeneous sector that is dominated by small and medium enterprises. Usually each one specifies in a single or a unique process of the whole chain process. The three main final products are clothing, home furnishing and industrial use.

Italy is by far the leading European producer for textiles, followed by Germany, France, and the UK and Spain, together accounting for over 80 % of the production in the EU.

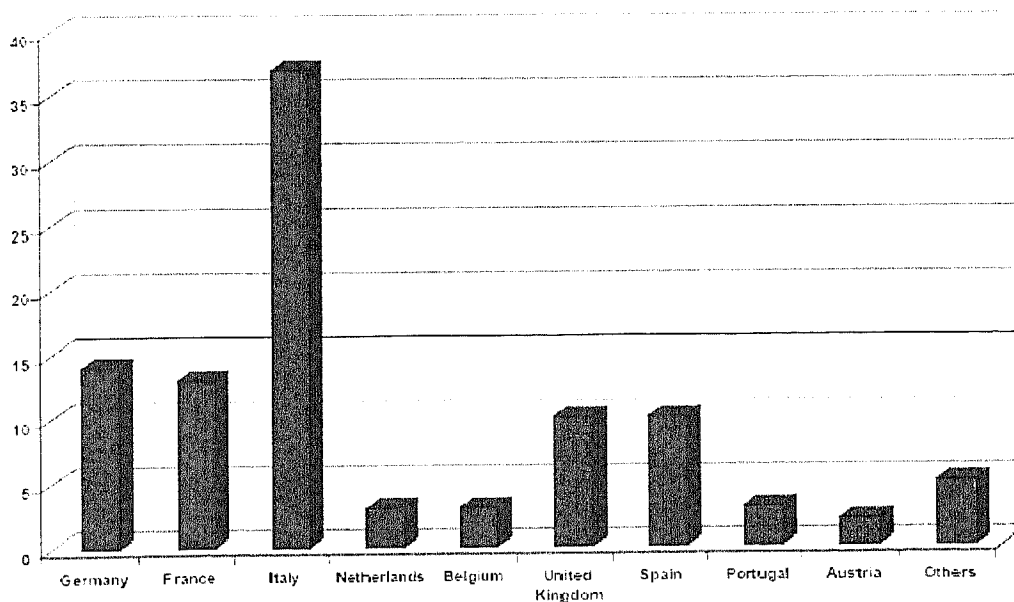


Figure 2 – distribution of textile finishing industry in the EU¹⁹

In 2006 the European Union textile and clothing industry represented 6.9 % of the industrial employment, with a billing of 201 979 millions €, with 146 613 companies which employed 2 122 924 workers. It had consumed textile products about 15-25 kg/habitants per year²⁰. The share of the main type of fibres applied on the textile industry in the EU is displayed in the follow table.

Table 1-fibres distribution in the EU (source: EURATEX 2005)

Type of fibber	% applied in EU
Cotton	45
Wool	8
Polyester	14
Silk	2
Viscose	12
Acrylic	4
Others	15
Total	100

The textile industry is composed of a wide number of sub-sectors, covering the entire production cycle since the production of raw materials (man-made fibres), to semi-processed (yarn, woven and knitted fabrics with their finishing processes) into final products (carpets, home textiles, clothing and industrial use textiles). The share of applications of the textile industry are displayed in the next table

Table 2-distribution of the textile application in the EU (source Euratex 2005)

Application	% applied in EU
Clothing textile	45
Household textile	20
Interior textile	10
Technical textile	18
others	7
Total	100

The liberalization on import quotas due the “*Agreement on Textiles and Clothing*” had flooded the European with textiles from Asian countries, causing a crisis in sector. This situation has been improving over time, with the European gaining new competencies in order to compete and have more exportation, but the cheaper hand labor, the abundance of raw materials and a less rigid legislation in the Asian continent has been interfering with the economic balance on the market.

1.5.4 Textile manufacturing process description

The textile manufacturing begins with the production or harvesting of raw fibre. The fibres used in textiles can be harvested from natural source such as wool or cotton, or can be manufactured from regenerative cellulose materials such as rayon or acetate, or it can be synthetic such as polyester or nylon. The basic steps in this chain are schematically represented in the following diagram and will be briefly described.

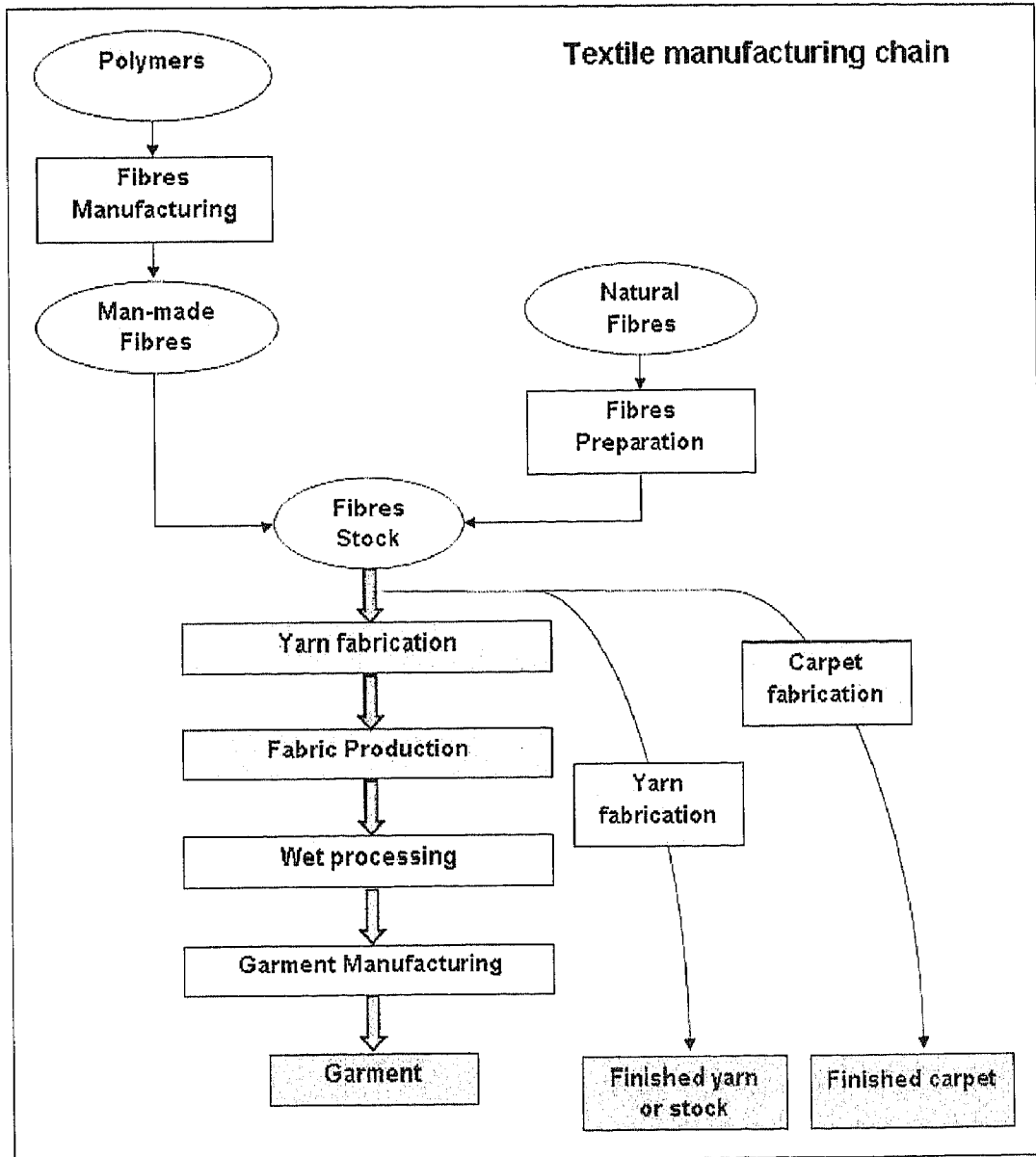


Figure 3- Simplified textile manufacturing chain ²¹

The first stage in the textile manufacture is the **fibre production**. There are different types and techniques of production depending on the origin of the raw-material. Usually this step is made in external factories, and then the final product is bought.

After the acquisition of fibres, there are two possibilities that depend from the textile purpose. It can be directly applied to **carpet fabrication**, or, it can advance to **yarn fabrication**. This is the process which converts raw fibre into yarn or thread. In this stage the fibres are prepared and drawn out and twisted to form yarn, and then wound onto a bobbin or a cone. Usually this process is entirely dry, but some yarns can be dyed and finished as a final costumer product which can be simply stored to future use or to be sold in the market (**Finished yarn or stock**).

The next step, **fabric production**, involves four main independent method, **weaving, knitting, tufting** or **non-woven**. These two last stages are relatively new in the industry, thus not as frequently present as weaving and knitting.

In production the most common is weaving. It is carried out of two sets of threads, which interlaces lengthwise (warp yarns) with width wise yarns (filling yarns).

The knitting method consists of loops called stitches pulled through each other. The active stitches are held on a needle until another loop can be passed through them, usually using sophisticated and high speed machinery but it can also be hand-made.

Tufting is the process of inserting additional yarns into the textile to create a denser textile. Patterns may be formed by varying the height of the tuft loops. It is used for apparel fabrics, blankets although most of tufting is applied in carpeting.

Non-woven fabrics are the newest in the range of fabric manufacturing. It has a strong appeal to manufacturers and public generally because it can be produced rapidly and cheaply and haves a good satisfaction by the consumers. They are defined as sheet or web structures bonded together by entangling fibres mechanically, thermally or chemically. They are flat, porous sheets that are made directly from separate fibres, molten plastic or plastic film. They are not made by weaving or knitting and do not require converting the fibres to yarn, and have different applications since medical until engineering purposes.

The fabric produced by the previous stage is in none very presentable conditions, it is rough to the touch and contains impurities that can be either natural from the fibres or been added to facilitate the manufacture. Wet processing (also called fabric processing) is done to improve the appearance and applicability of the fabric. There are generally four operations carried that includes pre-treatment, dyeing, printing and finishing.

Until this stage all operations involve mainly dry operations, which consumes very little water and chemicals, while this stage involves wet operations, and as so, the quantity of waste generated is relatively high.

In the pre-treatment operation the impurities are removed and the fabric is bleached and the tensile strength increased. After this is concluded, the dyeing operation is applied to give an all over shade to the fabric. It involves diffusion of dye molecules into the textile fabric, which imparts the required color. The next step, printing is a process in which colored patterns are produced on the fabric. Usually it is only carried on prepared fabric where it is applied to specific areas to achieve a planned design. The color is applied to the fabric and then treated with steam, heat or chemicals to fix the color on the fabric. The finishing step involves operations that are necessary for making the textile presentable and attractive. It dries the fabric, provides the required dimensions of width and length and gives the final treatment to the fabric have an attractive view and touch according to the application that are made. The final stage of garment production is the **garment manufacturing**. This stage while be further ahead described in case study chapter. The finished cloths are fabricated into a variety of apparel and household industrial products. The simpler products such as bags, sheets or towels are often produced by the textile mills themselves, but apparel or more complex house wares are usually fabricated by cutting trades.

1.5.5 Raw Materials

The raw materials in textile industry can be categorized in two general groups: natural and manmade fibres (see table below). The distinctions are made according the source of origin. Natural fibres are those obtained in the nature, are products of agriculture such as cotton, or wool (provided by animals). Manmade fibres covers both purely synthetic materials such as nylon that is a polyester derived from petrochemicals, and regenerative cellulose materials such as rayon or acetate, materials that are manufactured from wood fibres. A more detailed classification is displayed in the following table

Table 3-Types of fibres categories²²

Natural fibres	Animal	Raw wool
		Silk
		Hair
	Vegetable	Raw cotton
		Flax
		Jute
Manmade fibres	Natural polymers	Viscose
		Cupro
		Acetate
	Synthetic polymer	Polyester (PES)
		Polyamide (PA)
		Polyacrylonitrile (PP)
	Inorganic Polymer	Glass for fibre glass
		Metal for metal fibre

Although there is a lot of different kind of fibres, in our case study mostly all the raw material is cotton. As so, it will be described, although briefly.

1.5.5.1 Cotton²³

All varieties of cotton (botanical name "Gossypium") grew originally in the desert zones of both the old and new world. Cotton fibre was used at the end of the Stone Age to manufacture strings and fishing nets. The time that cotton started to be applied as a textile raw material is not known, but there was found at Mohen Daro (Pakistan) evidences that proved that cotton manufacture has already been made in 3000 B.C.

The word cotton comes from Arabic "Katun" which means plant of the conquered lands, with reference to the invasion of India by Alexander "the Great" in 327 B.C. The cotton plant, as it is originally from deserts, need much sunlight and a warm climate, consequently it cannot be grown naturally in Western Europe (except Greece and Spain). The major countries cotton producers are China, United States, India and Pakistan.

The cotton fibre is characterized by the presence of a cavity in its interior called "lumen". The quality assessment of the cotton fibres is based on the following characteristics: **staple length**; cross-section size, usually also denominated by **fineness**; and **linear mass**. The thinnest yarn counting (lowest fibres per cross-section of yarn) attainable in spinning process (further it will be described), also denominated by spin ability depends from the length and fineness of the cotton.

The tenacity of the yarn is related to the strength of the individual fibres as well as the number of fibres in the cross-section of the yarn which usually is between 90 and 120.

The fibre fineness is defined by the American standard ASTM D123-85 and D 1448-84 as the weighted average linear mass expressed in micrograms per inch or millitex $\mu\text{g}/\text{cm}$. These values were assessed with a gravimetric test method by weighing measured fibre lengths. For commercial purposes, the linear mass is assessed today more quickly through special micronaire testing (or similar) instruments.

Beside fineness, another very important property is the **maturity degree**, which is the ratio between the lumen length and the thickness of the fibre wall.

There are also other important factors that assess the fibre quality such as its color, purity and fibre preparatory process. These characteristics all together contribute to determinate the grade and consequently the market value of the fibre.

2 Methodology

As already been described, there are several different methodologies developed on MFA, and has this tool isn't worldwide standardized, there are different terminologies that may be applied. The most usual, and more accepted in our days is the definitions developed by Baccini and Brunner in the 1980s, and it will be employed from this point forward.

The starting point of MFA is the definition on the terminology applied²⁴. Terms such as **material**, **substances**, **good**, **process**, **stocks**, **flows**, **fluxes**, **system** and **system boundary** (or system limits) must be defined to avoid future complications or confusion.

In MFA, the term **material** stands for both **substances** and **goods**.

Substances are defined as a single type of matter consisting of uniform units, for example if the unit are atoms, the substance is called an element such as carbon or iron, if it is called molecules and it is called a chemical compound, such as carbon dioxide or water.

Goods are substances or mixtures that have economic value assigned by markets. The value can be positive (fuel, wood, textiles) or negative (municipal solid waste, sewage sludge). It can also include immaterial goods such as energy, services or information.

A **process** is defined as a transport, a transformation or storage of materials; it's applied when the material suffers an event.

Stocks are defined as material reservoirs within the analyzed system, and usually they have mass units.

The linkage between processes is made by **flows** if the unit is mass per time or **fluxes** if the unit is mass per time and cross section. Flows/fluxes across systems boundaries are called imports or exports. Flows/fluxes of materials entering a process are named input while those exiting are called outputs.

A **system** is defined as a space that groups a set of material flows, stocks and processes within a defined boundary. The **system boundary** is defined as a space in the Universe that is going to be focus in the study and will be defined in time and space. When the boundary in time is chosen, criteria such as objectives, data availability, appropriate period of balance etc have to be taken into count in order to perform a rigorous case study. Another term used in MFA is **activities**, that is defined as encompassing all relevant processes, flows stocks and materials that are necessary

to carry out and maintain a certain human need, which can vary depending on the case study that is being performed, but activities can be for example security, social recognition, a cafeteria, etc...

The symbology used in MFA which represents the terms above stated are displayed as an example in the next figure.

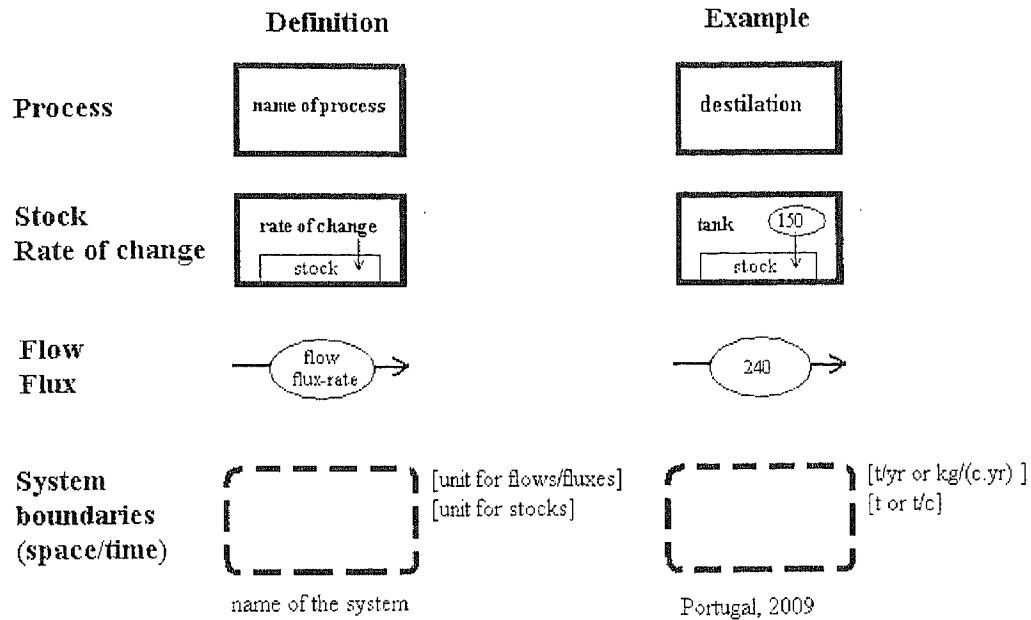


Figure 4 – main symbols used in MFA diagrams (note that if space is limited the ovals around the flow/fluxes can be omitted)

MFA is based on the law of conservation of matter and energy²⁵ thus:

$$input = output + generation$$

Generation represents all the materials that are produced inside the system, then:

$$\frac{stock\ variation}{time} = input\ flux - output\ flux + flux\ generation$$

$$flux\ generation \Rightarrow \begin{matrix} Production\ then > 0 \\ Consume\ then < 0 \end{matrix}$$

This is applicable at a given time interval Δt (year, semester, week, hour...)

Where flux is a quantity (mass or volume) in traffic in the system per time unit $[MT^{-1}]$

and stock is a quantity (mass or volume) resident in the system $[M]$ or $[L^3]$.

Thus, stock is the difference between the final stock the initial stock in the Δt period.

$$stock = stock_{final} - stock_{initial}$$

Assuming a time interval Δt

$$\frac{\text{accumulated material}}{\Delta t} = \frac{\text{material in}}{\Delta t} - \frac{\text{material out}}{\Delta t} + \frac{\text{material produced}}{\Delta t} - \frac{\text{material consumed}}{\Delta t}$$

This equation has the dimension of mass or volume, depending on the units that are applied. Dividing per Δt , it obtains:

$$\frac{\text{rate}}{\Delta t} = \frac{\text{rate}}{\Delta t} - \frac{\text{rate}}{\Delta t} + \frac{\text{rate internal}}{\Delta t} - \frac{\text{rate internal}}{\Delta t}$$

This has the dimension of mass per time unit or volume per time unit.

Assuming that the system evolves to a point where a steady-state scheme can be considered (fluxes are constant in time), then:

$$0 = \frac{\text{rate}}{\Delta t} - \frac{\text{rate}}{\Delta t} + \frac{\text{rate internal}}{\Delta t} - \frac{\text{rate internal}}{\Delta t}$$

In simple systems, where steady-state and without generation of material, then:

$$\frac{\text{rate}}{\Delta t} = \frac{\text{rate}}{\Delta t}$$

In MFA calculations is usual to determinate a **transfer coefficient (TC)**, which describes the partitioning of a substance in a process and It is defined as follows

$$TC_i = \frac{\dot{X}_{O,i}}{\sum_{i=1}^{K_I} \dot{X}_{I,i}} ; \quad \sum_{i=1}^{K_O} TC_i = 1$$

K_I = number of input flows

K_O = number of output flows

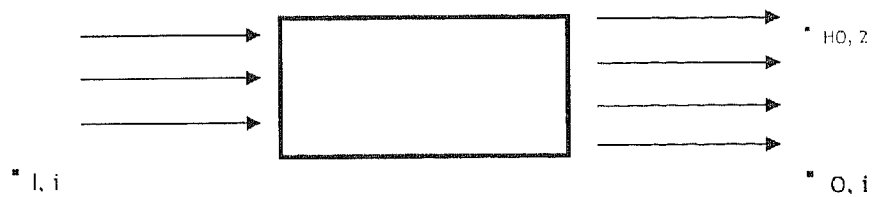


Figure 5- Transfer of substance X into output flow 2 is given as $TC_2 = \dot{X}_{HO,2} / \sum \dot{X}_{I,i}$

2.1 Umberto® Methodology

Umberto® software was developed by the Institute of Environmental and Energetic Research of Heidelberg University - IfEU (Institut für Energie und Umweltforschung Heidelberg). It is very flexible, enabling the development of any type of system, besides it allows the development of specific computations defined by the user for the model be faithful to the environment which it belongs. It allows a study of material and energetic flows through material flow network, making possible an analysis of both environmental (a vision of the exchange system with the environment) as well as financial aspects (costs) for all activities inside the system²⁶. To design the material flow network, Umberto® applies the methodology of Petri nets, composed by **places**, **transitions** and **arrows**. This is the unique difference between the symbology applied in MFA and this software²⁷.

“Places” are elements in the network where no transformation of materials occur but are used for other reasons. They can be stocks of materials, input or outputs to connect the material flow network with its environment (“import” and “export” according MFA terminology), or can be used to connect one output stream of a process to become a input of another (“internal” flows in MFA terminology). “Places” are represented as a circle.

“Transitions” represents processes where manipulations of materials occur. It is represented as a square, and according the methodology of Petri nets they can only be connected per “places”.

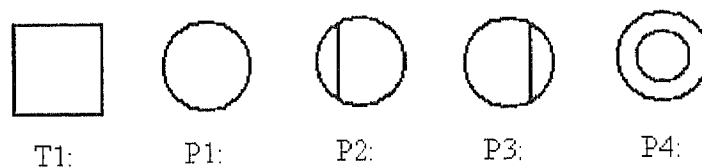


figure 6- Main symbols used in Umberto®, T1 represents the “transition”, P1 represents a Place not defined yet, P2 represents a “input place”, P3 represents a “output place” and P4 represents a “connection place” or a “stock place”

The connection between each transition, which is the processes itself, is done through the use of arrows and places. We cannot have places linking themselves and as equal cannot have transitions entangled. For two transitions be connected it's obligatory to have a place between and vice versa. All the connections are made by arrows which defines the direction of the process.

By having these features, the software allows to model systems such as factories, production lines, services, cities or even nations sub-systems and many others. It's a major importance describe the relationship between the data collected and their input and output correctly, because according the MFA methodology (and further the Life Cycle Analysis LCA), all inflows should flow to an corresponding output even if they are broken down into essentially different products, and Umberto applies these base definitions to draw up the balance in order to represent what happens in the process²⁸.

After inputting all material that will be used in the simulation, it's possible to begin the modeling of the material flow network. In the transitions will be defined the input/output flows, and the quality of data related to them will be defined and can be done through the use of mathematical formulas (Umberto allows that the input/output relations be defined by equations), or by numerical associations. The software allows evaluating separately the contribution of each material in the process. This is very useful when it is necessary to realize an individual assessment for each material.

3 Case Study

In this work the tool MFA was developed to suit the environmental analysis in the manufacturing of textile products. The process in study is a tailoring factory located at Arteixo (A Coruña - Spain) which produces coats practically made 100% cotton. In the following figure the manufacturing process is schematically represented.

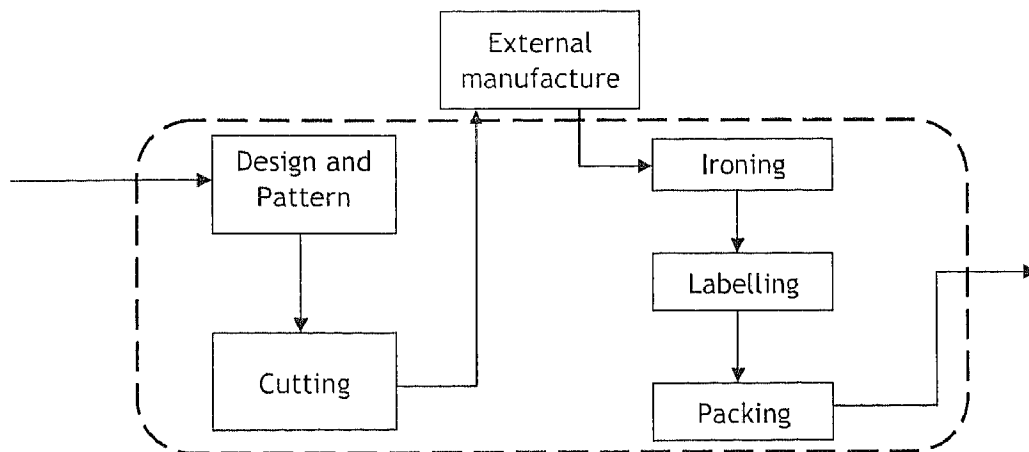


Figure 7- scheme manufacture process of study case

From all the process of textile manufacturing described previously, in this factory the only that is conducted is garment manufacturing. The cotton fabric arrives to the installation already manufactured. The design department accordantly with the new fashion tendencies draws the new models, after which these pieces are cut in paper and displayed over the pattern in such a way that minimizes the textile residues (**design and pattern**) and then cut. To avoid the displacement while cutting it's covered with a plastic. The lining is then attached to the piece by a thermo-bonding machine (**cutting**).

The cut pieces are then sent to external manufacture to be sewed. All the buttons, zips and ornamental elements are supplied from the factory, and as so they are counted in the inventory despite they are sewed externally. Note that this external manufactures are outside facilities that aren't part of the case study industry, and as so no data of these facilities can be taken in count (**external manufacture**).

After being sewed the coats return to the factory and are ironed so that they are visually suited for the market. For this operation there's a need of water (**ironing**). After ironed, the coats are labeled to distinguish them (**labeling**), and then are packed in plastic bags (**packing**) and sent to the warehouse to be distributed.

The MFA period applied in this study was from 2003 to 2005. The material list of the inventory was organized in two main groups, input group constituted by raw material, energy and water and output group which is constituted by production, air emissions, urban or assumable wastes and hazardous waste. The inventory supplied by the factory is described in the follow table

table 4- Inventory supplied from the factory since 2003 to 2005

		Year	2003	2004	2005	
Input	Energy	Electricity	kWh	210660	322059	386621
		Wind-Power	kWh	8980	14711	15244
		Propane	kg	96,3	123,9	133,9
		Gas-oil	m³	35,5	19,6	34,1
		Natural gas	kWh	485411	1045137	1105012
	Raw materials	Cotton fabric	kg	651881	798199	919504
		Stitch	kg	0	15800	35500
		Lining	kg	0	300000	350000
		Paper	kg	5740	6971	7173
		Plastic	kg	31459	24419	39313
		Buttons	kg	28000	28000	31864
		Zips	kg	8100	6300	7164
		Labels	kg	650	650	740
		Water	m³	160,9	110,3	124,6
Output	Production	number of items	508188	558078	635055	
	Air emissions	SO ₂	kg	330	182	316
		Nox	kg	3542	3554	6086
		CO	kg	11502	3652	4623
		CO ₂	kg	184975	196896	262527
	Urban or assimilable waste	Textile	kg	83353	104632	119065
		Paper and cardboard	kg	5740	6971	7173
		Plastic	kg	592	660	740
	Hazardous waste	Paint	kg	0	0	1,2
		Batteries	kg	15	4,8	2,4
		Fluorescent lamp	kg	5,4	13,7	6,8
		Ofimatic waste	kg	3,4	3,6	92,3
		Oil filters	kg	11,6	7,7	4,8
		Mineral oil	kg	115,7	100,8	0
		Contaminated containers	kg	1,6	4,6	3,2

*data not provided

4 Results and discussion

In this study the MFA methodology was modified to assure it's applicability to the textile industry implementing the process in Umberto®. The first task carried consisted on the implementation of the production line in the simulator.

In order to simplify the model and to make it as intuitive and user friendly possible, the scenario is compounded by a main network and two subnets (these are networks that in order to simplify the visualization are specified inside a transition, turning by this mode a transition in a subnet).

The main network structure is shown in the next figure, and represents all the inputs such as energy (P1), raw materials (P2) and water (P3) and all the outputs as production items (P4), urban or assimilable waste (P6) and hazardous waste (P7) of the process (represented as the subnet transition T1).

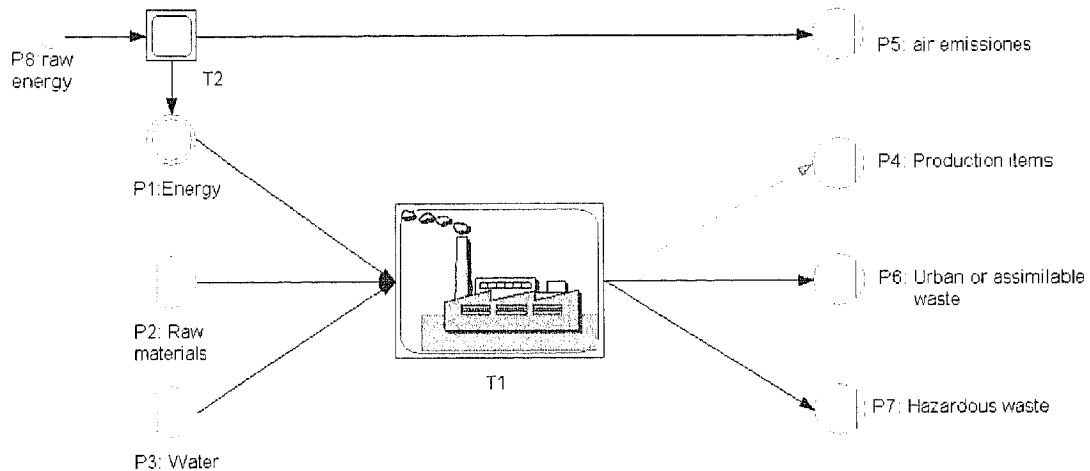


Figure 8- Main network of process implemented in Umberto

In this main network, the transition (represented as T_i , which i represents the index number of the transition) T_1 is a subnet where all the process is implemented. All the inputs are represented on the places (represented as P_i , and i represents the index number of the place), such as energy (P1), raw materials (P2) and water (P3), and all outputs, production items (P4), urban or assimilable waste (P6) and hazardous waste (P7).

The energy supplied to the process is achieved in subnet T2. This transition was implemented because there are 5 different raw materials (P8) to energy production and the inventory supplied had 3 different units, such as kWh, m³ and kg, and to assess an energetic consumption of the process it had to convert the data to uniform

units. The next displayed figure is the subnet T2, where there are the different raw sources of energy, and the cogeneration unit.

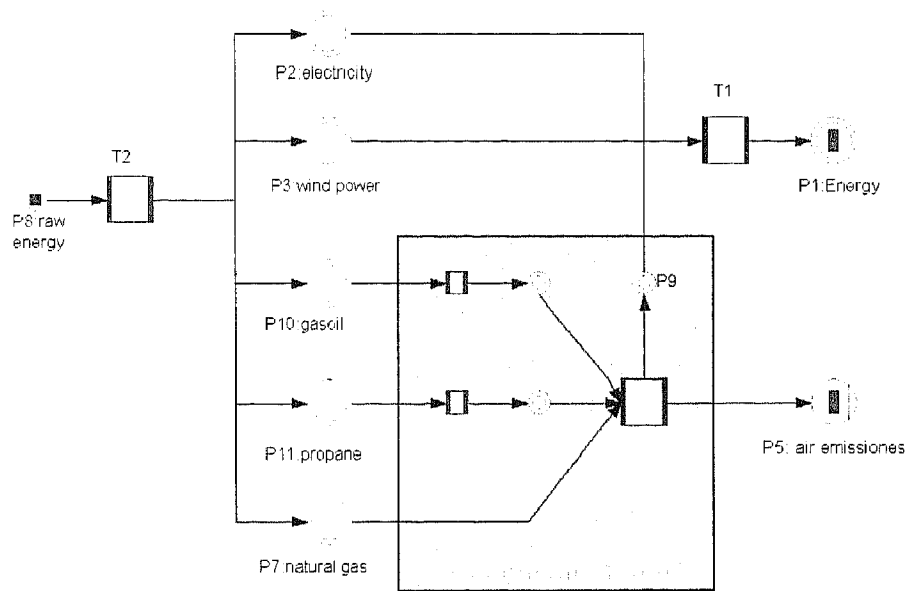


Figure 9- Subnet of the energy conversion on transition T2

The energy applied to the process is assured by electricity (maintained by an electricity supplier company from Galicia), wind power and a cogeneration unit of propane and gasoil located outside the facilities of the process. The wind power is supplied from a wind turbine that is common to all the facilities of the company, and a percentage is sent to this process. Despite the cogeneration unit is located outside the process in study the consumption results on certain residues, and as so they will be assessed. The residues provided from the electricity were excluded because it varies depending the electric provider so the environmental impact caused should be assessed from its source.

In this subnet, T2 was used to separate the different raw sources. As it has been chosen that the unit of energy was kWh due the large values of energy, the gasoil (m^3) and propane (kg) had to be converted.

To convert the different units to kWh research had been done to find the different units of conversion and properties of gasoil and propane.

The coefficients applied where:

$$1 \text{ kWh} = 3600 \text{ kJ}$$

$$\rho_{\text{industrial gasoil}} = 900 \text{ kg/m}^3$$

$$\text{HCV}_{\text{industrial gasoil}} = 38000 \text{ kJ/kg}$$

$$\text{HCV}_{\text{propane}} = 50350 \text{ kJ/kg}$$

Data obtained in references ²⁹ ; ³⁰ and ³¹

After the energy conversion is done, in the main network proceeds the subnet T1, which is the process of production. This subnet was subdivided in three to simplify the analysis and visualization. As so, a network was specified to subdivide the raw materials, other to subdivide the energy supplied to each sub-process of the production chain and the process chain itself. The sub-networks that constitute the T1 network are illustrated in the next figures

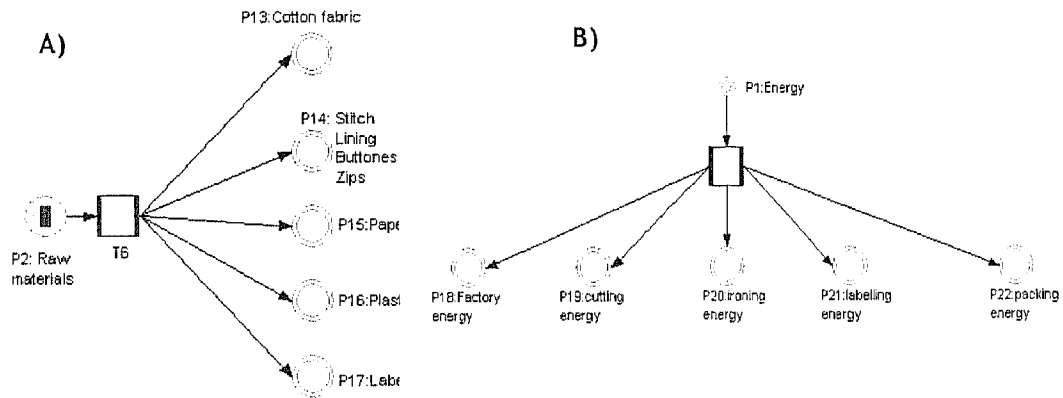


Figure 10- Subnet of the process a) subdivision of raw materials b) subdivision of energy

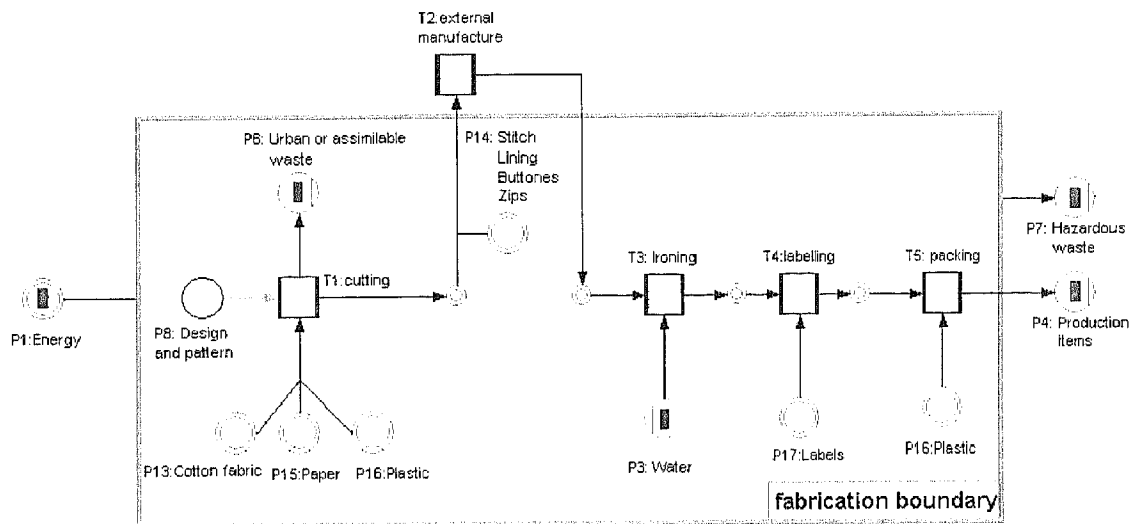


Figure 11 – network of the production chain in the process

This network shows at a MFA level the process explained previously in the case study chapter. Every materials and residues (except the air emissions because it dues the cogeneration unit) is detailed and integrated in the process.

The results obtained in the simulation are detailed in the next tables. As expected, they coincide with the inventory data supplied by the factory cause each year where linearized independently.

The next step was analyzing the residues produced by the process. Residues such as hazardous waste, water residues, urban or assimilable wastes and air emissions will be separately assessed.

Table 5- results obtained in simulation with Umberto detailed but the residues produced by year

Output	unit	2003	%	2004	%	2005	%
Air emissions							
CO	kg	11502	3,97	3652	1,15	4623	1,15
CO ₂	kg	184975	63,77	196896	62,19	262527	65,53
NO _x	kg	3542	1,22	3554	1,12	6086	1,52
SO ₂	kg	330	0,11	182	0,06	316	0,08
hazardous waste							
batteries	kg	15,0		4,8		2,4	
contaminated containers	kg	1,6		4,6		3,2	
fluorescent lamp	kg	5,4	0,01	13,7	0,01	6,8	0,03
ofimatic waste	kg	3,4		3,6		92,3	
oil filters	kg	11,6		7,7		4,8	
paint	kg	0		0		1,2	
Urban or assimilable waste							
paper'n'cardboard	kg	5740	1,98	6971	2,20	7173	1,79
plastic out	kg	592	0,20	660	0,21	740	0,18
textile	kg	83353	28,74	104632	33,05	119065	29,72
productive items	items	508188		558078		635055	

4.1 Hazardous waste

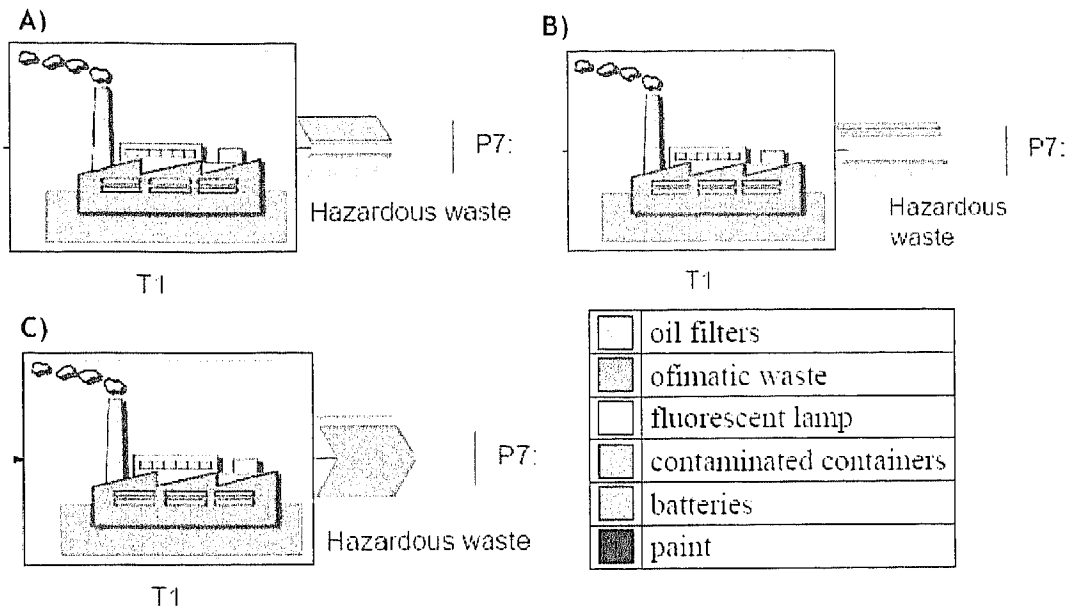


Figure 12- Sankey diagrams of Hazardous waste for the years A) 2003 B) 2004 C) 2005

There isn't any trend along the years in the hazardous waste but there are minorities in the process. They represent an average 0.02% of the debris. If handled and processed in accordance with the statutory requirements it doesn't represent an environmental threat. The generation of hazardous waste amounts to maintenance tasks, carried out by a joint service the different factories of the group. As expected, with the increase of production, these residues also increase.

4.2 Water residues

Table 6- Water consumption of the process from 2003 to 2005

	2003	2004	2005
water kg	160,90	110,30	124,60

The main consume of water in the process corresponds to ironing, though there is a consumption associated to sanitary, it is considered negligible due to its low use.

The amount of water used isn't relevant, and there is no generation of liquid effluents that are harmful to the environment so there is no need to implement a management system of wastewater. It's not influential in the environmental impact of the process so there is no need to amend its application.

4.3 Urban or assimilable waste

The contribution of urban waste has increased along time of the process. It's the second type of residues that most contributes to the environmental waste of the process. It evolves from an average 30,92% in 2003, 35,46% in 2004 and 31,69% in 2005. The next figure shows the evolution of urban wastes through the years studied.

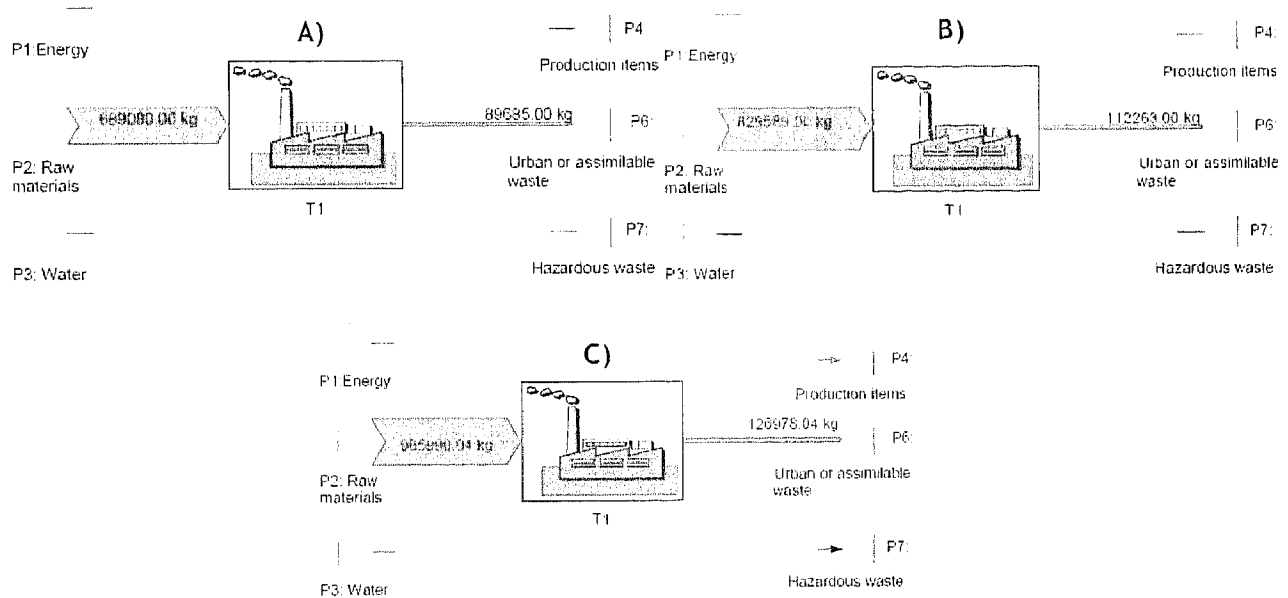


Figure 13- Sankey diagram of raw materials and urban or assimilable wastes from A)2003 B)2004 C)2005

According information supplied, the urban waste stems primarily from the design and cut stage. The residues provided from packing and labeling are very low due to high efficiency of the operations.

This waste can be minimized by the implementation of software and techniques that maximize the use of the fabric and allows minimizing the wastes. There is also a possibility of human error or even operation malfunction that contributes to an increase of waste, but this factor is extremely difficult to control and can only be achieved with an improvement in machinery, but this option is already the company's policy focus on quality machines and so this is not applicable.

Other options considered is the reuse of waste in other textile products such as tea towels or other items that require small quantities of fabric, thus reducing the environmental impact. The waste paper from the process of packaging and labeling should be reusable in the process wherever possible and where not, handle carefully so that it can be recycled in future. Another measure that should be adopted in all

process would be the use of recycled materials such as paper or fabric that is more environmental friendly.

Although the secondary raw materials such as buttons or zips, etc, they don't produce residues neither contribute to the environmental impact because all the leftovers are sent to other processes.

In the next figure the sankey diagram of secondary raw materials is shown in order to analyze the tendency of the use (denote that lining and cotton fabric aren't represented because they represent primary raw materials).

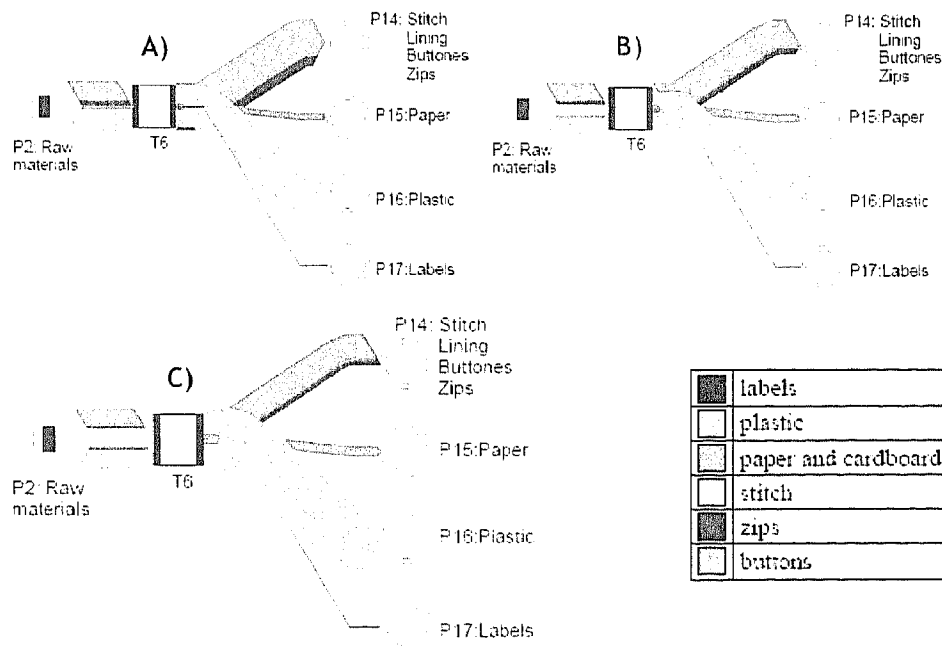


Figure 14- Sankey diagram of the secondary raw materials for A) 2003 B) 2004 C) 2005

The consumption of secondary raw materials is directly related to the production but also with the fashion trends for that year. Although production increases every year, the accessories use also increase but not linearly. As so, no significant conclusion can be taken in count for these items.

4.4 Air emissions

The main factor in waste production of the process is the air emissions derived from the energy supply to the process. It was responsible from 69,07% in 2003, 64,53% in 2004 and 68,28% in 2005 of the environmental impact. Therefore it is considered as the main factor to be optimized to reach a minimal impact. The next image represents the sankey diagram for the residues produced by the energy supply (note that only propane and gasoil are shown because this diagram is in mass, the other energy sources are in kWh).

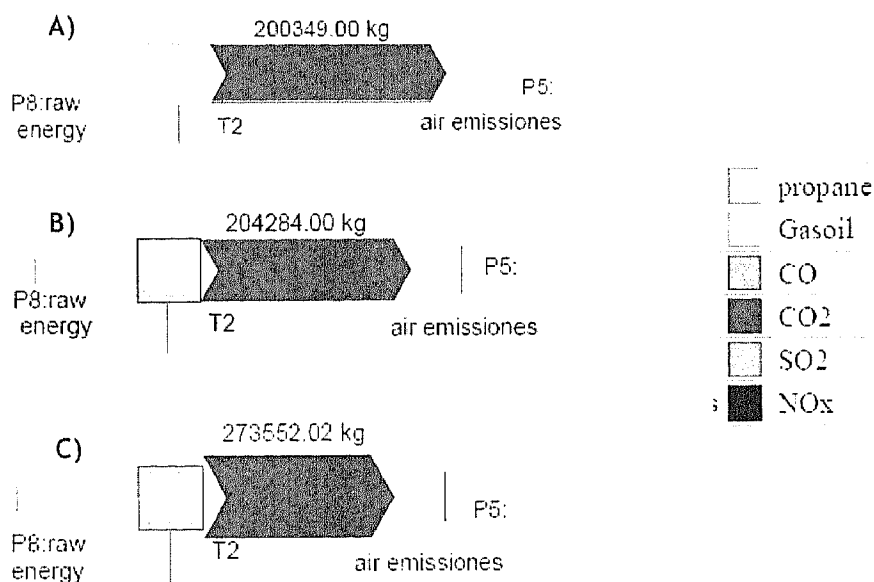


Figure 15 – Massic Sankey diagram of raw materials VS air emissions for A) 2003 B) 2004 C) 2005

It can be denoted an increase in the emission of gases, which is due to increased energy consumption of the process. For a better analysis sankey diagrams of the different types of energy used was made, and are displayed in the next figure.

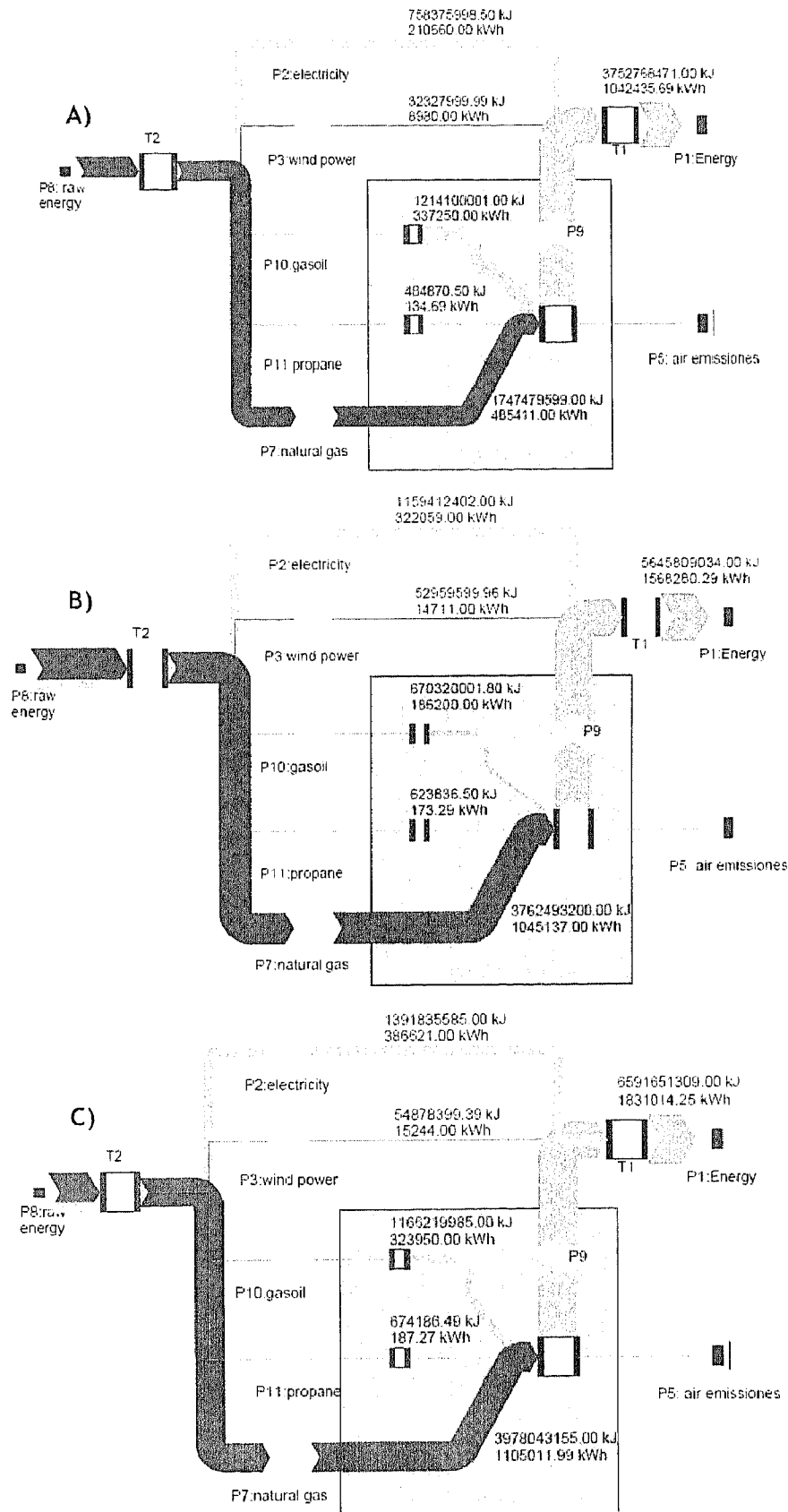


Figure 16 – Energetic Sankey diagram of the raw energy supply A) 2003 B) 2004 C) 2005

The production has been increasing annually, and consequently there has been a rising in energy consumption. Thus, despite the existence of renewable energy (wind power) and its provision have increased gradually, it does not follow the energy needs of production. The effect is that the energy consumption of polluting sources have increased, primarily coming from the cogeneration unit existing, thereby also the air emissions rises.

The wind energy comes from a direct source of the factory which has a wind turbine with 1.5 MW nominal powers that provides power to the various processes in the complex. One solution for the reduction of the environmental impact caused by the fossil fuels could be increase the energy supplied to the process by the wind turbine, but this solution has to be carefully analyzed because to supply to this process, others will have less renewable energy, so a study to define which is most advantage should be taken in count.

Another decision that may be taken into account is the study of supplier energy companies. Depending on the electricity supplier there will be different ratios on types of energy production from wind, biomass, hydroelectric, nuclear and solar energy. The environmental impact can be reduced if the company contracts a supplier that has a higher ratio of energy provided by renewable energies.

The analysis of the waste generation justifies investment in ecosystems conservation, such as reforestation, etc. This process will also generate new jobs, which contribute to the social component of the MFA, and also would help achieve the objectives of the Kyoto Protocol.

The inventory supplied information about the distribution of the energy consumed in each stage of the process as given in the next table. It's assumed that the energy distribution doesn't vary in time cause the only modifications are the drawing and shapes of the production..

Table 7- Distribution of the energy in the different stages of the process

Process	Installations	draw and cutting	Ironing	Labelling	Packing
% Energy	30	53	11	1	5

With this information there where made sankey diagrams of the energy consumed by each step that is represented in the next figure.

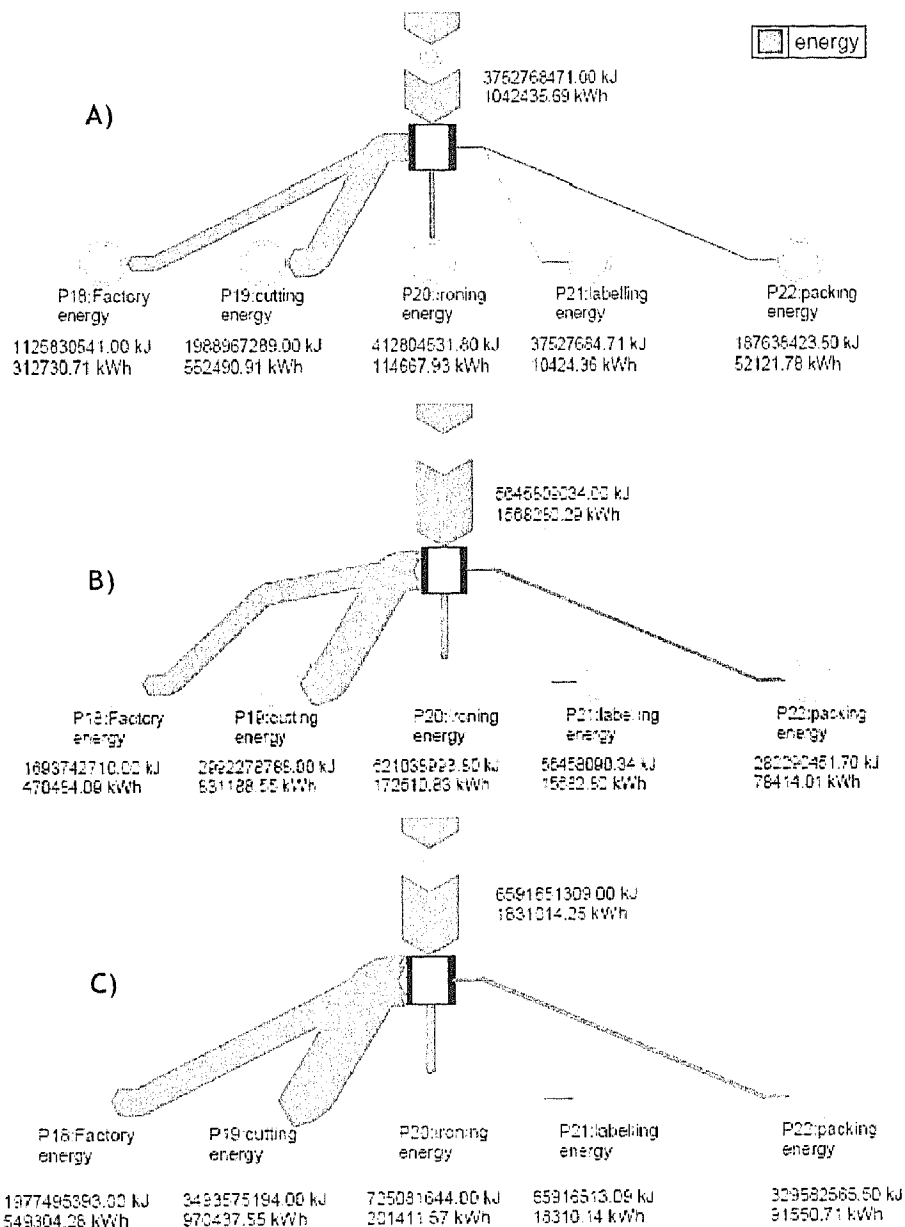


figure 17- Sankey diagram of the energy supplied to each stage of the process in A) 2003 B) 2004 C)2005

The step that requires more energy is cutting, owing most of the energy to the machinery used (see next table). An option could be save energy by only use the equipment while in use, but according to information from the company it consumes less energy if it is on continuously than interchangeably. Other option could be opt for the choice of equipment with a lower consumption, but this would cause higher losses in the fabric waste, because equipment with lower consumption tends to have higher probabilities of defects in the cut, which would cause a fall production and an

increase in waste. So the management decision was to implement equipments with a higher consumption, but in contrast with higher income at the procedure level. The next table shows the energy consumption of the different equipment applied in the process.

Table 8- Equipment consumption for each stage of the process

Equipment	Consumption (kW/h)	Process
Hand iron	0,5	Ironing
Iron table	1	
Iron dummy	2,5	
stain remover machine	1,9	
blower spreading machine	2,5	
termofixator	48,5	Cutting
stacker heat sealer	0,8	
automatic cutter	8	
vacuum cutter	55,95	
bagger machine	2	packing
spreading machine	2,5	
band saw	1,1	labelling
extension elevator	0,55	
sewing machine	0,55	

In the inventory supplied there was no information about the number of machines in each process, neither the energy consumed by the building such as lighting, heating, computer systems, air conditioning, etc, neither they could be given. Therefore, it is not possible to do an analysis on these factors.

5 Conclusions

In our days, one of the ultimate goal in designing or performing a optimization on a industry process is the integration of environmental considerations into the design, manufacture, distribution and other considerations that can achieve higher business benefits and combine these with and environmental improvement to reach a so called “green industry”, a manufacture that is environmental friendly with a reduce as possible impact on nature. We can conclude that MFA is a tool that can achieve such goals, or at least help to reach them as much as possible.

5.1 Strengths of Material Flow analysis

It's a tool that provides direct measures on the actual material and energy flows and serves as a linkage between them and the economy of the system studied. It quantifies the relationship between the human activities and the environmental problems that results from it, and helps to support the planning of decisions that can manage those impacts and provides also the monitoring and simulation of its efficiency. It's a powerful tool that allows early warnings and also provides precautionary measures so that future problems can be avoided.

5.2 Limitations of Material Flow analysis

Despite major efforts are been made to assure that MFA can be focus on ensuring adequate data availability, some of them aren't very accurate, or even the data given isn't very reliable. This can interfere on the results obtained, and the decisions given are as much accurate as the data supplied to the case study. As so, it's a tool that depends on the data given and its accuracy.

As it is a relative new tool, there isn't yet a single standardization on the methodologies applied, but efforts are been taken to assure it.

5.3 Software Umberto®

Umberto is a powerful software that allows the modeling of practically any case study, and relies on the concept of the material flow networks used in MFA and at the same time is a intuitive and user friendly tool that allows the user to obtain rigorous results without the lost of comprehensibility.

In the project, Umberto assisted in the preparation of the material flow network and the creation of the different scenarios (for the different years studied) that allowed an optimization of the process and to find hotspots that allowed the reduction of the natural resources, energy or pollutants. It also allowed the automatic generation and

comparison on the balance of the issues where their assessment contributed to the achievement of the objectives proposed.

5.4 Process conclusions

This study implemented a simulation that allows an environmental analysis of the process, but serves also as a future reference for comparison to surround industries in Galicia. It allows also adjusting with minor modifications it's applicability to similar processes.

The hazardous waste is minimal, and does not represent a threat to the environment as well as the water residues Urban or assimilable waste represents a average 33% of the residues produced, composed primordially by cotton fabric and paper. An option for minimize its impact is the reutilization of the leftovers to produce other items or to be reintroduced in the process. Other option when this is not possible is recycle them, and to apply recycle products the production line.

The major environmental impact is caused by the air emissions due the use of fossil fuels such as gasoil. This is considered the hotspot in the process in an environmental analysis. There are some options to reduce them such as opt for a renewable source of energy such as the wind-power or solar energy. Other option is the study of the electricity suppliers available and chooses which a higher rate of energy has produced by renewable sources.

One option to reduce the environmental impact is the investment in ecosystem conservation in order to restore the environmental balance disturbed by the air emissions.

5.5 Work Assessment

5.6 Aim achieved

The main objective of this project was the study of material flow analysis methodology, and its implementation by a software simulation on a tailoring factory and performing an environmental impact analysis.

The simulation was implemented in order to analyse the residues produced, and several options to reduce the impact were done. It also serves as a future reference for all surrounding processes that are similar to the case study.

5.7 Limitations and further work

The MFA methodology is only limited by the information given in the inventory. As the main contribution of the environmental impact is done by the air emissions that provide from the energy production, higher details should be given, particularly on the equipment and energy consumption in each step of the process. This would not also allow a better analysis but would turn possible the optimization by comparing different equipments available.

Further work that would be advisable is the continuation of this project, by performing a Life Cycle Analysis (LCA). This thesis would serve as a foundation, because in order to calculate a LCA it is necessary to be familiar with the concept of material flow analysis and networks, as well as its implementation. The main goal of a LCA is to determinate the task-oriented quantitative expenses to produce a unit of the output. In general this output will be a unit of the product. This is possible in Umberto® because it has in its features cost accounting and cost allocation.

5.8 Final appreciation

Realizing the project in a foreign institution and in a foreign country allowed me to achieve a higher independency as well as a bigger autonomy concerning this project and also my life.

Working on this thesis permitted me to test my know-how and my initiative in several moments. The fact of working on a subject that involve computational simulation on a real industry, fact that I have never thought about it until now, allowed me to acquire a higher knowledge in this area, area that I consider of extremely interest.

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