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Abstract: An increasing number of textile firms are adopting sustainability strategies for achieving long-term competitive advantage. In this paper, a new decision-making process for the textile sector, exploiting the Organisational Life Cycle Assessment methodology, is proposed. It provides a management system able to support companies in monitoring and evaluating environmental performances with a dynamic perspective and identify which activity and/or mechanical plant needs to be improved or changed in order to reduce the environmental impact, enabling cost savings, and at the same time, developing the business case for sustainability. In particular, for each Organisational Life Cycle Assessment phase, an operational tool was established. The tools were developed both by reviewing specific literature and by conducting in-depth semi-structured interviews in six textile companies. Across firms, informants included the Managing Director, the Plant Manager, shop floor supervisors and workers, and representatives from Corporate Social Responsibility Committee, Manufacturing, Quality, and Accounting. Additionally, direct observation (e.g., plant tours) was also used as data collection method. A case study of a spinning company reveals the potential benefits of this decision-making process.

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# Enhancing environmental management in the textile sector: an Organisational-Life Cycle Assessment approach

**Abstract.** An increasing number of textile firms are adopting sustainability strategies for achieving long-term competitive advantage. In this paper, a new decision-making process for the textile sector, exploiting the Organisational Life Cycle Assessment methodology, is proposed. It provides a management system able to support companies in monitoring and evaluating environmental performances with a dynamic perspective and identify which activity and/or mechanical plant needs to be improved or changed in order to reduce the environmental impact, enabling cost savings, and at the same time, developing the business case for sustainability. In particular, for each Organisational Life Cycle Assessment phase, an operational tool was established. The tools were developed both by reviewing specific literature and by conducting in-depth semi-structured interviews in six textile companies. Across firms, informants included the Managing Director, the Plant Manager, shop floor supervisors and workers, and representatives from Corporate Social Responsibility Committee, Manufacturing, Quality, and Accounting. Additionally, direct observation (e.g., plant tours) was also used as data collection method. A case study of a spinning company reveals the potential benefits of this decision-making process.

**Keywords:** Organisational Life Cycle Assessment (O-LCA); Environmental sustainability; Textile; Decision-making process; Environmental management.

## 1 Introduction

The textile and clothing industry is one of the biggest industries, globally worth over \$1 trillion (Research and Markets 2011), and, at the same time, one of the most polluting (Eryuruk 2012). The major environmental burden caused by this sector is associated with (Beton et al. 2011; DEFRA 2008; Draper et al. 2007; Fletcher 2008; Gardetti and Torres 2012; Gwilt and Rissanen 2011; Kocabas et al., 2009; Vajnhandl and Valh, 2014): i) energy consumption in the production of man-made fibres, in yarn manufacturing, in finishing processes, and in the use phase for washing and drying clothes; ii) water and chemicals consumption associated with fibre growth, wet pre-treatment, dyeing and finishing activities, and laundry; iii) solid waste arising from textile and clothing manufacturing and, mostly, from the disposal of products at the end of their life; and v) direct CO<sub>2</sub> emissions, particularly related to transportation processes within globally-dispersed supply chains.

During the last years, the demand for environmental-friendly textiles and clothes, manufactured and distributed minimising negative impacts on the environment, has vigorously emerged from a plethora of stakeholders, including consumers (Casadesus-Masanell et al. 2009; Goswami 2008), renowned brands and retailers (such as Levi's, Gap, H&M, and Wal-Mart), non-profit organisations, public attention and mass-media (i.e., Detox by Greenpeace, Clean Clothes Campaign, Roadmap to Zero Discharge of Hazardous Chemicals, etc.), regulatory bodies and public authorities (EU REACH regulation).

Therefore, sustainability principles, approaches and strategies have then become vital for textile and clothing companies to stay competitive in the market (Smith 2003).

However, there is an inconsistency between companies opportunities to leverage sustainability and its actual implementation: while many companies commit to sustainability, only few put their commitment into actions (Chi 2011; Deloitte 2013). As demonstrated by Berns et al. (2009), there are many reasons why companies experience difficulties in tackling sustainability more decisively; in particular, the authors point out three root causes: i) companies often lack the right information upon which to base decisions; ii) companies struggle to define the business case for value creation; and iii) when companies do act, their execution is often flawed. These three main issues entail a critical need for structured decision-making approaches to execute companies' sustainability strategies. This paper aims at partially filling this gap by developing a decision-making process, based on the Organisational Life Cycle Assessment (O-LCA) approach, in order to support management in making environmentally and economically sound choices among the best available practices (BATs) at technical level (i.e., more efficient production equipment), suppliers' level (i.e., use of recycled materials) and management level (i.e., introduction of lean production techniques for waste minimisation). In particular the goal is to give specific guidance, methods and tools for the identification and the

assessment of life cycle environmental impacts of a company, from the definition of the functional unit to the selection of the best environmental alternatives. This process will help textile and clothing companies integrate environmental objectives into corporate management control and decision system in order to achieve, at the same time, environmental and economic advantages. A management system able to support companies in monitoring and evaluating environmental performances with a dynamic perspective will be proposed. Such management system will rely on the systematic identification of hotspots that need to be managed in order to reduce the corporate environmental footprint, enabling cost savings, and at the same time, developing the business case for sustainability.

The remainder of the paper is organised as follows. Section 2 presents the theoretical background related to approaches and methods for supporting and improving decision-making towards sustainability. Section 3 describes the proposed decision-making process for the textile sector, while Section 4 introduces an application to an illustrative real case. A discussion of the results precedes the conclusions (Section 5).

## 2 Theoretical background

As argued by Waite (2009), Life Cycle Thinking (LCT) (Frankl and Rubik 2000) is one of the approaches that can support companies in making the manufacturing industry, including the textile and clothing sector, more sustainable and less damaging to the environment, while at the same time remaining competitive (Waite 2009). Life Cycle Management (LCM) makes LCT “operational for businesses through continuous improvements of product systems” (Remmen et al. 2007, p. 5). LCM is defined as “an integrated framework of concepts, techniques and procedures to address environmental, economic, technological and social aspects of products and organisations to achieve continuous environmental improvement from a life-cycle perspective” (Sonnemann et al. 2001, p. 325), from raw material acquisition, through manufacturing, use and final disposal. LCM is a management framework that support firms to minimise the environmental burdens related to their value propositions, while maximizing the economic value generated (UNEP/SETAC, 2012). Within the LCM framework, sustainability goals are achieved through the use of life cycle approaches and techniques, analytical and procedural tools, programs, strategies and policies (Sonnemann et al., 2015).

In particular, Life Cycle Assessment (LCA) is one of the most prominent techniques for the systematic evaluation of the potential environmental aspects of a product or service system through all stages of its life cycle (Rebitzer et al. 2004). The science of LCA methodology has grown and developed significantly in the last decade, as broadly reviewed by Finnveden et al. (2009). Despite its relevance for the scientific field, the influence and application of LCA for business decision-making are still limited (Choi et al. 2008). This aspect is reflected into a predominance of model and tool development, and a lack of focus on the use of LCA method in everyday management practice (Frankl and Rubik 2000). It could partially be due to the traditional focus of LCA on environmental impacts and effects only (Reap et al. 2008), that does not take into consideration the important relationships and potential trade-offs between the environmental and economic performance (Norris 2001; De Benedetto and Klemes 2009). The consequences of not integrating environmental and economic assessments can be missed opportunities or limited influence of LCA for decision-making, especially in the private sector (Shapiro 2001). Consequently, various scholars have started to study ways to integrate LCA with other approaches for building a robust support to product-related decision-making (e.g. cost-benefit analysis, material flow analysis, social LCA, life cycle costing, and input-output analysis) (Manfredi et al. 2011), and synthesizing all the information into a decision vector (Nowack et al. 2012). However, while LCA was originally developed for products and services, enlarging the unit of analysis at organisational level is becoming a relevant stream of research (Guinée et al. 2011; Hellweg and Canals, 2014). To this extent, a flagship project named “LCA of organizations” was launched in 2013 by the UNEP/ SETAC Life Cycle Initiative to explore the applicability of a life-cycle-perspective to an organisation (O-LCA) (Martínez-Blanco et al., 2015a). According to ISO/TS 14072 (ISO, 2014), O-LCA is “a compilation and evaluation of the inputs, outputs and potential environmental impacts of the activities associated with the organisation adopting a life cycle perspective”. This methodology is able to meet multiple corporate needs: i) identification of environmental hotspots throughout the entire value chain; ii) monitoring and control of environmental performance; iii) strategic decision support; and iv) provide information for corporate sustainability disclosure (UNEP/SETAC 2015). Overall, O-LCA empowers organisations to both define their sustainability strategy and improve their operational activities, facilitating the change into more sustainable consumption and production patterns, towards a resource-efficient and circular economy.

Most of the requirements and guidelines specified in standards for product LCA (ISO 1404x series) are suitable also for O-LCA (Finkbeiner, 2014). In particular, O-LCA implementation is based on the same four-phase methodology used

for product LCA. The main differences between the two approaches refer to the scope and inventory phase, as the object under study is different (Matinez-Blanco et al., 2015c). Moreover, O-LCA should not be used for comparative analyses between organisations and their communication to the public (e.g., corporate ranking), but rather for addressing improvements in the given organisation (ISO 2014).

Similarly to the UNEP/SETCA initiative on O-LCA, at European level DG Environment has worked together with the European Commission's Joint Research Centre (JRC IES) and other European Commission services towards the development of a technical guide for the calculation of the environmental footprint of organisations. The methodology, called Organisation Environmental Footprint (OEF), is grounded on a multi-criteria measure of the environmental performance of an organisation from a life cycle perspective (European Commission, 2013). Although OEF can be considered as a particular type of O-LCA, it is not fully coherent with some principles and requirements of product LCA as standardised by ISO (ISO 2006) (Finkbeiner, 2014).

Even if the interest around O-LCA is rapidly increasing and significant explorative experiences are emerging, complete and rigorous applications of O-LCA are not yet a common practice (Martínez-Blanco et al., 2015b) and substantial research is still needed in order to understand how O-LCA should be implemented by companies. Moreover, no case applications have been published in the textile and clothing sector.

### 3 Development of the decision-making process

In order to support textile and clothing companies in operationally implementing their commitment towards sustainability to integrate synergistically short- and long-term profitability with their efforts to protect the ecosystem, a decision-making process, based on the O-LCA method, is here proposed. The decision-making process is built on the technical framework for the O-LCA standardised by the International Standards Organization (ISO 2014). In particular, O-LCA, in line with a product LCA (ISO 2006), should include four phases: i) definition of goal and scope; ii) inventory analysis; iii) impact assessment; and iv) interpretation of results.

In this paper, each O-LCA phase is discussed with reference to the textile sector and, where appropriate, operational tool were established. The methodology applied to develop the tools is broken up into literature review, interviews and empirical application. Literature review was undertaken to assess the state-of-the art and continuously carried out throughout the research to keep its relevance along with the whole research program. Based on initial analysis of literature an agenda for the interviews was created and 20 in-depth semi-structured interviews in six textile companies were conducted. Across firms, informants included managers from Corporate Social Responsibility (CSR), Production, Quality, and Accounting functions, as well as shop floor supervisors and workers. Interviews were typically two hour long, having ranged from 1 hour to 4 hours. Additionally, direct observation (e.g., plant tours) was also used to increase the reliability of the study and triangulate the data obtained during the interviews. Key lessons were distilled and used to tools building as presented in this paper. Eventually, an empirical application was provided in a pilot case study, to ensure the model robustness and applicability in real context. In particular, data was collected through semi-structured interviews and several audits performed by the authors and their research group. The gathered information was then discussed with a panel of experts (i.e. textile professors and practitioners), who supported the definition of the potential solutions to implement to reduce the company's impact on the environment.

#### *Phase 1: Goal and scope definition*

Scoping phase defines the breadth, depth, and detail of the study in accordance to the specified goals (ISO 2006). The goal and scope state the framework for the assessment and affect the following phases. In an O-LCA, the reporting organisation is the unit of analysis, and the reporting flow is the measure of the outputs from the reporting organisation during the reference period (UNEP/SETAC 2015). System boundaries are the limits that define which are processes, resources and emissions associated with the reporting organisation and included in the study (UNEP/SETAC 2015).

In order to support textile companies in defining the unit of analysis as well as the system boundary, the textile production chain, as defined by NACE Code 13 is considered. It includes the preparation and spinning of textile fibres as well as textile weaving, finishing of textiles, finishing (but not manufacturing of) wearing apparel, the manufacture of made-up textile articles, except apparel (for example, household linen, blankets, rugs, cordage and so on), that is classified to NACE Code 14 (manufacture of wearing apparel). Textiles may be produced from varying raw materials, natural or man-made fibres. The preparation and spinning of textile fibres contains the reeling and washing of silk, degreasing and carbonising of wool and dyeing of wool fleece, carding and combing of all kinds of fibres, spinning and manufacture of yarn or thread, twisting, folding, cabling and dipping of filament yarns. Finishing of textiles embraces bleaching, dyeing, dressing, pleating, waterproofing, coating, rubberising, impregnating or silk screen-printing. The

manufacture of other textiles concerns knitted or crocheted fabrics, carpets and rugs, rope, narrow woven fabrics and trimmings and made-up textile articles such as blankets, travelling rugs, bed, table, toilet or kitchen linen, quilts, eiderdowns, cushions, pillows, sleeping bags, made-up furnishing articles (for example, curtains, blinds or bedspreads), tents, sails, sun blinds, dust cloths, dishcloths, life jackets and parachutes. Excluded are preparatory operations carried out in combination with agriculture (NACE Code 01) and the manufacture of synthetic fibres (which forms part of chemicals manufacturing, NACE Code 20). In total 13 macro-processes were incorporated in the textile O-LCA scoping map, as represented in Figure 1: spinning, weaving, knitting, non-woven manufacturing, cutting, making, trimming, desizing, scouring, bleaching, dyeing, printing, and finishing.

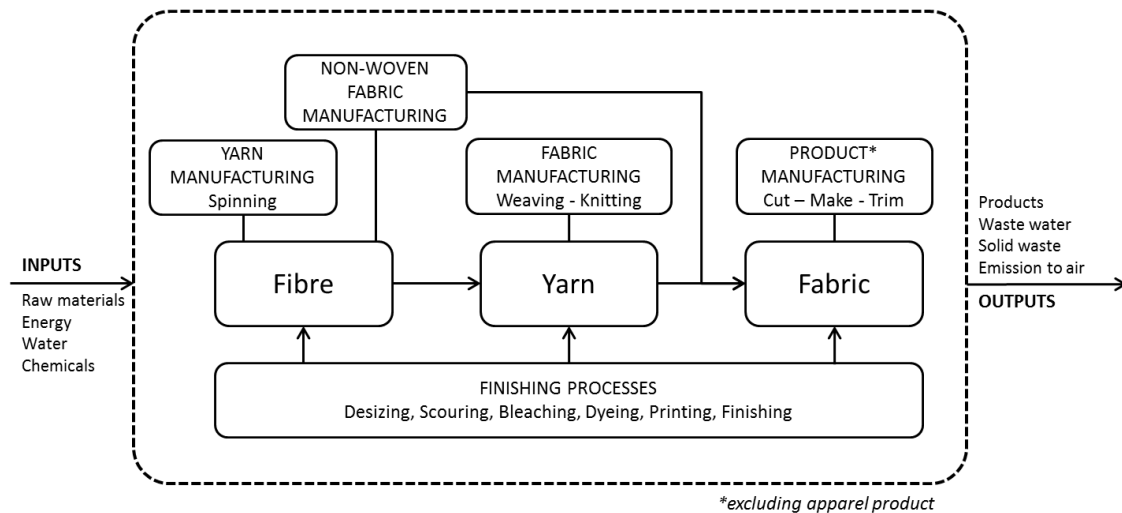


Figure 1: The textile O-LCA scoping map

Ideally O-LCA system boundary should consider the entire organisation and value, including direct activities carried out by the reporting organisation, as well indirect upstream and downstream activities (cradle-to-grave assessment). However, as argued by Suh et al. (2004), including entire value chain would often mean spanning the global economy and modelling the downstream activities is not always feasible. In this paper a cradle-to-gate perspective (i.e., up to the gate of the reporting organisation) is adopted, thus downstream stages are excluded. This choice is coherent with the main goal of developing a O-LCA-based decision-making process for textile companies to integrate environmental considerations into corporate management control and decision system in order to achieve, at the same time, economic and environmental advantages, both in the long- and short-term. As such, the textile O-LCA scoping map could be used by textile companies to define indirect upstream and direct activities and to draw the O-LCA system boundary diagram, as exemplified in Figure 4.

## Phase 2: Inventory analysis

During the inventory analysis phase data is gathered, systems are modelled, and Life Cycle Inventory (LCI) results are achieved, coherently with goal and scope definition. The inventory should consist of all inputs (e.g., energy, water and materials) and outputs (e.g., environmental releases in the form of emissions to air, water and soil) connected with the direct activities included in the O-LCA system boundary defined in the previous stage. In particular, for each macro-process defined in the “Goal and scope definition” phase, both primary and support processes were defined and mapped. Primary activities “are those involved in the physical creation of the product” (Porter and Millar, 1985), while support activities “provide the inputs and the infrastructure that allow the primary activities to take place” (Porter and Millar, 1985). For each process, inputs, outputs () and resources (intended as equipment and tools that support the processes execution) were identified and coded. Moreover, supporting mechanical plants at the service of the production plant were considered (e.g., electrical, water, heating and cooling, pneumatic, lighting system, etc.). As for primary and support processes, inputs, outputs and resources were identified.

The main supporting tool of for this phase is a comprehensive Textile Inventory Matrix (TIM), containing 147 primary processes, 25 support processes, 11 mechanical plants, 242 inputs, 136 outputs and 105 resources. Overall, this matrix depicts a systematic accounting of the environmental flows within the organisation. Table 1 shows the general structure of the TIM. In the rows, inputs, outputs and resources are listed. In the columns, for each macro-process, primary processes, support processes and mechanical plants are recorded.

TIM is a comprehensive tool including all the primary and support processes as well as all the mechanical plants that characterise the textile and clothing sector. As such, it can be applied by any textile and clothing company, regardless of the type(s) of processed fibres or the final product manufactured. When a company uses such tool, only the processes that are performed within its business or the processes that need to be controlled can be selected, coherently with the O-LCA system boundary diagram.

		Macro-process # 1										
		Primary Processes (PPs)				Support Processes (SPs)				Mechanical plants (MPs)		
		PP1	PP2	...	PPm	SP1	SP2	...	SPn	MP1	...	MPo
Inputs	I1	x			x				x			
	I2				x		x					
	...											
	Ii		x		x	x				x		x
Outputs	O1		x		x			x		x		x
	O2	x			x	x	x			x		x
	...											
	Oo	x			x				x	x		x
Resources	R1	x	x			x						x
	R2				x							
	...											
	Rr	x			x		x		x	x		

**Table 1: The Textile Inventory Matrix – Macro-process # 1**

### *Phase 3: Impact assessment phase*

During the impact assessment phase LCI results are used to evaluate the significance of potential environmental impacts. In general, this process involves associating inventory data with specific environmental impacts and attempting to understand those impacts. While it is clearly useful to cover only specific and relevant environmental areas, a systematic approach is needed to prevent shifting of burdens- solving one problem while creating another (Finkbeiner, 2014). The ultimate aim is to reduce the overall environmental impact of an organisation, or to find an appropriate balance of impacts between those aspects. By considering multiple impacts, companies have several perspectives from which to assess how their processes affect the environment, which in turn may offer more sustainable innovative solutions (Draucker, 2013). Operationally, the inventory is firstly compiled with “consumption data” for inputs and “produced quantities” for outputs. Then, inputs and outputs should be translated into environmental impacts in accordance with one of the existing impact assessment methods. In particular, two obligatory steps should be carried out: classification and characterization. Regarding the classification phase, the ReCiPe mid-point impact categories have been considered (Schryver and Goedkoop, 2009) and have been linked to the inputs and outputs included in the TIM. The resulting tool, named Sustainable Textile Assessment Tool (STAT), that can be used by textile companies to classify their inputs and outputs into reference impact categories, is exemplified in Table 2.

[illegible]



Impact categories (source Schryver and Goedkoop, 2009)		
CC - Climate change	HT - Human toxicity	WD - Water depletion
OD - Ozone depletion	TE - Terrestrial ecotoxicity	FEu - Freshwater eutrophication
POF - Photochemical oxidant formation	FE - Freshwater ecotoxicity	MEu - Marine eutrophication
PMF - Particulate matter formation	ME - Marine ecotoxicity	ALO - Agricultural land occupation
IR - Ionising radiation	MD - Metal depletion	ULO - Urban land occupation
TA - Terrestrial acidification	FD - Fossil depletion	NLT - Natural land transformation

**Table 2: The Sustainable Textile Assessment Tool (STAT)**

As different forms of resources use and pollutants emissions identified in the life cycle inventory phase usually have different potential environmental impacts within each impact category, characterisation methods that associate the scale of a pollutant emission to selected characterisation/conversion factors are used (Pennington et al., 2004). Traditionally, characterisation proceeds by a simple formula (1) (Schryver and Goedkoop, 2008):

$$(1) \quad IR_c = \sum_s CF_{cs} * m_s$$

where  $IR_c$  is the indicator result for impact category  $c$ ,  $CF_{cs}$  the characterisation factor that connects intervention  $s$  (i.e., substance  $s$  emitted) with impact category  $c$ , and  $m_s$  the size of intervention  $s$  (i.e., the mass of substance  $s$  emitted).

Specifically for the textile area, several data, methods and tools have been developed for characterising the environmental impacts of textile products along their life (i.e., Nieminen et al., 2007; Muthu, 2014). In particular, the Instant LCA Web portal for textile and footwear, developed by Intertek, is an online solution for LCA and product eco-design that enables instant calculation, improvement and reporting of environmental impacts for textile, apparel and footwear products in four quick steps. The GABI Database “Textile finishing” (by thinkstep AG), includes inventory data for pre-treatment activities, dyeing, printing, and finishing processes, while the EIME software, developed by Bureau Veritas CODDE and GEMTEX, contains textile-specific database and numerous LCI textile datasets. Modint Ecotool developed by CE Delft, is an Excel-based tool that contains LCA information on the processes in each phase of the textile production chain.

In order to identify the “hotspots”, defined as the elements within the system that contribute most to the environmental burden, the environmental impact categories should be normalized and weighted.

LCA normalisation translates abstract impact scores into relative contributions of the organisation to a reference situation, intended as the environmental profile of an economic system that the organisation is part of. At the end of this step, all the normalised category indicators are expressed in the same unit, making different impact categories comparable (Norris, 2001). As reviewed in Sleeswijk et al. (2008), several normalisation methods have been developed during the last decade. For our purpose, the European textile sector and the environmental impacts of textile consumption in the EU-27 have been selected as the reference economic system, with specific reference to the production phase (Beton et al. 2011), as reported in Table 3.

Impact category		Unit	Reference value (RV)
CC	Climate change	Mt CO2 eq.	213
OD	Ozone depletion	t CFC-11 eq.	16.5
POF	Photochemical oxidant formation	Mt NMVOC	0.521
PMF	Particulate matter formation	kt PM10 eq.	263
IR	Ionising radiation	Mt 235U eq.	79.9
TA	Terrestrial acidification	kt SO2 eq.	851
HT	Human toxicity	Mt 1.4-DB eq.	12.5
TE	Terrestrial ecotoxicity	kt 1.4-DB eq.	943
FE	Freshwater ecotoxicity	Mt 1.4-DB eq.	1.68
ME	Marine ecotoxicity	Mt 1.4-DB eq.	0.376
MD	Metal depletion	Mt Fe eq.	10.9
FD	Fossil depletion	Mt oil eq.	73.0
WD	Water depletion	Billion m <sup>3</sup>	5.77
FEu	Freshwater eutrophication	kt P eq.	49.5
MEu	Marine eutrophication	kt N eq.	342
ALO	Agricultural land occupation	km <sup>2</sup> per yr.	81200
ULO	Urban land occupation	km <sup>2</sup> per yr.	939
NLT	Natural land transformation	km <sup>2</sup>	75.8



**Table 3: Environmental impacts of textile consumption in the EU-27 according to the midpoint indicators of ReCiPe – production phase (Beton et al., 2011)**

In particular, the applied formula is (Finnveden et al., 2002):

$$(2) \quad N_{IR_c} = IR_c / RV_c$$

where  $c$  denotes the impact category,  $N_{IR_c}$  is the normalised indicator,  $IR_c$  is the category indicator from the characterisation phase and  $RV_c$  is the reference value.

After normalisation, the weighting step allows to adjust the normalised indicators to reflect the real perceived relative importance of the different impact categories. In fact, the same impact category can be judged as more or less relevant by different stakeholders and decision-makers (even within the same organisation), following their own agenda imposed by economical, ethical, or social drivers. A higher value of an indicator may not be sufficient to prioritize it with respect to another indicator with a lower value if the former is deemed less important than the latter. Therefore, the normalised value of the  $N_{IR_c}$  must be considered by the light of the relative importance each impact category has in the specific case under analysis and for the specific set of decision-makers.

In the weighting step, the normalised results are usually multiplied by a set of weighting factors ( $w_{IR_c}$ ), one for each impact category (3).

$$(3) \quad W_{IR_c} = IR_c * w_{IR_c}$$

The weight of each category is meant to reflect the relative importance of the category with respect to the other categories. Clearly, weighting requires making value judgements as to the respective importance of the impact categories considered, potentially considering several attributes. These judgements may be based on expert opinion, cultural/political viewpoints, or economic considerations (European Commission, 2013).

Especially when several decision-makers are involved in defining the weights, and there are many attributes to evaluate for each category, this step may difficultly converge to a common point. To avoid this issue, the weights definition and the subsequent ranking of the impact categories can be accomplished using several approaches, from simple pairwise comparison to more complex ones such as the Delphi methods, or methods pertaining to Multi-criteria Decision Analysis (MCDA), such as the Analytic Hierarchy Process (AHP) (Saaty, 1980). The level of sophistication and required effort can vary quite substantially from one approach to another; thus, the proposed decision-making process does not recommend any specific approach, leaving to the decision-maker the choice, that should be made according to the specific characteristics of the case organisation.

Through the results from the impact assessment phase, the organisation gains insights into its current environmental impacts and reduction opportunities, and can formulate strong arguments for effective actions. Such interventions can be divided into different classes, as discussed in the next phase.

#### Phase 4: Interpretation of results

Based on the results from the “Impact assessment” phase, a priority list can be created by ranking the weighted  $IR_c$ , thus identifying the most critical impact category. Then, since each impact category is linked to the TIM with the Sustainable Textile Assessment Tool (Table 2), it is possible to identify the environmental hotspots in terms of inputs, outputs and, consequently, processes. An example is reported in Table 4. In this case, particulate matter formation (PMF) is the most critical impact category, and the hotspots are input I2 and O2. From the TIM is then possible to identify the most critical processes having I2 as input and/or O2 as output (for the example reported in Table 4: PP1, PPM, SP1, SP2, MP1 and MPo).

		Impact categories																	
		CC	OD	POF	PMF	IR	TA	HT	TE	FE	ME	MD	FD	WD	FEu	MEu	ALO	ULO	NLT
$W_{IR_c}$		8	0.7	5	19.1	7	0.2	1.5	6.3	9.4	1.8	9.2	4.6	18.2	0.9	4.3	7.2	1.6	0.4
Inputs	I1	x		x															
	I2				x														
	...																		
	Ii		x			x				x	x		x	x					x

<i>Outputs</i>	O1		x															
	O2	x	x		x				x					x			x	
	...																	
	Oo	x																

Macro-process # 1												
Primary Processes (PPs)					Support Processes (SPs)				Mechanical plants (MPs)			
	PP1	PP2	...	PPm	SP1	SP2	...	SPn	MP1	...	MPo	
<i>Inputs</i>	I1	x			x			x				
	I2				x	x						
	...											
	Ii		x		x	x			x			x
<i>Outputs</i>	O1		x		x		x		x			x
	O2	x			x	x	x		x			x
	...											
	Oo	x			x			x	x			x
<i>Resources</i>	R1	x	x			x						x
	R2				x							
	...											
	Rr	x			x		x		x			

Table 4: Identification of environmental hotspots

Such information can be used to define a set of solutions that potentially could decrease the environmental impact, focusing on the most critical elements identified. Basically, potential solutions could refer to:

- technical solutions, at production level, such as the installation of a solar plant that allows a green production of electricity and/or of hot water for the heating system;
- managerial solutions to drive processes towards sustainability, such as the application of lean manufacturing principles that can be adopted to optimize the workshop efficiency in using inputs and resources;
- at suppliers' level, including the use of sustainable materials, reuse, recycling and recovery.

With particular reference to the textile sector, a list of Best Available Techniques (BATs) for supporting the identification of potential solutions is available (European Commission 2003). BATs are generically defined under the scope of the European IPPC (Integrated Pollution Prevention and Control) Directive (European Commission 2008, p. 24) as “the most effective and advanced stage in the development of activities and their methods of operation which indicate the practical suitability of particular techniques for providing in principle the basis for emission limit values (ELV) designed to prevent and, where that is not practicable, generally to reduce emissions and the impact on the environment as a whole”.

The identified solutions, aiming at mitigating the corporate environmental impacts, are then evaluated with financial tools, to assess their investment returns and economic impacts. The financial analysis must be able to capture all relevant and significant costs related to the alternatives, as prescribed by the Total Cost Assessment (TCA) method (Epstein 1996). TCA is similar to traditional capital budgeting techniques except that it attempts to include all costs and benefits associated with each alternative, including environmental expenditures and savings. In accordance with Curkovic and Sroufe (2007), four tiers of costs are considered (Table 5): direct costs, hidden costs, contingent costs, and less tangible costs.

<i>Direct costs</i>	<i>Hidden costs</i>
Buildings	Regulatory Compliance
Equipment Installation	Environmental Monitoring
Project Engineering	Legal Support
Material	Sampling and Testing
Labour	Education and Training

Waste Management	Utilities
<i>Contingent liability costs</i>	<i>Less tangible costs</i>
Accidental Releases	Corporate Image
Legal Damages	Community Goodwill
Settlement for Remedial Actions	Customer Acceptance

Table 5: Tiers of costs (from Curkovic and Sroufe 2007)

Once all the costs (and savings) associated with each solution are identified, financial tools for rating investments, familiar to many businesses, are then used to evaluate the economic added value of each option: Net Present Value (NPV), Internal Rate of Return (IRR), and Payback Period. Additionally, environmental savings are calculated to assess environmental gains of each solution. Economic and environmental added value can be then represented into a Cartesian coordinate plane, for example (Saved emissions; NPV), to identify the solution(s) with a meaningful combination of economic and environmental benefits (Figure 2).

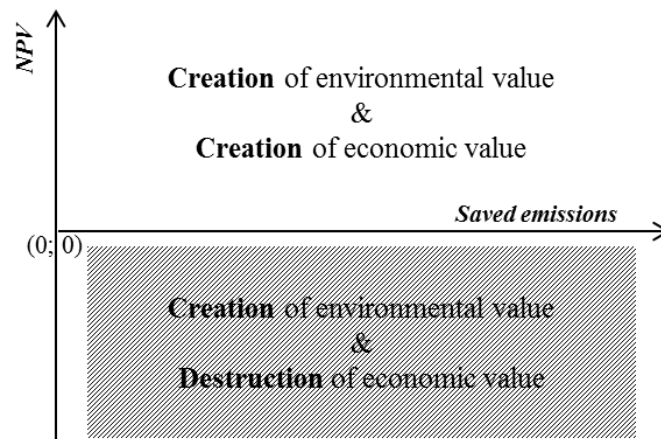


Figure 2: Cartesian coordinate plane (Saved emissions; NPV)

Finally, by constantly collecting data and calculating the indicators defined in the Impact assessment phase, new hotspots could be identified and new solutions could be proposed, in accordance with a continuous improvement approach. Additionally, the TIM might be updated as a consequence of the implemented solution(s).

Figure 3 shows the final decision-making process and its supporting tools.

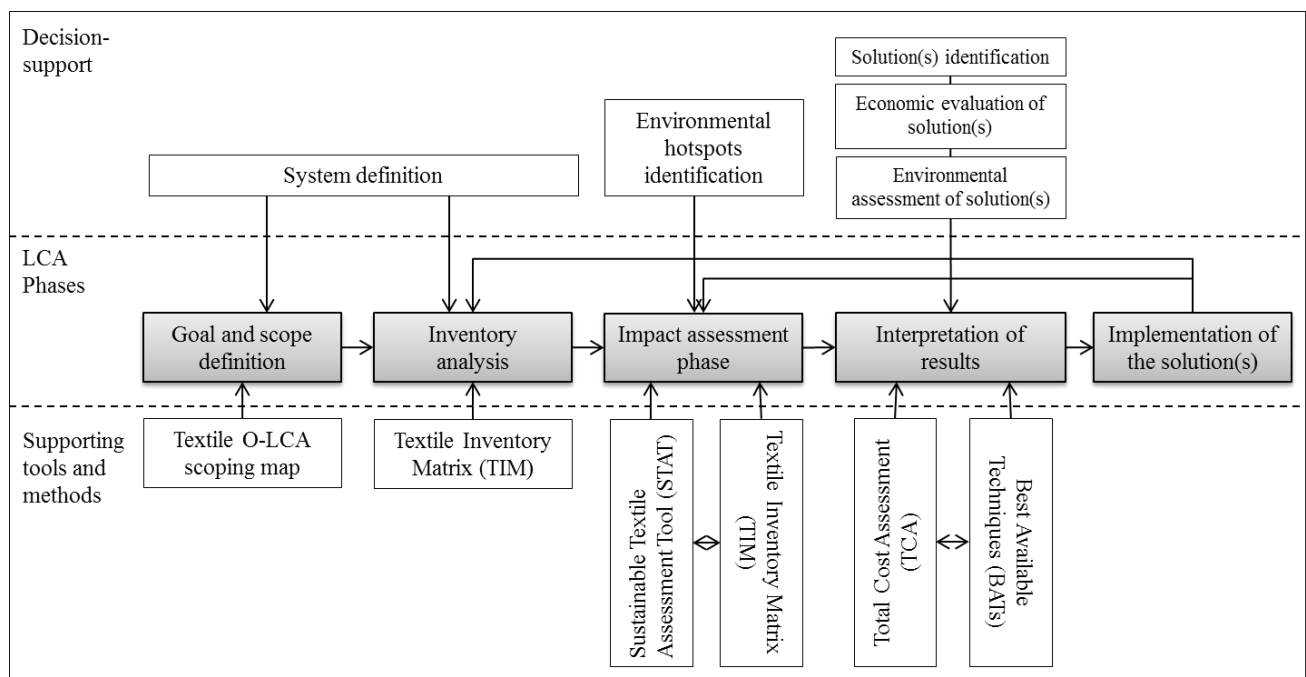


Figure 3: The decision-making process

In the next section, a case study example is used to reflect on the application of the developed decision-making process and to illustrate and analyse its applicability, consistency and benefits.

#### 4 An empirical application

In this section, the application of the decision-making process to a yarn-spinning company (hereafter referred to as Texco) is presented.

Firstly, the scope of the decision-making process was limited to the spinning macro-process and its indirect upstream activities (Phase 1), as represented in Figure 4.

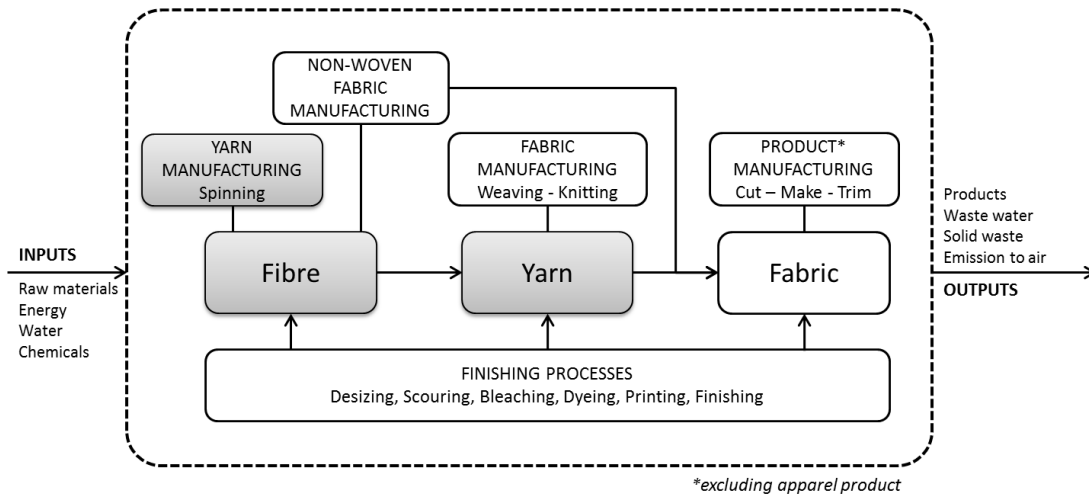


Figure 4: DoreTex system boundary diagram

Then, the processes and facility features associated to the company's business were selected from the comprehensive TIM (Phase 2 – See Appendix A). For each process/mechanical plant, inputs, outputs and resources were measured. Afterwards the impact categories were calculated (*IR<sub>c</sub>*) and then normalised (*N\_IR<sub>c</sub>*) (Phase 3), as reported in Table 6.

			IR	N_IR (10 <sup>-6</sup> )
CC	Climate change	kg CO2 eq.	42.960.172,01	201,69
OD	Ozone depletion	kg CFC-11 eq.	0,80	48,48
POF	Photochemical oxidant formation	kg NMVOC	3.826,09	7,34
PMF	Particulate matter formation	kg PM10 eq.	133.874,65	509,03
IR	Ionising radiation	Kg 235U eq.	16.000.000,00	200,25
TA	Terrestrial acidification	kg SO2 eq.	549.497,75	645,71
HT	Human toxicity	kg 1.4-DB eq.	7.941.927,05	635,35
TE	Terrestrial ecotoxicity	kg 1.4-DB eq.	21.200,00	22,481
FE	Freshwater ecotoxicity	kg 1.4-DB eq.	285.412,82	169,89
ME	Marine ecotoxicity	kg 1.4-DB eq.	144.416,31	384,09
MD	Metal depletion	Kg Fe eq.	2.000.000,00	183,49
WD	Fossil depletion	kg oil eq.	5.891.668,22	80,71
FEu	Water depletion	m <sup>3</sup>	8.734.237,00	1,51 *10 <sup>-15</sup>
MEu	Freshwater eutrophication	kg P eq.	6.110,80	123,45
ALO	Marine eutrophication	kg N eq.	191.827,14	560,90
ULO	Agricultural land occupation	m <sup>2</sup> per yr.	19.680.000,00	242,37
NLT	Urban land occupation	m <sup>2</sup> per yr.	35.000,00	37,27
CC	Natural land transformation	m <sup>2</sup>	8.000,00	105,54

Table 6: Doretex impact assessment – characterisation and normalisation

The weighting step was performed using the rank order centroid (ROC) technique (Barron and Barret, 1996). The ROC technique is a simple way of assigning a weight to a number of items, which have been ranked by one (or more) decision makers, according to their importance. The ROC method was selected because of the relatively large number of impact categories (18) that made impractical a pairwise comparison. Moreover, one of the main advantages in using of the ROC is that decision makers usually can rank items much more easily than give a weight to them. Thus, the

research team discussed the impact categories with the company's team, and defined a rank (see Team's rank in Table 7) of the four most important impact categories, regardless their normalized value. The rank provided by the working team allowed defining a set of weights as follows (4):

$$(4) \quad w_i = \frac{1}{4} \sum_{k=i}^4 \frac{1}{k} \quad \forall i = 1 \dots 4$$

where  $w_i$  is the weight associated to the  $i$ th element in the Team's rank. Multiplying the weights by the normalized values, the resulting rank highlights the Climate Change as the most critical category (see ROC rank in Table 7).

Team's rank	Impact category	Normalized value (10 <sup>-6</sup> )	ROC weight	Normalized value * ROC weight (10 <sup>-6</sup> )	ROC rank
1	Climate change	201,69	0,52083	105,05	1
2	Water depletion	1,51 *10 <sup>-15</sup>	0,27083	4,1*10 <sup>-16</sup>	4
3	Human toxicity	635,35	0,14583	92,66	2
4	Freshwater ecotoxicity	169,89	0,06250	10,62	3

Table 7: Ranking of the most relevant impact categories

Within this impact category, energy consumption was recognized as the most critical hotspot, since it was responsible for the major contribution to climate change (Table 8).

	<i>Climate change Detailed assessment (kg CO2 eq.)</i>
Fibres	12.612.800,00
Other materials	10.586.473,00
Water	1.289.423,00
Energy - Electricity	17.200.000,00
Total waste	13.884.276,01
<b>TOTAL</b>	<b>42.960.172,01</b>

Table 8: Contribution of inputs and outputs to CC (aggregated data)

As represented in the TIM (Appendix A), energy is an input in 11 primary processes (PP2-Bale plucking, PP3-Blending, PP4-Opening and Cleaning, PP5-Carding, PP6-Drawing, PP7-Lapping, PP8-Combing, PP9-Post-combing drawing, PP10-Roving, PP11-Spinning, PP12-Winding), 1 support processes (palletizing), and 4 mechanical plants (pneumatic system, lighting system, conditioning system for roving and for spinning). The contribution of each process to energy consumption is shown in Table 9.

Process / Mechanical plant	Contribution to energy consumption
Spinning	23%
Conditioning system (for pre-spinning processes)	21%
Winding	12%
Pneumatic system	11%
Conditioning system (for spinning)	10%
Carding	6%
Bale plucking	4%
Lighting system	4%
Roving	3%
Combing	1%
Post-combing drawing	1%
Lapping	1%
Palletizing	1%
Opening and Cleaning, Blending	1%
Drawing	1%
<b>Total</b>	<b>100%</b>

**Table 9: Contribution to energy consumption**

“Spinning” is the most critical process, mostly contributing to company’s energy consumption. Among the available BATs, a panel of experts selected the installation of high-efficiency motors as a potential solution able to decrease the energy consumption of the spinning process. Economic and technical data of such solution are reported in Table 10, while Table 14 includes the financial analyses of the investment (with 10% discount rate). The latter refers to the nine spinning machines used by the company.

Working hours/year	5000
Energy cost	0,15€/KWh
Initial investment for motor purchasing	1600€/motor
Initial investment for motor installation	200€/motor
“Traditional” motor power	40 KW
High-efficiency motor power	45 KW
Energy saving	2,2%

**Table 10: Technical parameters and costs of high-efficiency electric motors for spinning machines**

The second critical process is the “Conditioning system (for spinning preparation)”. In this case, a panel of experts focussed its attention on the Air Handling Unit (AHU), suggesting the installation of an inverter on the centrifugal fan. Table 11 shows technical parameters and cost characterising this solution.

Working hours/year	5000
Energy cost	0,15€/KWh
Energy consumption/hour	73 KWh
Inverter purchasing	3925 €
Electric system upgrade	5000 €
Dampers for centrifugal fan	5000 €
Energy saving	4%

**Table 11: Technical parameters and costs of installing an inverter on the centrifugal fan of the conditioning system**

In Table 14, economic and financial evaluation of the investment are reported (with 10% discount rate).

Winding is the third energy-consuming process . As for the spinning process, the solution proposed by the experts relates to the installation of high-efficiency motors on the winding machines (Table 12 for technical parameters and costs, and Table 14 for financial analyses of the investment). The latter refers to the 2 winding machines installed in the production plant.

Working hours/year	5280
Energy cost	0,15€/KWh
Motor power	45 KW
Mean energy consumption/hour	41 KWh
Motor purchasing	21500 €
Energy saving	1,3%

**Table 12: Technical parameters and costs of high-efficiency electric motors for winding machines**

Additionally, a fourth option was proposed by the experts: the substitution of neon lighting with LED technology (Table 13 and Table 14).

Energy cost	0,15€/KWh
Working hours/year	5000
Neon lamp lifetime	15840 hours
LED lamp lifetime	50000 hours
Neon lamp power	60 W
LED lamp power	30 W
Number of lamps	150
Neon lamp purchasing cost	2,6€/Neon lamp
Neon lamp power supply and starter purchasing cost	5€/Neon lamp
LED lighting fixture installation cost	10€/LED lighting fixture



LED lighting fixture purchasing cost	55€/ LED lighting fixture
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Table 13: Technical parameters and costs of LED lighting technology

The four proposed solutions are compared in Table 14, where the estimated saved energy is also calculated and converted into CO<sub>2</sub> equivalent.

	Installation of high-efficiency electric motors on spinning machines	Installation of inverter on the centrifugal fan of the conditioning system	Installation of high-efficiency electric motors for winding machines	LED technology for the lighting system
NPV (10 years)	11357€	-1809€	-29.956,80€	5879€
IRR	25%	10%	-11%	25%
Pay Back Period	5 years	15 years	>100 years	5 years
Saved CO <sub>2</sub> emissions	87297 kg	143506 kg	27400 kg	301105 kg

Table 14: Environmental and economic comparison of the proposed solutions

Results are then represented into a Cartesian coordinate plane (Figure 5).

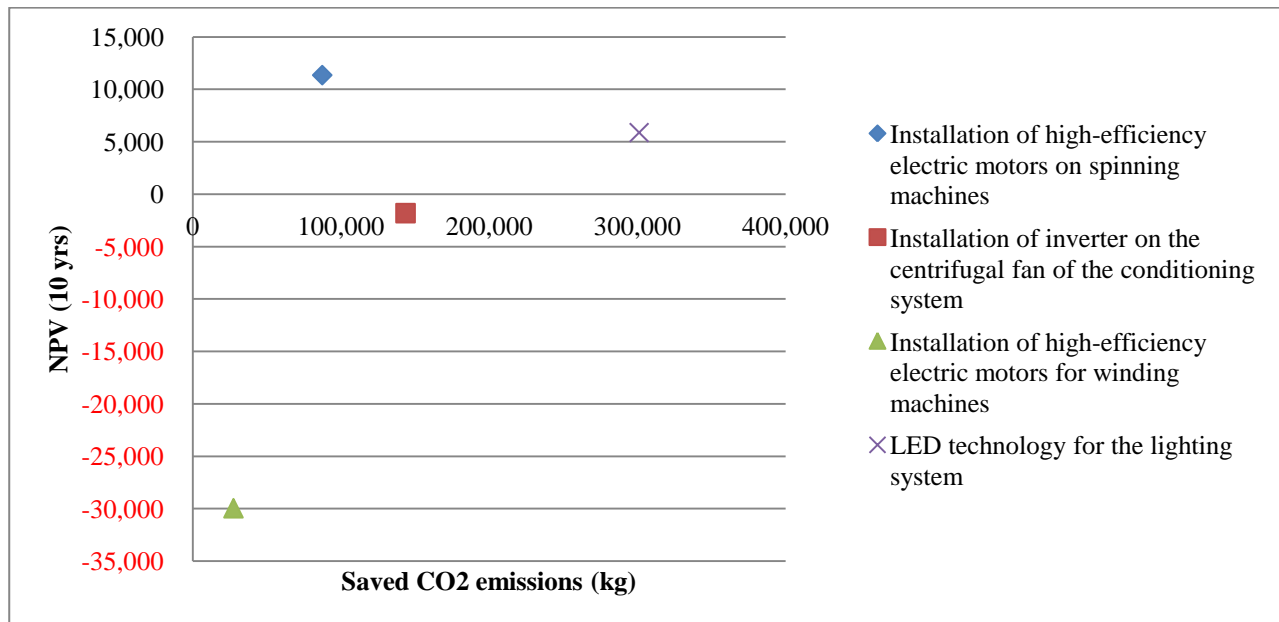


Figure 5: Cartesian coordinate plane of the proposed solutions (Saved CO<sub>2</sub> emissions; NPV(10 years))

The best environmental and economic solution is the substitution of the neon lighting system with the LED technology, while the installation of high-efficiency electric motors on spinning machines is the second best solution. With the implementation of these two options it is possible to save 388402 kg of CO<sub>2</sub> equivalent per year. Although the other two solutions (installation of inverter on the centrifugal fan of the conditioning system and installation of high-efficiency electric motors for winding machines) bring environmental savings, economic value is destroyed (negative NPV).

## 5 Conclusions

Sustainability is gaining more and more relevance on the manager's agenda since it can positively contribute to the firm's value creation process. The benefits are numerous, ranging from cost reduction, through risk management and business innovation, to revenue and brand value growth. In the textile sector, several companies are starting to pave the way towards sustainability through a number of different approaches.

In such a context, this paper proposes a decision-making process to help textile companies in fulfilling environmental, economic and competitive benefits. In particular, it is a reference process built upon the O-LCA methodology to help operations managers make informed decisions about potential environmental impacts of processes, and to support the

identification of opportunities for preventing pollution and for reducing resource consumption through a systematic analysis. Summarizing, the process provides a management system able to support managers to: i) monitor and evaluate environmental performances with a dynamic perspective, providing companies with the right information upon which to base decision; ii) identify which activity and/or mechanical plant needs to be improved or changed in order to reduce the environmental impact, enabling cost savings in both the short- and long-term, developing the business case for sustainability; iii) define strategies for sustainability and foster the sustainable development of a company; and iv) increase a sustainable image.

As demonstrated by the pilot case study that has been used to illustrate and analyse the applicability and consistency of the model, the solution proposed and implemented has enabled significant economic and environmental savings through a lower resource utilization.

To conclude, this paper can be considered as a basis for further research. In particular, in order to overcome the limitations of this work, some possible directions are hereafter pointed out. First of all, the social dimension should be included in the decision-making process. Secondly, the goal and scope definition could be enlarged in order to cover the entire textile and clothing chain, from raw material growing and production, up to distribution and retailing of the final product to the customers. Third, a Decision-Making Software (DMS) could be developed to support the analysis involved in decision-making processes. Finally, the logic behind the decision-making process could be applied to different sectors, through the creation of a sector-specific Inventory Matrix, Sustainable Scorecard and the selection of proper footprint(s) (carbon, water, energy, etc.).

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## Appendix A

TIM for the spinning macro-process.

Macro-process: SPINNING																					
		Primary Processes (PPs)												Support Processes (SPs)				Mechanical plants (MPs)			
		PP1	PP2	PP3	PP4	PP5	PP6	PP7	PP8	PP9	PP10	PP11	PP12	SP1	SP2	SP3	SP4	MP1	MP2	MP3	MP4
Inputs	Ball bearing*																X				
	Battery*																X				
	Belt*																X				
	Bush*																X				
	Circular comb*																X				
	Clothing fixed flat*																X				
	Compressed air		X		X	X			X	X	X	X	X		X						
	Fibres	X																			
	Corrugated board														X						





Broom															X				
Can					X	X		X	X	X									
Carding machine					X														
Centrifugal fan																X			
Color scanning cameras				X															
Combing machine								X											
Compressor																		X	
Drawing frame						X			X										
Dust separator		X		X	X														
Forklift truck	X												X						
Lapping frame							X												
Lighting system																			X
Opening and cleaning machine				X															
Packaging machine													X						
Palletizing machine													X						
Pressure switch					X														
Pump																X	X		
Repair tools															X				
Roving frame									X										
Scissors	X																		
Spark detector		X																	
Spinning machine										X									
Static filter system																			
Strapping band cutting machine	X																		
Winding machine											X								

*Primary Processes:* Bale laydown (PP1), Bale plucking (PP2), Blending (PP3), Opening and Cleaning (PP4), Carding (PP5), Drawing (PP6), Lapping (PP7), Combing (PP8), Post-combing drawing (PP9), Roving (PP10), Spinning (PP11), Winding (PP12).

*Support Processes:* Picking and handling (SP1), Palletizing (SP2), Facility cleaning (SP3), Maintenance (SP4)

*Mechanical Plants:* Conditioning system for roving (MP1), Conditioning system for spinning (MP2), Pneumatic system (MP3), Lighting (MP4)

# Enhancing environmental management in the textile sector: an O-LCA approach

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## **Highlights:**

- The textile and clothing sector is one of the largest and most polluting industries.
- O-LCA can support companies in making the textile industry more sustainable.
- A new decision-making process exploiting O-LCA methodology is proposed
- A case study of a spinning company reveals the benefits of the decision-making process.