UNIVERSITA' DEGLI STUDI DI PARMA

Dottorato di ricerca in Ingegneria Industriale

Ciclo XXVIII

Sustainability-driven innovation: technologies, methodologies and business models for a more sustainable manufacturing

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1 Introduction

The 2015 United Nations Climate Change Conference, COP 21, held in Paris at the end of 2015, proposed a further discussion of the 1997 Kyoto Protocol and resulted in the so-called Paris Agreement, a global contract between the 196 participating nations concerning the restraint of elements and behaviours causing climate change. On 22 April 2016, 174 countries signed the agreement in New York, and began adopting it within their own legal systems. The aim of the convention is described in Article 2, "enhancing the implementation" of the UNFCCC (United Nations Framework Convention on Climate Change, [1]) through:

- holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5 °C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change;
- increasing the ability to adapt to the adverse impacts of climate change and foster climate resilience and low greenhouse gas emissions development, in a manner that does not threaten food production;
- making finance flows consistent with a pathway towards low greenhouse gas emissions and climate-resilient development.
- countries furthermore aim to reach "global peaking of greenhouse gas emissions as soon as possible".

The convention is seen as an encouragement to divest from fossil fuel [2].

As the world investigates approaches to adopt COP21 principles through proper legislations and regulations, the **manufacturing communities** should explore their role as co-responsible of environmental and social impacts, and thus as enablers of sustainable development [3]. In fact, production is often the cause of many undesired impacts, making it a good focus for sustainability-enhancing innovations and investments.

But why and how a private manufacturing company should invest in improving its sustainability profile?

According to literature ([4]; [5]), one of the major problems with sustainability-centred business approaches relates to the simultaneous pursuit of private (companies' and customers') and public (society and environment) benefits. As long as public benefits don't result into countable (monetary) private advantages, more sustainable production systems and products may be competitively disadvantaged. This has an evident result: though sustainability is generally considered something highly desirable, the main challenge threatening its actual implementation in manufacturing contexts derives from adopting approaches able to simultaneously improving competitiveness and business performance through positive social and environmental performances, which neither always nor automatically bring about financial benefits.

In fact, if the promoters of the idea of sustainability consider it to be the "mother lode of organizational and technological innovation, the key to progress and […] an integral part of development" [6], several authors also claim the potential disadvantages related to more sustainable business practices.

Key arguments in this respect are "making operations suitable places at a disadvantage vis-à-vis rivals in developing countries that don't face the same pressure; sustainable manufacturing demand new equipment and processes and customers will not pay more for eco-friendly products" ([6]). This means that as companies are not compensated for reducing negative externalities or creating positive externalities per se, they are not motivated to engage in such activities.

"*It isn't just citizens and NGOs that truly care about a responsible environmental policy. Entrepreneurs like me care too. In fact, industrial companies might even be particularly valuable in the fight against climate change. […] An ambitious agreement in Paris is not opposed to the interests of industry. This is why it makes sense to invite industry to the table when discussing environmental policy. We are, in fact, a part of the solution.*" ([7]). This is an excerpt of an interview

(November 2015) to Dr. Reinhold Festge, president of VDMA, the German Engineering Federation: western countries' manufacturers start to look at sustainability as a picklock to assure their competitive differentiation.

In this context, most farsighted manufacturing enterprises started investing on sustainability to seize the opportunity of such a global trend: being sustainable is becoming a picklock for accessing most demanding customers, and a lever to differentiate from lower wages countries productions. This results in exploring **sustainability-related strategies** as a guide to re-design business processes, with companies either motivated by end customers' (or other stakeholders') increased pressure towards environmentally- and socially- compliant products and processes [8] or, less virtuously, interested in catching the latest marketing wave. In both cases, such (prospective) early adopters are looking for actual implementation examples and/or practical procedures they could follow in order to become "sustainable" or "more sustainable" (than before or than the competitors). Unfortunately, a **formalized approach** comprehensively supporting sustainability strategy implementation is still missing (some high-level examples are available but focussing on mere environmental parameters and/or with limited applicability [9]): which are the steps a potential sustainable entrepreneur has to follow? Which are the available tools he can adopt? Which product/company lifecycle phases are more appropriate for starting such a path? A practical, experimented and industrial-oriented sustainability implementation procedure has been never described in literature (apart from [10], where authors propose an *exercise* addressing a wooden component): lack of descriptive capabilities or lack of actual examples?

The here reported work aims at providing an integrated, comprehensive and prospective point of view on sustainable manufacturing considering all the steps a prospective adopter should go through in order to implement the sustainability principles and paradigms.

- **Assessment and Advisory**. Measuring the sustainability performances of a company/process/product is the first, mandatory step to be completed in order to diagnose the actual sustainability status of a target. This requires to address three, sequential issues:
    - a unified and detailed description of the **sustainability concept** (§2.1) is a fundamental initial task, needed in order to assure a common understanding of the undergoing terminology (what does "sustainability" means? And "manufacturing sustainability"?) Nowadays several definitions have been proposed in literature and adopted in specific manufacturing and non-manufacturing contexts. The proposed discussion aims at giving a personal point of view on the topic, selecting a reference definition to be adopted during the whole work;
    - unfortunately, definitions and proposed statements of meaning are often not followed by practical approaches and tools supporting the actual measurement of the real "performances" of the target (product, process, company, …). For this reason, a proper set of sustainability **metrics** is reported in §2.2. Enabling a "standardized" measurement of sustainability and, specifically, of private (and, incidentally, public) benefits allows comparison, thus enables decision-making. Many international initiatives have developed indicator sets, formulae and recommendations for this purpose, even if rarely addressing specific requirements of manufacturing environments. The here presented discussion relies on findings from two industry-oriented research projects addressing this specific purpose, with a set of manufacturing-focused metrics consolidated and validated in real production contexts;
    - **assessment tools** are finally presented in §2.3, including three approaches that can be used to have a picture of the sustainability performances of a product/company/supply chain. The last one is a properly developed sustainability assessment tool developed within a funded research project and aimed at providing an innovative point of view on sustainability assessment.
- **Sustainability-driven innovations**. With a clear picture of current sustainability performances in their hands, entrepreneurs need to face the challenge to improve their profile. Improvement has to be perceived more from a Taiichi Ōno point of view: as a

continuous, evolving, never ending project. Initiatives and investments aimed at improving sustainability performances of products, companies or groups of companies can address (also simultaneously) different elements of a company business profile: the technology they use, the way they design product or processes, the way they create value and the underlying business model, regulations they need to comply with. These issues are presented in §3.1 and deepened in the form of case studies, as follows:

  - Innovative technologies intended to exploit by-products in specific manufacturing contexts are presented in §3.2 with the goal to demonstrate the possibility to simultaneously pursue economics and environmental objectives;
  - business modelling for sustainability is discussed in §3.3 including a focus on sustainable clusters and a properly designed business model developed for manufacturing agglomerations aimed at adopting industrial symbiosis.

- **Reporting**. Manufacturers need to comply with existing regulations and legislation on sustainability topics and need to communicate the results achieved thanks to the adopted sustainability-enhancing measures. Chapter 4 aims at exploring this topic discussing:
  - the role of legislation and regulations in mastering manufacturers' behaviours (§4.1);
  - the importance of **sustainability labelling** to report the achieved results (§4.2).

In the concluding Chapter some open issues are presented discussing the role of current technological and methodological evolutions (such as IoT, Industrie 4.0 and CPS) for the future of sustainable manufacturing.

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2 Sustainability Assessment

Chapter 2 focuses on the first step of any sustainability-related project, that is: sustainability assessment. Assessing means knowing, and knowledge is the most relevant starting point towards improvement. As soon as you perfectly seize your sustainability performances, you are aware of the needs you have for improving them.
A good sustainability assessment necessarily requires:

- a consistent and standardized **definition** of sustainability is discussed in §2.1
- reliable **metrics**, useful for a unified and univocal quantification of sustainability performances, thus enabling comparison, benchmarking and easy usage are then proposed in §2.2
- §2.3 focuses on three sustainability assessment tools/methodologies (the last one has been properly designed ad developed) adopted in real manufacturing contexts.

2.1 Sustainability: relevance and definitions

2.36 millions occurrences in Google Scholar, 120 millions results in a standard Google search: sustainability has become a common theme in many knowledge areas.
The topic is addressed in several production contexts with more than 450'000 Google Scholar occurrences of "sustainable agriculture" and related searches (as of 1 January 2017), over 100'000 occurrences for "sustainable manufacturing" (and similar keywords) and some 50'000 occurrences for "sustainable services" and similar. This is a plain and apparent picture of the relevance this topic has in several spheres: sustainability is an increasingly important requirement for human activity, making sustainable development a key objective in human development.
The attention for sustainability issues has been increasing sharply among the public, policy makers, practitioners and academics, especially since the United Nations Conference on Environment and Development (UNCED) in Rio - the Earth Summit - having taken place in 1992. A major outcome was an action program called Agenda 21, which acts as a global forum for sustainable development in all areas where humans impact the environment. Indeed, public concern about sustainable development has profoundly transformed attitudes and, to a lesser extent, practices in manufacturing industries over the past decade.

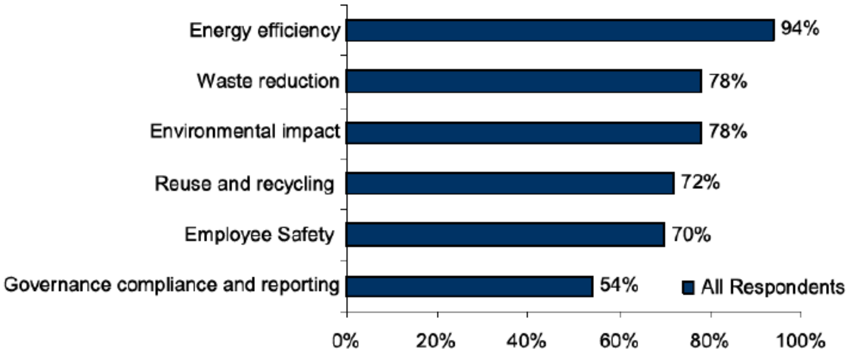
Sustainability has gained importance in several human activities starting from the 1992 Rio Earth Summit

Environmental issues started affecting public opinion since late nineties, with an increasing and increasingly widespread attention towards (especially) green topics (while social issues started to be considered in detail a bit later). According to Eurobarometer (2013 data) around 90% of final customers ask for green products [11]: they consider "green as good", and they are convinced their purchasing habits may influence, let's use an overstatement, the planet health.
In specific contexts, (declared) environmental performances of products are even more important than their price. Unfortunately (from customers' point of view), green or environment-friendly products are not easily accessible and available in the shops. Or, at least, it is not so easy to distinguish between green and not green solutions. How can they (the customers) believe in declared performances? How to be sure about actual performances?

Lack of metrics? Lack of / overuse of environmental- green- labels generating confusion and overthrowing customers trust also against those who are in good faith?

And what about the suppliers? Are they conscious about environmental-related issues? What's their behaviour? Many data show how environmental topics are a new opportunity for competing in a global market, to differentiate Western countries productions from low-wage countries offer, and to justify higher costs and … prices. As usually happens, the smartest companies started turning an apparent constraint into an opportunity. According to [12], 93% of CEOs worldwide sees sustainability as a strategically important issue for the future success of their business. Several studies tried to quantify and measure the perception of the concepts behind sustainability by entrepreneurs, managers and other decision makers in the manufacturing contests. See, for example, the chart below.

Figure 1: Attention towards sustainability of major manufacturing companies - source: Aberdeen Group-September 2009



Another study performed by Deloitte ([13]) and reported in a whitepaper focussing on the Swiss MEM (Machine Electronics and Metal) Industry shows that 88% of respondents point to "efficiency and environmental technologies" as the most important opportunity to increase their competitiveness (2014 data): environment is actually perceived as an opportunity!

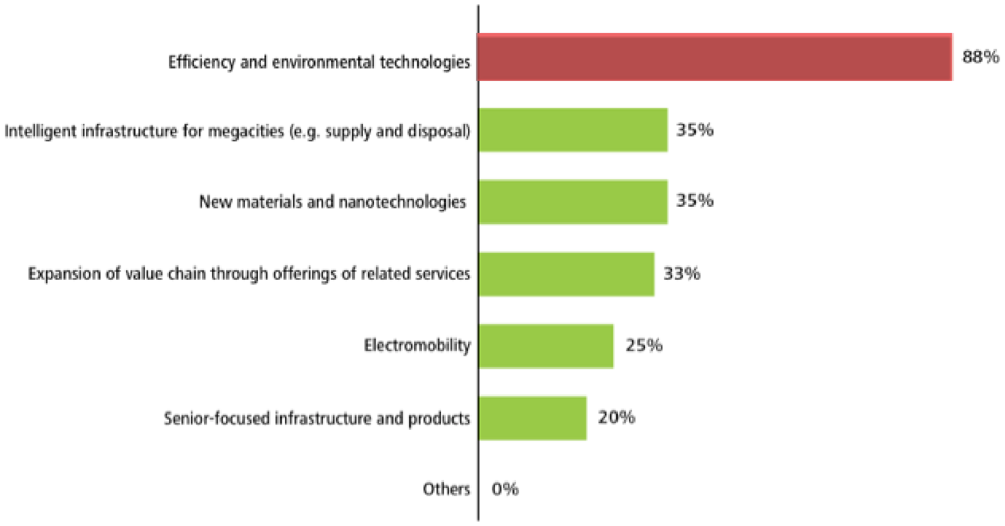


Figure 2: DELOITTE - White paper on Swiss Manufacturing Industry

In the same report, researchers and industrial managers suggest put "better resource utilization" at the centre of their strategic agenda for improving their competitive position, and "sustainability" is mentioned as one of the most important strategic approaches for the future of manufacturing (see charts below). This is surely true for Switzerland, but several similar reports have been published for other Western countries, definitely highlighting that sustainability (either "soft" or "strong", see below for definitions) is no more perceived as a constraint, but as a business and strategic opportunity to differentiate European productions from low-wages countries ones.
As resulting from the report: "The issue of sustainability and climate protection will continue to be important drivers for the manufacturing industry in the future. MEM companies will be able to utilise these issues to differentiate themselves strategically and operationally from the competition and fain a competitive advantage. Sustainable corporate management is primarily characterised by environmentally friendly products, sustainable manufacturing and product development, recycling systems, the use of renewable energy and social responsibility."

Figure 3: DELOITTE - White paper on Swiss Manufacturing Industry: Options for action for the Swiss Manufacturing industry – strategic vision

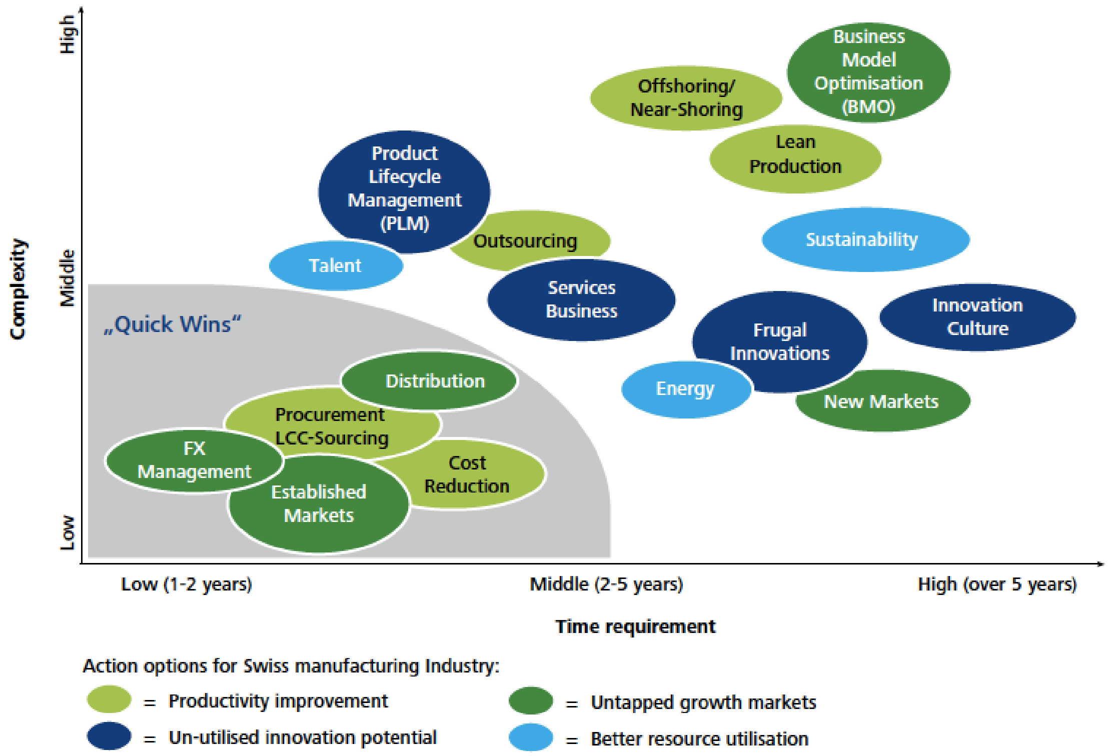


Figure 4: DELOITTE - White paper on Swiss Manufacturing Industry: Options for actions for MEM companies

As discussed in [14], good environmental practice is increasingly becoming essential for several stakeholders. This has transformed sustainability from a constraint into a competitive opportunity. To demonstrate such a thesis, the mentioned report gives some figures:

- the green marketplace is worth trillions: a 2010 survey of UK-based manufacturing SMEs shows that 56% are already investing in low-carbon technologies and strategies. The global market for low-carbon products is already estimated to be worth over USD 5 trillion and growing.

- Retailers are demanding that suppliers respond to green consumers: In 2009, Walmart, the largest retailer in the world, introduced a worldwide sustainability index. The index will be applied to over 100 000 global suppliers to give consumers a clear environmental and social rating for every product it sells.
- A green reputation drives up your financial value: a study by Harvard and London Business Schools found that financial analysts rate companies with a visible reputation for environmental responsibility higher than others. Conversely, poor performance can be a serious risk. Companies with significant environmental problems, including litigation, have to pay up to 0.64% more to service their debts and secure credit.
- A little investment in greening may lead to big savings: The UK's Carbon Trust estimates that most businesses can cut their energy bills by up to 20% with only a small investment – a saving that could equate to as much as a 5% increase in your overall profits.
- Young workers value sustainability and demand green workplaces: A 2010 survey of 5,300 respondents worldwide, carried out by Johnson Controls Global WorkPlace Solutions, shows that over 96% of 18-45 year olds want their employer and workplace to be environmentally friendly or at least environmentally aware. Over 70% of all respondents would like to share printers and have recycling bins in the office, while 47% want to have water saving devices and solar panels installed on site.

A sustainable approach to manufacturing involves evaluating where a product or system has the greatest environmental impact and then prioritising strategies which reduce that impact. This should, however, be pursued with the customer in mind. In [15], for instance, authors suggest that the values and expectations of customers impose significant pressure on firms to act in environmentally responsible ways and therefore to design appropriate products to meet these expectations. According to [16] any industry sector feels the management of environmental sustainability as relevant. The worsening of ecosystems, global warming, increased energy usage, have all become key issues for all humans. And manufacturing has an undisputable role in this. It is thus mandatory that all steps going from design to manufacturing, middle and end of life activities take actions on environmental sustainability concerns through appropriate strategies, and adopt standards assuring improved process and product environmental performances.
Authors suggest companies to be pro-active for what concerns sustainability: in [17], authors observed that pro-active companies are usually more successful by introducing innovations to their products and by voluntarily meeting sustainability standards.

In the manufacturing arena, both customers and suppliers started to handle the sustainability-related topics either as a constraint to be fixed or respected, or as an opportunity to be seized.

But how many of these end-users, customers, companies and studies use a *correct* **definition of sustainability**?

Several authors report how the term 'sustainability' appears to be confusing and trite. Yet it stands for a great evocation. In fact, although humans are constantly surrounded by the word, it is still vague and not specific at all. Some studies report several divergent (or partial) opinions expressed by interviewed people, providing a wide variety of answers. Sustainability surely means being viable for the future, assuring equilibrium or acting responsibly. Other people understand it to mean humility, mindfulness or even being fit for generations to come ([18]). When something is sustainable, it is durable, resources-friendly, and environmentally sound. But also effective, perpetual, long-lived or even symbiotic. Or persistent, weighty or pervasive. Given such a large number of meanings, especially producers are not keen to use such a term. A crucial contribution to this "bad reputation" of the term derives from its misuse or, also, abuse, such as in *greenwashing* campaigns ([19]). These marketing-triggered initiatives resulted in distrust against the sustainability word and concepts behind.

Figure 5: The 7 sins of green-washing

1. Sin of the Hidden Trade-off, committed by suggesting a product is "green" based on an unreasonably narrow set of attributes without attention to other important environmental issues.
2. Sin of No Proof, committed by an environmental claim that cannot be substantiated by easily accessible supporting information or by a reliable third-party certification.
3. Sin of Vagueness, committed by every claim that is so poorly defined or broad that its real meaning is likely to be misunderstood by the consumer.
4. Sin of Worshiping False Labels is committed when a claim, communicated either through words or images, gives the impression of a third-party endorsement where no such endorsement exists.
5. Sin of Irrelevance, committed by making an environmental claim that may be truthful but which is unimportant or unhelpful for consumers seeking environmentally preferable products.
6. Sin of Lesser of Two Evils, committed by claims that may be true within the product category, but that risk distracting consumers from the greater environmental impact of the category as a whole.
7. Sin of Fibbing, the least frequent Sin, is committed by making environmental claims that are simply false

The term "sustainability" is often misused and abused, thus adopters either provide a good and reliable definition or adopt alternative terms.

There are many definitions of the term "sustainability" in the scientific community. The term originally comes from the field of forestry in Germany: in 1713 it was used to define the management approach to guarantee a permanent supply of timber, which was needed to build silver mines. The approach was not to cut more trees than could grow back. That is, actually, really similar to the currently adopted definitions of the term, even if focussing just on the economic standpoint. In the scientific community the term started diffusing thanks to a work on sustainable development written by Dennis Meadows in 1972. The book caused a great discussion across the globe and created a completely new audience for environmental and development topics, but the term did not really catch on until 1987, when the former Norwegian Prime Minister Harlem Brundtland submitted her Brundtland Report for the United Nations. The report contained a definition of sustainability that many politicians and scientists still agree with: development is sustainable if it "**meets the needs of the present without compromising the ability of future generations to meet their own needs**."
Since the mid 90s, the topic of sustainability has also been discussed outside the scientific community and the most important trigger behind this diffusion was the 1992 Earth Summit in Rio de Janeiro, which resulted in the "Agenda 21", a global action plan for sustainable development. Today, thousands of Agenda 21 groups are still working at local level throughout the world. The Rio Summit thus had a very concrete impact: many researchers, politicians and industrial representatives worked on the topic of sustainability for more than 20 years after the world summit. These groups produced a wide set of definitions for sustainability, but also a good amount of white reports, case studies, list of "Best Available Technologies" and so on able to improve the understanding and the diffusion of the topic, but especially a set of suggestions on how to define sustainability-related targets at various levels and in different domains, and to pursue sustainability enhancing objectives in everyday choices and behaviours. Looking at the different definitions that appeared in literature, it is possible to say that there are several aspects to the term 'sustainability'. Actually, the widest adopted point of view claims three aspects to be simultaneously considered, and researchers have drawn up a three-pillar model involving economic, social and environmental aspects as equal elements. Sustainable development must take account of all these three areas (see below for a more detailed discussion). Some people refer to this as 'weak sustainability' and most of the economic definitions of the term are derived from this concept.
Another party of scientists criticise this concept and believe that environmental aspects must be the only focus. They also call this body of knowledge as 'strong sustainability', since all other aspects are seen as secondary with respect to intact natural resources.

A slightly revised definition is included in the "EU Contribution to the Millennium Development Goals – Goal 7" report ([20]), and describes sustainability as: "…meeting current human needs without undermining the capacity of the environment to provide for those needs over the long term…", giving a strong focus on environmental aspects.

Going back to the “soft sustainability”, that is probably the most accredited approach at least for manufacturing and industry in general, as we wrote in [21], the concept of sustainability can be depicted as the intersection of three Sets (symbolized by ellipses), representing solutions coping with environmental, social and economical constraints, known as the "three pillars" ([22]).

In academic debates and business arenas, hundreds of definitions have been proposed referring to a more humane, more ethical and more transparent way of doing business ([23]). Several parties tried to foster sustainability proposing guidelines, theoretical models, standards, tools and monitoring instruments, tackling both private companies and public entities. They have been supported by a number of organizations including scholars, practitioners, public bodies, governmental and non-governmental agencies, and consulting firms. A full review of sustainability frameworks goes beyond the objectives of this chapter, hence, we introduce the concept of sustainability here adopted and we refer to [24] for a more extensive review.

The “sustainability” concept deals with a simultaneous pursuing of social, environmental and economic benefits.

In particular, we refer to sustainability as a **multi-objective** and **multi-stakeholders** issue. Moving from the first point, sustainability is multi–dimensional in scope, i.e. it regards a wide range of different aspects, such as safeguard of the environment, fair operating practices, consumer issues, community involvement and development. This means that companies that aim to improve sustainability can act on different issues also with relevant trade-offs among different objectives. As mentioned, usually the literature refers to three dimensions of sustainability: environmental, social, and economic (e.g. Global Reporting Initiative [25]). However, this classification is very broad and therefore could not be sufficient to operationally support companies in implementing sustainability.
Second, sustainability is a multi-stakeholder issue, i.e. to pursue sustainability different subjects, sometimes with contrasting interests, are to be involved: private and public organizations, individuals and companies, policy makers and governmental agencies.
Though sustainability is generally considered something highly desirable, the main challenge threatening its actual implementation consists in succeeding in improving competitiveness and business performance through outstanding and voluntary social and ecological performance, which neither always nor automatically bring about financial benefits.
If the promoters of the idea of sustainability consider it to be the “mother lode of organizational and technological innovation, the key to progress and *…+ an integral part of development”, several authors also claim the potential disadvantages related to more sustainable business practices. Key arguments in this respect are “making operations suitable places at a disadvantage vis-à-vis rivals in developing countries that don’t face the same pressure; sustainable manufacturing demand new equipment and processes and customers will not pay more for eco-friendly products during recession” ([26]). According to the literature, the central barrier to business cases with sustainability relates to the **co-creation of private benefits for companies and customers and positive contributions to society and environment – i.e. public benefits** (e.g. [27]; [28]). **Public benefits cannot be appropriated as private benefits for technology investors and customers and as long as negative externalities of incumbent systems are not fully internalized in market prices, eco-friendly alternatives may suffer from competitive disadvantages** (e.g. [28]). As companies are not compensated for reducing negative externalities or creating positive externalities per se, they are not motivated to engage in such activities ([29]). However, when public benefits from eco-innovations cannot be appropriated as private benefits, they will be created in too small amounts from a societal perspective.

Already in 2002, Schaltegger and Synnestvedt ([30]) discussed about the link between being `green' and being an economically successful company. According to their analysis, some authors assume that environmental impact mitigation is a cause of costs to a company, whereas other authors believe green behaviours pay off and thus improve the firms bottom line. Several empirical studies are reported providing arguments for both theories.

> The low appropriability of benefits deriving from sustainable-aware behaviours is the central barrier to the establishment of successful sustainability-conscious business models in manufacturing enterprises: why should an entrepreneur act sustainably if it costs more?

From this perspective, business models act as meta-factors that can support the adoption of cleaner products and processes, sustainable supply chains and further contributions to a transition towards sustainable consumption and production ([31]). They should translate sustainability strategies into business activities and to market eco-innovations competitively to create customer value and public benefits.

The key role of business models in relation to sustainability is widely recognized in the literature (e.g.: [32]). For instance, in [26] identify five steps that companies have to perform in order to become more sustainable, paying particular attention to the development of an appropriate business model:

1. Viewing compliance as opportunity
   It's smarter to comply with the most stringent rules and to do so before they are enforced. Conforming to the gold standards globally actually saves companies money that can turn antagonist regulator in allies by leading the way.
2. Making value chains sustainable
   The drive to be more efficient extends from manufacturing facilities and offices to the value chain. The initial aim is usually to create a better image, but most corporations end up reducing costs or creating new business as well. Companies develop sustainable operations by analysing each link in the value chain. Some company introduced incentives to induce suppliers and retailers to become environment-conscious, and have also started laying down the law.
3. Designing Sustainable Products and Services
   A sizable number of consumers prefer eco-friendly offerings. To design sustainable products, companies have to understand customer concerns and carefully examine product life cycle.
4. Developing New Business Models
   Creating a sustainable business model entails:
   - Rethinking the customer value proposition and figuring out how to deliver a new one
   - Novel ways of capturing revenues and delivering services in tandem with other companies
   - Exploring alternatives to current way of doing business and understanding how companies can meet customer's needs differently
5. Creating next-practice platforms
   - When a company's top management team decides to focus on the problem, change happens quickly
   - Recruiting and retaining the right kind of people is important

Actually, to provide a valuable voice in the debate, we need to go back to the 2005 World Summit on Social Development. As mentioned, in this meeting participants identified as **complementary** elements for a "sustainable development": economic development, social development and environmental protection. Complementarity must be elicited from two points of view:

1. for being sustainable, all the three elements must be **pursued simultaneously**. This means that choices and behaviours worsening one of the three pillars while improving the others are, at least, questionable;
2. **the three elements are** not mutually exclusive, but can be mutually reinforcing. According to [33] these three elements are **interdependent**, **and** in a longer time horizon **none can exist without the others**.

Especially the latter element provides a strategic effect to the sustainability paradigm implementation. Actually, this results in sustainability-related strategies explored as an opportunity to catch a new competitive advantage: manufacturing companies are asked to invest in re-defining their business processes (either motivated by end customers' increased pressure towards environmentally- and socially- compliant products and processes ([34]) or interested in catching the latest marketing wave), but often they actually don't know the "what?" and the "how?" In fact such (prospective) adopters of sustainability-oriented approaches and paradigms are looking for actual implementation examples and/or practical procedures they could follow in order to become sustainable or more sustainable (than before or than the competitors).

Pursuing sustainability must be adopted (almost axiomatically) as an everyday behaviour: considering a longer time horizon, just investments improving all the three elements of sustainability will assure company survival.

2.2 Sustainability metrics for valuable assessment

Translating sustainability-oriented strategies into virtuous tactical and operational behaviours is a not-answered concern for managers, for many reasons:

- **metrics** and algorithms for pondering products and processes sustainability performances still lack of standardization;
- **data** used for sustainability assessment are usually too much high-level and aggregated: referred to the whole manufacturing site and to long time-horizons, thus:
  - inhibiting the identification of underperforming tasks, machines or products;
  - leading to the creation of sustainability profiles (/labels) that are always based on average samples, representing the typical production object of the company;
- batch- or single product-wise sustainability-enhancing is unworkable: sustainability-relevant gathered data usually feed the strategy definition process, with limited or none interventions performed on the now processed item/job.

Let's start from metrics. As published in chapter III of our book ([21), we developed a *Sustainability Assessment Model*, meant to be a practical and usable tool to assess sustainability performances of products and processes, with a primary focus on manufacturing and industry. The underlying model is based on a set of indicators resulting from an extensive literature review: this revealed a considerable amount of methodologies addressing the evaluation of sustainability of product, manufacturing systems and supply chains. However, indicators found in literature proved to be unbalanced or too much qualitative to be concretely applied, and, additionally, to be incomplete at least at social level. The main innovation here promoted lies in the development of an holistic set of indicators capable to evaluate sustainability considering a Stable Solution Space[1] as a whole: the product is produced within a defined manufacturing system and delivered by a supply network, and all these entities are involved in determining the final sustainability level of the Solution Space. The assessment results have been related to a single unit of product, thus fostering an immediate perception of the burden set to the environment, society and economy connected to the final act of buying. Before developing indicators, reference to existing standard and approaches is briefly discussed in §2.2.1.

2.2.1 Reference standards and approaches

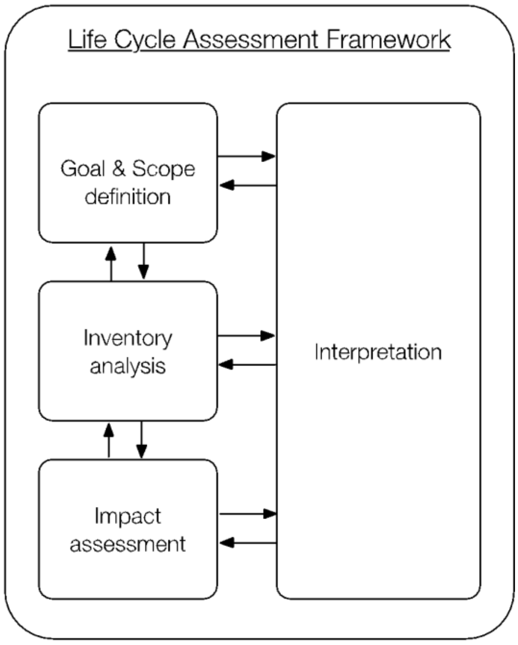
The first Life Cycle Assessment study was performed by the Midwest research Institute (MRI) for the Coca-Cola Company in the early 1970s. Within the study, the resource requirements, emission loadings, and generated waste flows of different beverage containers have been evaluated. At the end, Coca-Cola acted not to remove or improve its worst-performing materials but by working with local authorities to develop a recycling infrastructure in order to collect aluminium cans and reduce by 90% the energy used throughout the can's life time.
During the following years, from 1970s to 1990s, many industries performed Life Cycle Assessment using different methods and without a common theoretical framework, producing conflicting analysis results also considering the same object of study. In the early 1990s the SETAC (Society of Environmental Toxicology and Chemistry) brought LCA practitioners, users and

[1] the Stable Solution Space represents both the product blueprints (i.e. the sum of all the product configurations) and the capability and degrees of freedom of the production system and its supply chain.

scientists together to collaborate on the creation of LCA framework, terminology and methodology, formalized into the “SETAC- Code of Practice” ([35]).
In 1994 the ISO (International Organization for Standardisation) formalised the tasks made by SETAC, adopting the formal task of standardisation of methods and procedures. Currently two international standards define the LCA: ISO14040 (Environmental management – Life Cycle Assessment – Principles and framework) and ISO14044 (Environmental management – Life Cycle Assessment – Requirements and guidelines). A key result of ISO standardisation work was the definition of a general methodological framework. Several life cycle impact assessment methods were introduced during this period, such as the CML1992 [36] (Centre of Environmental Science), end point or damage approaches [37].and a multiple approach for assessing human and ecotoxic emissions [38].
Years until 2010s were full of news regarding the LCA evolution. UNEP and SETAC have launched the Life Cycle Initiative in order to enhance the participation of the companies in environmental activities improving products or services. LCA has raised a high interest even in Europe from 2002 to 2005, where several legislations (Integrated Product Policy - IPP) highlighted the importance of the environmental aspects developing strategies on the Sustainable Use of Resources, on the Prevention and Recycling of Waste and promoting the application of the Life Cycle Thinking among the stakeholders. In addition, the European Platform on Life Cycle Assessment was developed in order to promote the availability, exchange, methods, life cycle data, and studies to support public policies and companies.
Afterwards there was an elaboration of the LCA regarding the interpretation and use of the ISO requirements with a use of diverging approaches respecting the definition of system boundaries and allocation methods. In this sense other assessments emerged such as Life Cycle Cost (LCC) and Social Life Cycle Assessment (S-LCA) causing conflicts with some basic principles of LCA and consistency problems in terms of system boundaries, time perspective, calculation procedures, etc. An EU-FP6 project (CALCAS project in 2006) was commissioned in order to structure the varying field of LCA approaches and to define research lines and programmes to further LCA where necessary. A main result of the CALCAS project was the definition of a framework for Life Cycle Sustainability Analysis (LCSA) which comprehends the three main tools: LCA, LCC and S-LCA act to cover not only the environmental aspects but all the three sustainability dimensions (Environment, Economic and Social). Life Cycle Sustainability Analysis extends the scope from product-related questions (product level) to questions related to sector (sector-level) or even economy-wide level (economic level). In addition, it deepens LCA including both technological aspects and economic and behavioural relations.
One of the most important dilemmas about LCSA concerns its compatibility with the ISO14040-44 because only the environmental field perfectly fits with those standards, while the implementation of the other two themes (economic and social) is not supported by a specific ISO standard. Several studies have investigated the problem, promoting the use of the same framework provided by the ISO for LCA, but including some adjustments for conducting LCC and S-LCA analyses.
In recent years, LCSA has become an important topic for several companies and organizations. In fact, a recent study in the LCSA context called MEASURE, highlighted the importance of the whole sustainability concept inside different organizations. Part of the MEASURE study resulted in a survey accomplished on approximately 67 respondents. Showing that more than 75% of the respondents perform LCA. The MEASURE survey also stated that the main elements driving companies towards LCSA are: gaining market advantages, exploiting business opportunities (commercializing certified “green” and/or “safe” products), interest in strengthening their core business, and focus on complying with regulatory issues for the specific sector.

Environmental area – LCA
Life Cycle Assessment (LCA) is a tool for the evaluation of the environmental aspects of a product or service system considering all life cycle phases. LCA went through many improvements (as described in the previous paragraph) since its creation, around the 1970s, and its consolidation provided by the International Organisation for Standardisation (ISO) thanks to the ISO 14040 series on Life Cycle Assessment. Following the ISO principles, the LCA is carried out in four phases:

- The first one is called Goal & Scope definition phase. It includes the detailing of technical information such as the functional unit, the system boundaries, the assumptions and the (de)limitations of the study, the impact categories such as “global warming potential”, and the methods used during the environmental allocation phase when there is more than one product. All the information detailed in this phase must be stated clearly in order to avoid possible misunderstandings among stakeholders and mistakes during the interpretation phase.
- An inventory of input/output data with regard to the system being studied is the focus of the second phase. It is called inventory of resources use and emissions or, more commonly, Life Cycle Inventory (LCI). In this phase all the emissions released into the environment and resources used along the whole life cycle of a product are collected from the process themselves or through pre-constructed databases provided by the major LCA tools (Gabi, Ecoinvent, SimaPro, etc.) and grouped accordingly.



- The Life Cycle Impact Assessment (LCIA) is the third phase of an LCA evaluation. During this step, the LCI results are detailed and translated into environmental impacts to better understand the LCI environmental significance. Impacts may be assessed at the midpoint or endpoint level. The midpoint level, also known as problem-oriented approach, translates impacts into environment themes like climate change, human toxicity, acidification, etc. The endpoint level, also known as damaged-oriented approach, translates environmental impacts into issues such as human health, natural environment, and natural resources.
- The life cycle interpretation of the assessment results is carried out in the last phase. This is necessary for identifying, quantifying, checking and evaluating information from the results of the LCI and the LCIA. This phase aims at providing a set of conclusions and recommendations, including an evaluation of the study considering different aspects such as limitations, consistency, etc.

Economic area – (LCC)

LCC was first developed in 1933 when the United States of America General Accounting Office (GAO) requested an assessment of the costs of tractors considering a life cycle perspective. Life Cycle Cost (LCC) is a technique for the evaluation of the economic performance that products or services generate during their life cycle, considering one or more actors (suppliers, producers, users, distributors, etc.) and internal or external costs from extraction to the End of Life (EoL) phase. According to The SETAC-Europe Working Group on Life Cycle Costing [39], three different types of LCC are defined:

Convectional LCC: it assesses all costs covered by the main producer or user associated during the life cycle of the product. The assessment is mainly focused on real, internal costs, sometimes even without End of Life or use costs if other actors generate them. A convectional LCC usually is not accompanied by separate LCA results.

Environmental LCC: it takes into account the costs covered by one or more actors in the product life cycle (supplier, manufacturer, user or consumer, and/or EoL actor), with the inclusion of external relevant costs and benefits. A product system framework according to ISO 14040/44:2006 should be used as a basis for the assessment.

Societal LCC: it includes all the elements of environmental LCC plus additional assessment of further external costs covered by anyone in the society, either today or in the long-term future.

Nowadays LCC is extremely useful for monitoring costs, making decisions and adding interests at products for costumers and financial sectors point of views. Unfortunately, LCC has not a dedicated standard for its development but it is possible to follow the same procedure provided into the 14040/44:2006 ISO for the Life Cycle Assessment. According to this assumption, four steps are defined:

- Similarly to the Goal and Scope definition stage for LCA even for LCC must be determine the goal of the study, a functional unit, specific system boundaries, apply allocation procedures, discount rates, etc. The last one is important for durable goods with cost flows in the future. The discount rate is useful to convert future costs into a present value for current decision making. In this phase it is also important to correctly specify the viewpoint of the life cycle actor (supplier, manufacturer, distributor, user or consumer).
- In the second step, costs are inventoried on a unit process level. In this phase, an allocation method must be defined in order to quantify the specific costs related to a product, since more than one product is produced by most enterprises.
- In the third stage (aggregate cost by category), the obtained costs are aggregated by cost categories for example maintenance costs, material costs, VAT, administrative costs, etc.
- The last phase, the interpretation of results, has the same meaning of the LCA interpretation. Regarding the LCC interpretation, the IEC [40] provided a method to characterize costs using a three dimensional matrix: 1) the life cycle stage (e.g. design and development), versus 2) the cost category (e.g. labour cost), versus 3) the single product or component (e.g. motherboard).

Social area – (S-LCA)

The Social Life Cycle Assessment (S-LCA), as defined into the S-LCA guidelines [41] provided by UNEP/SETAC, is a social impact assessment technique that aims to assess the social and socio-economic aspects of products and their potential positive and negative impacts along their life cycle encompassing extraction and processing of raw materials, manufacturing, distribution, use, re-use, maintenance, recycling, and final disposal. The social impacts are mainly on human capital, human well-being, cultural heritage, socio-economy and social behaviour [42]. As to LCC, the S-LCA does not have an own framework but, following the UNEP/SETAC guidelines it is possible to adopt the ISO 14040 with some adaptations. The S-LCA could be carried out in four phases:

- Goal and Scope definition: the first step is meant to clearly define the statement of purpose, this statement describes the intended use and goal pursued. The second step is meant to define the scope. Within the definition of the scope, also the function and the functional unit of the product could be defined. The boundaries of the study are another element that must be defined in this phase.
- Inventory: the aim of the inventory phase is to identify categories where social impacts could be positioned. In this phase, the participation of different stakeholders such as workers, local communities, society, consumers and value chain actors could be useful. Using this list, the social impacts could be categorized in a comprehensive set of sub-categories. For example, a classification could include the sub-category "child labour" related to the stakeholder category "workers". The sub-categories can be either qualitative or quantitative and cannot always be summed one another. Due to the indicators characteristics, data are not only collected at the level of unit processes or facilities but also at the organizational, national and global levels.
- Impact assessment: regarding this phase, a definition of the impact methodologies is not clearly explained. Due to the particular typology of data, qualitative and quantitative, it is not so simple to characterize a specific impact assessment method related to the social impacts. Dreyer et al., [43] and Jørgensen et al., [44] identified a list of social indicators and a possible methodology to pursue this work. In 2015 Kumar et al. [45] explained the two commonly used methods for S-LCIA: performance reference point and impact pathways opening a possibility to a future social database development. Concerning this last point, in the recent period, two main projects on social sustainability have developed the first two social databases: PSILCA [46] (Product Social Impact Life Cycle Assessment database) and Social Hotspot [47] database.
- Interpretation: S-LCA is still in an early stage and there are very few examples to implement a reliable interpretation. Obviously, it is possible to follow the ISO14040 that recommends to have a consultation with the stakeholders and other valuable actors of the processes.

Life Cycle Sustainability Assessment (LCSA)

The LCSA mentioned in the first paragraph is nowadays an important topic that companies and organizations are focused on in order to make decisions considering not only environmental but also economic and social aspects. Life Cycle Sustainability Assessment is expressed by the following equation, firstly formulated by Klöpffer [48], and later by Finkbeiner et al. [49]:

$$LCSA = E\text{-}LCA + LCC + S\text{-}LCA$$

The main issue regarding the development of a common LCSA framework is the ability to effectively combine the three techniques, though respecting the different peculiarities of single assessment frameworks. An important contribution to the definition of an LCSA framework was carried out by the UNEP/SETAC association, that in “Towards a Life Cycle Sustainability Assessment” ([19]) presents indications and recommendations on how to start a LCSA according to the LCA framework. Inside the book, a clear explanation of the concepts behind Life Cycle Sustainability Assessment is provided through an interesting case study that takes into account a comparison between four types of marble’s production. Taking this case as a basis, four are the main steps of the LCSA:

- Goal and scope, and system boundaries: in this phase the goal and scope and the system boundaries of the LCSA are defined. Remembering that the LCA, LCC and S-LCA have different aims, it is important to deeply understand the differences between them in order to implement the most accurate goal and scope definition. Even for the definition of the functional unit, a correct approach is to study the situation using a common unit both for technical utility of the product and product social utility. As regards the delimitation of the system boundaries, the different life cycle techniques are focalized on a delineated area that, often, is not the same for the LCC and LCA (for example, the R&D process is relevant for assessing the life cycle costs but usually it does not have environmental impacts). The best approach in this case is to take into account all unit processes relevant for at least one of the techniques (Figure 6). In cases where one or more processes are not assessed, the reason must be justified.

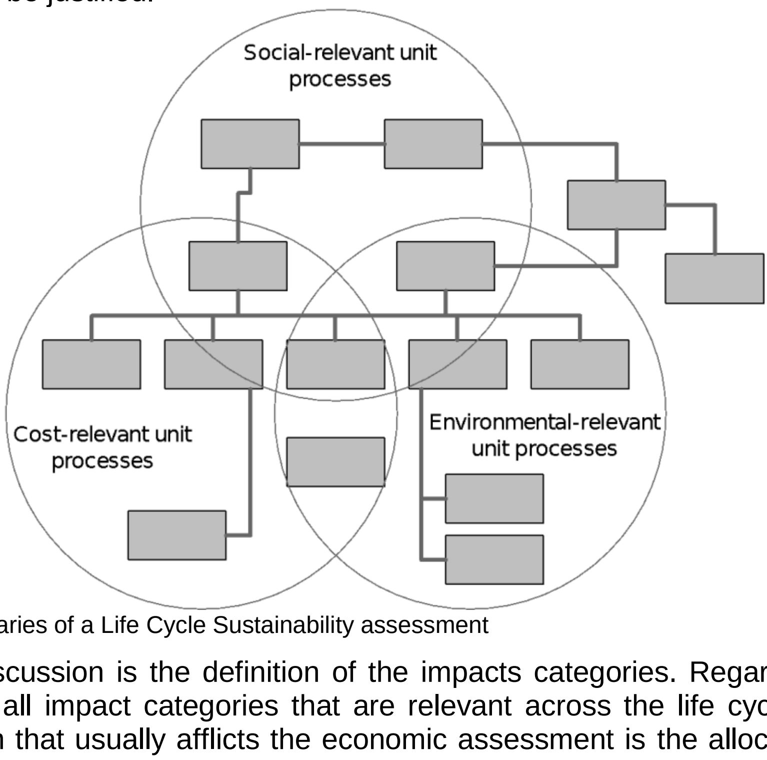


Figure 6: System boundaries of a Life Cycle Sustainability assessment

Another point of discussion is the definition of the impacts categories. Regarding the LCSA it is recommended that all impact categories that are relevant across the life cycle of a product are selected. A problem that usually afflicts the economic assessment is the allocation method of the impacts. This is a relevant issue only if a process results in more than one output. A common allocation method suggests the use of a physical or economic proportion.

- Inventory: the inventory phase (LCI) must be conducted considering the different typologies of data; quantitative, qualitative and semi-quantitative information is available and all these three elements must be considered. As regards the level at which the information is gathered, it is important to collect data at production unit and at organization level because not all the information about the three area (environmental, economic and social) could be found at both levels. Another issue is the availability of data. While for the environmental LCA and LCC, these can be found within enterprises and organizations (e.g. inside product's safety sheet or inside the balance sheet of the company), or in public statistics and databases (e.g. Eurostat, ELCD databases, U.S. life cycle inventory database, etc.), there is still a lack of social LCA data. However, some social database have been already developed and integrated into (few) Life cycle assessment software solutions.

- Impact assessment: to accomplish this part of a LCSA evaluation it is strongly recommended to follow the principles suggested by the ISO14040/44 considering the limitation persisting into the single Life Cycle techniques, mainly LCC and S-LCA. In this step a classification of the assigned impact categories is accomplished. Regarding the Life Cycle Sustainability Impact Assessment, a problem occurs trying to aggregate the different impacts using a unique characterization factor. Unfortunately, for the LCSIA it does not exist a method to convert the LCSA inventory data into common units nor to aggregate them according to each impact category. A feasible approach may be to base the impact assessment on the individual S-LCA, LCC and LCA framework. Normalization, aggregation and weighting are not necessary because the three techniques are not comparable each other.
- Interpretation: similarly to what happens for the single frameworks (S-LCA, LCA and LCC), the interpretation phase is accomplished combining the results in accordance to the goal and scope definition, and taking into account the data quality gathered during the second phase (Inventory). The evaluation of the results may help to identify: the presence of trade-offs between economic, social and environmental burdens; which life cycle phases or impact categories are critical; and if the product is socially and environmentally friendly. The use of the LCSA's interpretation results to support decision-making processes can be challenging due to the triple sustainability information (Environmental, Economic and Social impacts) outgoing from a Life cycle sustainability assessment.

2.2.2 Indicators

The first step is to define the **criteria** used in the identification of the suitable indexes. The identification activity then started with a literature review of sustainability assessment indexes trying to figure out those most frequently used to measure the performances of solution spaces (product, production system and supply chain). This preliminary list highlighted that many sustainability areas could be analysed through indicators taken from existing sources, but also that some indexes should be created ad hoc for the our sustainability assessment model.
Criteria used in the selection of the sustainability indicators are discussed below:

- **Measurable**: the indicator has to be measurable. The measured impact and its sources can be translated and conveyed in a quantitative measure.
- **Understandable**: the indicator is easy to understand, even by people who are not experts. People do not end up arguing over what the indicator means.
- **Exploitable and Relevant**: the indicator measures something that is important to the company implementing it for highlighting existing problems and enhancing its performances.
- **Balanced and fitted**: the selected indicators provide a comprehensive view of the key issues. There isn't any overlapping over same issues or incoherence between indicators.
- **Potential for influencing change**: the evidences collected will be useful for the decision-makers inside the companies. The indicators enable decision-makers to understand what the necessary corrective actions are.
- **Reliable**: the process that transforms the input data into the final indicator outcome provides a measure that can be trusted.
- **Achievable**, based on accessible data: the information is available or can be gathered while there is still time to act.
- **Comprehensive** (Product / Process / Supply Chain): an indicator is desirable to be applicable to the different design entities: product, manufacturing and supply chain. Including all the design level, the indicator allows the overall assessment of the sustainability and the mass customization of the product system.

- **Flexible**: an indicator must be flexible and multipurpose, that is, it can be applied to different kind of products, production process and supply chains.
- **Established**: an indicator, and the way to calculate it, is desirable to show a large consensus in the academic and industrial environments especially if the indicator addresses some sustainability or mass customization areas that are studied by long time and the industrial application is well established.

The discussion of the indicators selection process is presented in the mentioned book, chapter 2. After the book publication, the engine has been used in selected production contexts and thus some revisions have been carried out to the indicators. In the following tables the current version of the indicators is presented.

Environmental Indicators

Thanks to the Life Cycle Assessment (LCA) methodology, the evaluation of the environmental performances of products and companies is quite an established issue. The state of the art analysis on the environmental indicators provided a very long list of environmental indexes. In this analysis, different sources of environmental indicators have been considered.

As suggested by Guinée (50), a preliminary selection of the environmental indicators has been performed considering the positioning of the focal point of the indicators in the cause-effect chain that is meant to describe the environmental mechanism from "exchanges" to "endpoints". In the impact chain, the "exchange" represents the flow of matter and resources between the environment and the techno-sphere. The "endpoint" is the "thing" to be protected, such as trees, rivers and human health. "Midpoint" refers to all the elements in an environmental mechanism that fall between environmental exchanges and endpoints. An example of an "exchange" is the emission of CFC (chlorofluorocarbon) gases, which causes a depletion of the ozone layer in the stratosphere (mid-point), which results in increased levels of radiation (mid-point) that eventually cause a certain number of people to die from skin cancer (end-point).

For the environmental evaluation, both a *midpoint* methodology (the CML2001) and an *endpoint* methodology (the IMPACT 2002+) have been used with the final goal to assure the "understandability" and "usefulness" of the two alternative methods.

Environmental Mechanism Level	Indicator	Description	Unit of measurement
Endpoint (H,A)	Total	Endpoint indicator calculated through the ReCiPe methodology and the Hierarchic perspective.	points
Midpoint (H,A)	GWP – Climate Change	The GWP indicator measures the contribution to the global warming caused by the emission of green house gasses in the atmosphere.	kg eq. CO_2
	POF - Photochemical Oxidant Formation	The POCP indicator calculates the potential creation of tropospheric ozone ("summer smog" or "photochemical oxidation") caused by the release of those gases which will become oxidants in the low atmosphere under the action of the solar radiation.	kg eq. NMVOC
	FE - Freshwater Eutrophication	The FE indicator measures the contribution to the water eutrophication (enrichment in nutritive elements) of lakes caused by the release of polluting substances in the water.	kg eq. P
	ME - Marine Eutrophication	The ME indicator measures the contribution to the water eutrophication (enrichment in nutritive elements) of	kg eq. N

Environmental Mechanism Level	Indicator	Description	Unit of measurement
		marine waters caused by the release of polluting substances in the water.	
	OD - Ozone Depletion	The OD indicator measures the contribution to the depletion of the stratospheric ozone layer caused by gas emissions.	kg eq. CFC-11
	TA - Terrestrial Acidification	The TA indicator measures the contribution to the air acidification caused by gas emissions in the atmosphere.	kg eq. SO_2
	FET - Freshwater Ecotoxicity	The FET measures the relative impact of toxic substances on the freshwater aquatic environment due to the emissions to environmental compartments air, fresh water, sea water, agricultural and industrial soil.	kg eq. 1,4-DCB
	PMF - Particulate Matter Formation	The PMF measures the emission of particulate matter in the air.	kg eq. PM10
	MET - Marine Ecotoxicity	The MET measures the relative impact of toxic substances on the marine aquatic environment due to the emissions to environmental compartments air, fresh water, sea water, agricultural and industrial soil.	kg eq. 1,4-DCB
	IR - Ionising Radiation	The IR measures the equivalent ionizing radiation exposure on living beings.	kg eq. U235
	TE - Terrestrial Ecotoxicity	The TET measures the relative impact of toxic substances on the terrestrial environment due to the emissions to environmental compartments air, fresh water, sea water, agricultural and industrial soil.	kg eq. 1,4-DCB
	HT – Human Toxicity	The HT measures the relative impact of toxic substances on human beings related to the to the emissions in environmental compartments, namely air, fresh water, sea water, agricultural and industrial soil.	kg eq. 1,4-DCB
	FD - Fossil Depletion	The FD indicator measures the depletion of fossil resources as the fraction of the resource reserve used weighted by the fraction of the resource reserve that is extracted in one year.	kg eq. oil
	MD - Metal Depletion	The MD indicator measures the depletion of metal resources as the fraction of the resource reserve used weighted by the fraction of the resource reserve that is extracted in one year.	kg eq. Fe
	ALO - Agricultural Land Occupation	The ALO indicator measures the land occupation caused by agriculture	m^2a

Environmental Mechanism Level	Indicator	Description	Unit of measurement
		activities.	
	NLT - Natural Land Transformation	The NLT indicator measures the equivalent natural land transformed .	m^2
	ULO - Urban Land Occupation	The ULO indicator measures the land occupation caused by urban areas.	m^2a
	WD – Water Depletion	The WD indicator measures the water of any quality (drinkable, industrial,...) consumed during the whole life cycle of the product.	m^3

Economic Indicators

Achieving economical sustainability means to use resources in an efficient way in order to provide long-term benefits with minimal waste. In other terms, it aims at maximizing the level of quality while minimizing the costs (Global Reporting Initiative, 2000-2011). The assessment of the economic sustainability can be referred to different unit of analysis: a single organization, a country or an industry. At the organizational level, standards and global reporting state that the economical sustainability can be assessed considering the direct economic value (as revenue) and operating costs. In literature, some contributions are focused on the assessment of economical sustainability of specific industries. In this case, the assessment is based on the measurement of efficiency and profitability levels ([51]). Finally, some researches consider a district (state or country) and base the assessment on national economy and production competitiveness ([52]).

According to the aim of the SAM assessment model, the selection of indicators considers the organization level and, in particular, the unit of analysis includes product, production system and supply chain of a new solution space.

Economic Aspect	Indicator	Description	Unit of measurement
Efficiency	UPVC - Unitary Production Variable Cost	The UPVC indicator measures the direct variable costs (deducting overheads and taxes) related to the manufacturing of one product unit, calculated as the average one weighted on the expected product mix.	$
	MRC – Mould Replacement Cost	The MRC indicator measures the cost related to product manufacturing. Test and tuning are not considered.	$
Profitability	PLC - Product Lifecycle Cost	The PLC indicator measures the total costs afforded by the company during the product lifecycle: UPVC + cost of usage (e.g. energy consumption and labor cost, cost of the wasted material,...), cost of maintenance and end of life costs.	$
	UEIP – Unitary Expected Induced Profit	The UEIP indicator measures the difference between the revenues generated by the sales of the product and the Product Lifecycle Cost.	$

Economic Aspect	Indicator	Description	Unit of measurement
Investments in technologies and competences	RDII - R&D Investments Intensity	The RDII indicator measures the R&D investments made by the company and its suppliers, allocated to the analysed product.	$

Social Indicators
Social indicators have not achieved the same level of maturity as environmental ones yet. This can be explained by the focus given during last decades on the environmental dimension of sustainability. The literature of social sustainability assessment methods and indexes shows that life cycle thinking has also emerged in the social assessment of products, but there are no standards yet, neither methodologies nor indicators. The efforts here are meant to foster the characterization of social impact of products all over their life cycles, facilitating by the standardization of the life social evaluation methods. The relevance of a reference here investigated is tributary of 1) its frequency in sustainability literature and 2) its date of issue or last update (the nearest the latter, the more relevant is the reference).
Jensen and Remmen ([53]) gave insights on life cycle management and its integration in sustainability dimensions, including social one. GRI ([54]) established sustainability reporting guidelines applicable to several organizations. Kruse et al. ([55]) proposed a socioeconomic indicators system that has been also applied to a case study demonstrating applicability. Benoît and Bernard ([56])) provided more guidance for the establishment of a Social Life Cycle Assessment (S-LCA). Dreyer ([57, 58, 59) attempted to formalize the social life cycle assessment by proposing a methodology that was applied to different case studies.
Investigated literature also includes initiatives that provide comprehensive indicators but they are not applicable at enterprise level. Further literature on social sustainability indicators can be found in Jorgensen et al. ([60]). The authors presented a review meant to highlight areas of agreement and disagreement in S-LCA. Thus the survey included several initiatives that are not extensively mentioned.

Social Aspect	Indicator	Description	Unit of measurement
Working condition and workforce	II - Injuries Intensity	The II indicator measures the number of yearly work-related injuries, diseases and fatalities occurred in the company and its suppliers, allocated on the analysed product.	#
	WTI - Workforce Turnover Intensity	The WTI indicator measures the employees leaving the company and its suppliers, allocated on the analysed product.	#
	SDII - Staff Development Investments Intensity	The SDII indicator measures the staff development investments made by the company and its suppliers, allocated on the analysed product.	$
	IL - Income Level	The IL indicator measures the ratio between the average yearly income per employee and the average yearly income per person in the country where the company or the suppler is located. The indicator is calculated considering the contribution of both the company and its suppliers.	-

Social Aspect	Indicator	Description	Unit of measurement
	WH - Worked Hours	The WH indicator measures the number of worked hours per employee per week considering the contribution of both the company and its suppliers.	h
Local community	CCI - Charitable Contributions Intensity	The CCI indicator measures the expenditures and charitable contributions made by the company and its suppliers in favour of the local community, allocated on the analysed product.	$

Concluding remarks

The paragraphs above addressed the development of the sustainability assessment model, a *sine qua non* cornerstone towards the concrete activation of sustainability projects. In fact, the proposed model deals with the issue of concretizing the effects of the decisions taken at design level down into numbers.

Selection of the indicators was focused on obtaining a homogenous and balanced set of reliable indicators that measures the overall impact of all the entities involved in the product lifecycle on the three sustainability aspects. Such an ambitious target was never set in the existing literature so far and is meant to promote a real possibility to evaluate the performances of the Stable Solution Space for the companies as well as communicating in a transparent and reliable way the achieved improvements to customers

Experiences from implementation of the model in real manufacturing environments allowed to derive a set of suggestions to improve the model adoption. In particular, it emerged that each industrial sector and, namely, each company have their own critical elements. As far as an industry-wise set of sector/product category rules are not available, an initial “tuning” of the model is mandatory. This setting up operation should result in more specific indicators (e.g.: normalized on each kg, unit of cm^3 of produced product, or considering/excluding maintenance costs according to their relevance), and in adapted calculations and data sources. Once the model succeeds in wider adoption, a standardization becomes compulsory n order to allow benchmarking and trans-company data comparison.

2.3 Tools supporting the sustainability assessment

Literature is full of methodologies promising more sustainable performances for adopters, but practical tools intended for actual decision makers are few and just partial (in terms of contexts of use, addressed product lifecycle phases, pondered sustainability dimensions, target users).

2.3.1 Available tools and methodologies

Analysing the current offer of sustainability-recognising instruments (e.g.: 61, 62, 63, 64), three levels can be identified.

Some CAD (Computer-Aided Design) software (e.g.: SOLIDWORKS Sustainability module ([65]) recently started integrating sustainability measurements functionalities. These libraries allow the designer to obtain a pondering of the environmental impacts of the object they are designing providing a screening-level life cycle assessment (LCA). Relying on third-party standards (such as GaBi LCA software from PE International), these tools still have some limitations: (1.i) they are not intended for any profiles other than the designer; (1.ii) they are usually focused on environmental impacts, while social and economical impacts are not evaluated; (1.iii) just a sub-set of lifecycle steps is considered: in some tools impacts are estimated only for the manufacturing phase, while the use and end-of-life phases are often left aside; (1.iv) impacts of the manufacturing process and technology are (at most) considered using generic weights and not specific inventories of the given machine, thus resulting in a limited accuracy.

In the second level, we mention GaBi ([66]), SimaPro ([67]) or Umberto ([68]), which are assessment tools enabling the analysis of sustainability impacts of products. They are based on accurate impacts inventory and specifically intended for the mentioned purpose. Unfortunately: (2.i) (again) they are intended to be used by expert practitioners, which are usually different from designers and managers within the company; (2.ii) they provide a level of granularity not detailed enough for specific application contexts (e.g.: they provide a unique value for energy consumption of injection moulding machines, not taking into account differences among technologies and materials used); (2.iii) they focus on assessing existing products, while advisory functionalities for new product concepts or designs are not included.

LCA and Lifecycle Costing (LCC) methodologies are a third group of available instruments. These are widespread-used methodologies to assess lifecycle-long impacts of analysed products. Limitations of these approaches are: (3.i) (again) the focus on just environmental or economical dimensions (depending on the used technique); (3.ii) the great part of available resources are merely standards, with a minimum operative attitude; (3.iii) the operative tools enabling LCA and LCC implementation in real industrial cases are intended for literate users; (3.iv) such elective users are rarely decision makers with an actual influence on developed products performances and a limited capability to identify potential technological or organizational improvements.

2.3.2 Screening LCA: a good starting point for environmental sustainability assessment

Life-cycle assessment (LCA), also known as life-cycle analysis, is a technique to assess environmental impacts associated with all the steps of a given product lifecycle, starting from raw material extraction until its final disposal or recycling. LCA can help identifying potential environmental criticalities of the product during the design phase.

A screening LCA study is an optional first step of the LCA methodology application and may serve as an initial (quick) overview of the environmental impacts of a target. The challenge is to adapt the LCA methodology and simplify the use of LCA at the early design stage. The screening LCA is not meant to retrieve detailed results on the environmental performance of a product, and comparative assertions according to ISO 14044 cannot be based on it. This type of study yields a “quick and dirty” estimation of the environmental performance, which can be helpful in the early stages of design. A screening study would typically focus on the main contributors to the system under assessment, including the input materials, water and energy use (if relevant).

A screening study might focus on one single indicator or several. As a general rule, a set of between five and seven relevant core LCIA indicators can be used

Application example

In order to roughly understand the impacts of the single phases within the whole lifecycle of a mould, a screening LCA was performed considering a specific mould, called P397. A complete LCA is an activity highly time and resource consuming. In order to rapidly obtain the calculation of a selected set of environmental indicators, the assessment was performed by means of an Excel file and using the datasets extracted from the Ecoinvent database.

In order to perform the screening LCA, the following modelling simplifications have been applied:

- in *Extraction* the whole mould is considered to be constituted completely by 450 kg of low alloyed steel, neglecting the possible existence of other kind of material or other kind of steel. This simplification is admissible since usually more than the 90% of the mould is constituted by steel (indeed of different typologies).
- in *Material processing* only the *steel hot rolling* operation is considered since most of the steel constituting the mould is constituted by plates and sheets.
- in *Manufacturing* all the most common operations such as turning, milling, drilling are represented by an equivalent “average” operation available in the Ecoinvent database. In this case the related environmental impacts are calculated considering the weight of the final component: the whole mould in our case.
- in *Use* of the mould, both the extraction of the thermoplastic material and the *Injection moulding* operation are considered.

- the *Assembling*, the *Maintenance* and the *End Of Life* phases has been ignored by the screening LCA since, at the time of the analysis, few data concerning this phases has been collected.

Table 1 reports all the basic data characterizing the P397 mold:

Parameter	***Value***
Weight	450 Kg
Yearly production volume	1.200.000 pieces
Average items weight	3.86 g
Estimated mould production life	10 years
Moulded polymer type	PP

Table 1: Basic data of the P397 mould

Table 2 reports the LCIA methodologies and the environmental indicators selected for the screening LCA.

LCIA methodology	CML2001		IMPACT 2002+			
Indicators	GWP [kg CO_2]	HTTP [kg 1.4-DCB]	Climate change [points]	Ecosystem quality [points]	Human health [points]	Resources [points]

Table 2: Ecoinvent datasets and indicators

For the environmental evaluation, both a midpoint methodology (the CML2001) and an endpoint methodology (the IMPACT 2002+) have been selected.

Table 3 shows the screening LCA results, reporting the values of the environmental indicators.

	GWP [kg CO_2]	**HTP [kg 1.4-DCB]**	**Climate Change**	**Ecosystem Quality**	**Human Health**	**Resources**
Extraction	7.90E+02	3.25E+03	7.53E-02	2.70E-02	1.33E-01	8.18E-02
Material Processing	1.62E+02	7.67E+01	1.56E-02	2.34E-03	1.48E-02	1.88E-02
Part manufacturing	8.12E+02	1.04E+03	7.87E-02	1.99E-02	7.36E-02	9.07E-02
Use (plastic extraction)	9.18E+04	3.12E+03	8.24E+00	8.21E-02	8.57E+00	2.31E+01
Use (inj. mould.)	6.18E+04	3.20E+04	5.92E+00	8.59E-01	4.29E+00	8.36E+00
Transportation (steel)	8.34E+01	1.23E+01	8.13E-03	2.37E-03	1.04E-02	8.94E-03
Transportation (plastic)	8.58E+03	1.27E+03	8.37E-01	2.44E-01	1.07E+00	9.20E-01
Tot	1.64E+05	4.08E+04	1.52E+01	1.24E+00	1.42E+01	3.26E+01

Table 3: Assessment outputs data

The results of the screening LCA are also presented in the pie-chart form, as shown in Figure 7.

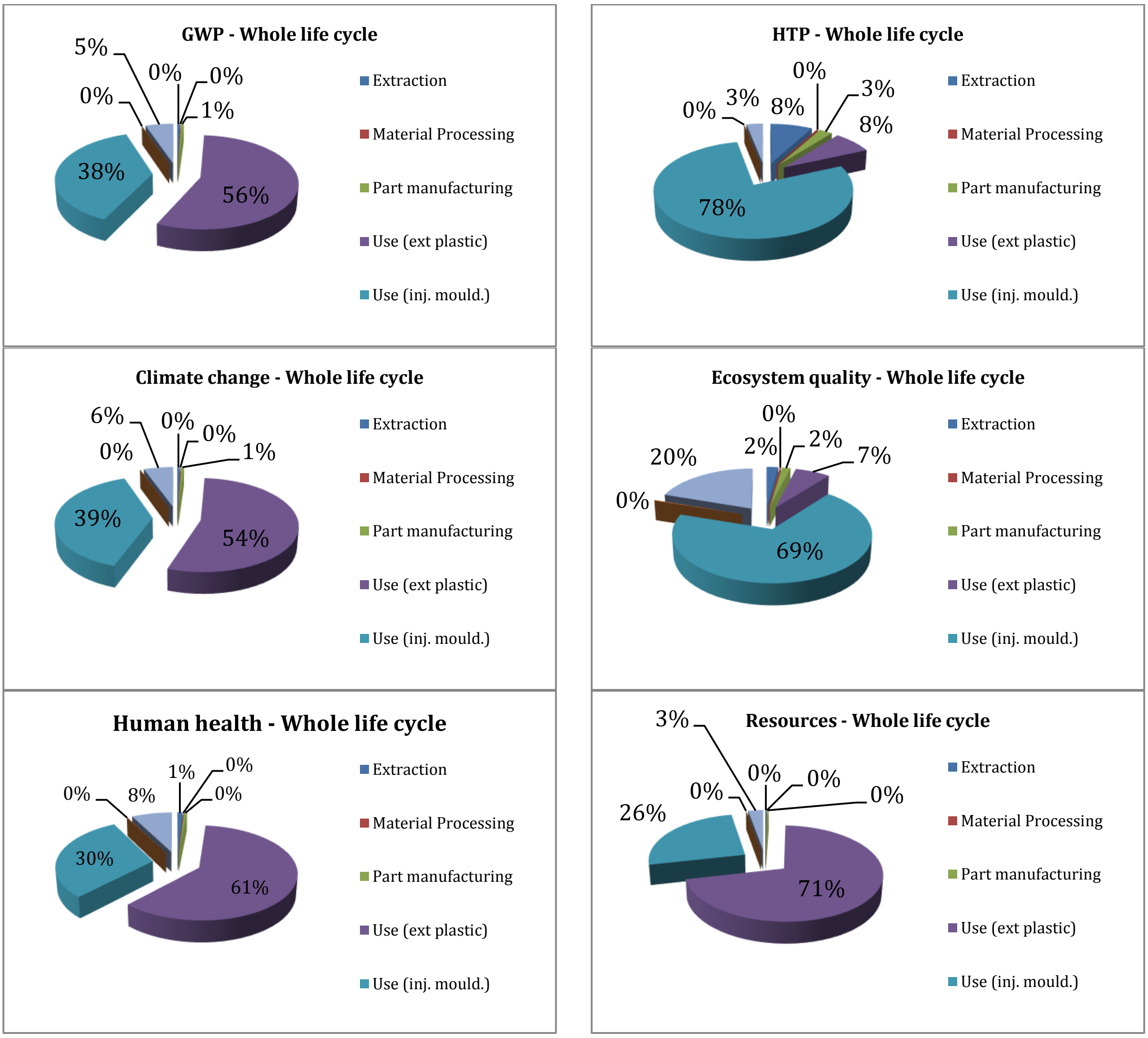


Figure 7: Assessment pie-charts

As shown in Figure 7, the "use phase" dominates the environmental impacts of the mold lifecycle (even if for *HTP* and *ecosystem quality* indicators this is less evident).
Considering that the target is the mould and that the impacts generated by the *thermoplastic production* and the *thermoplastic transportation* operations are not strictly related to the mould design, the complete mould life-cycle assessment could be re-performed excluding this kind of impacts, as reported in Figure 8 and Table 4.

	GWP [kg CO_2]	HTP [kg 1.4-DCB]	Climate Change	Ecosystem Quality	Human Health	Resources
Extraction	7.90E+02	3.25E+03	7.53E-02	2.70E-02	1.33E-01	8.18E-02
Material Processing	1.62E+02	7.67E+01	1.56E-02	2.34E-03	1.48E-02	1.88E-02
Part manufacturing	8.12E+02	1.04E+03	7.87E-02	1.99E-02	7.36E-02	9.07E-02
Use (inj. mould.)	6.18E+04	3.20E+04	5.92E-00	8.59E-01	4.29E+00	8.36E+00
Transportation (steel)	8.34E+01	1.23E+01	8.13E-03	2.37E-03	1.04E-02	8.94E-03
Tot	6.36E+04	3.64E+04	6.10E+00	9.11E-01	4.52E+00	8.56E+00

Table 4: "No plastic" assessment outputs data

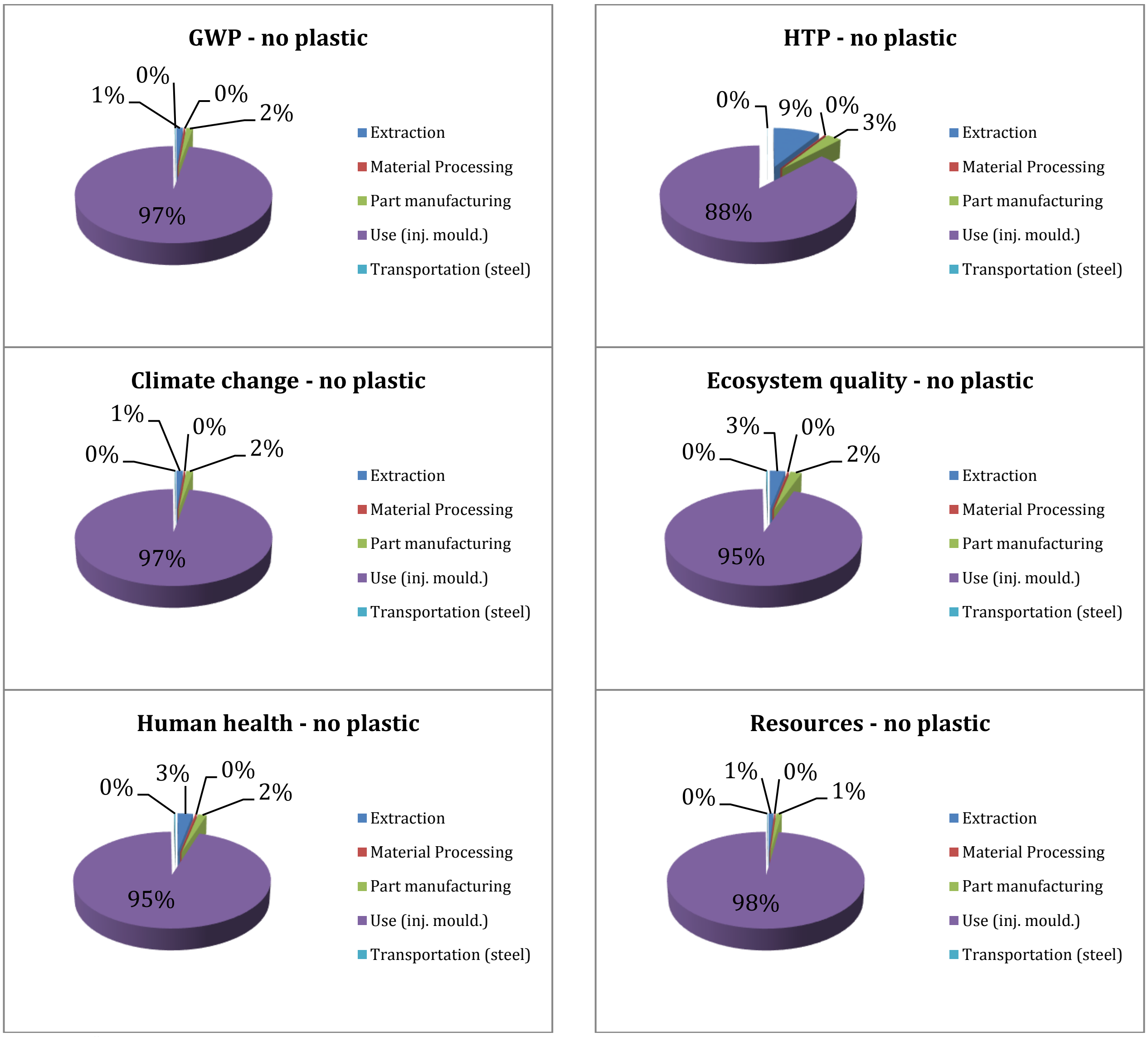


Figure 8: “No plastic" assessment pie-charts

Despite the eliminations of the impacts related to the moulded plastic, the use phase is still the most impacting one. Only for the *HTP*, the *Ecosystem quality* and the *Human health* indicators the extraction of the materials constituting the mould is no more negligible.

In order to better understand the structure of the impacts relating to the mould manufacturing, it is possible to neglect the “use phase”, so ignoring the impacts related to both the production of the moulded plastic and the injection moulding process. This evaluation is illustrated in Figure 9 and Table 5.

	GWP [kg CO_2]	HTP [kg 1.4-DCB]	Climate Change	Ecosystem Quality	Human Health	Resources
Extraction	7.90E+02	3.25E+03	7.53E-02	2.70E-02	1.33E-01	8.18E-02
Material Processing	1.62E+02	7.67E+01	1.56E-02	2.34E-03	1.48E-02	1.88E-02
Part manufacturing	8.12E+02	1.04E+03	7.87E-02	1.99E-02	7.36E-02	9.07E-02
Transportation (steel)	8.34E+01	1.23E+01	8.13E-03	2.37E-03	1.04E-02	8.94E-03
Tot	1.85E+03	4.38E+03	1.78E-01	5.16E-02	2.32E-01	2.00E-01

Table 5: No "use phase" assessment output data

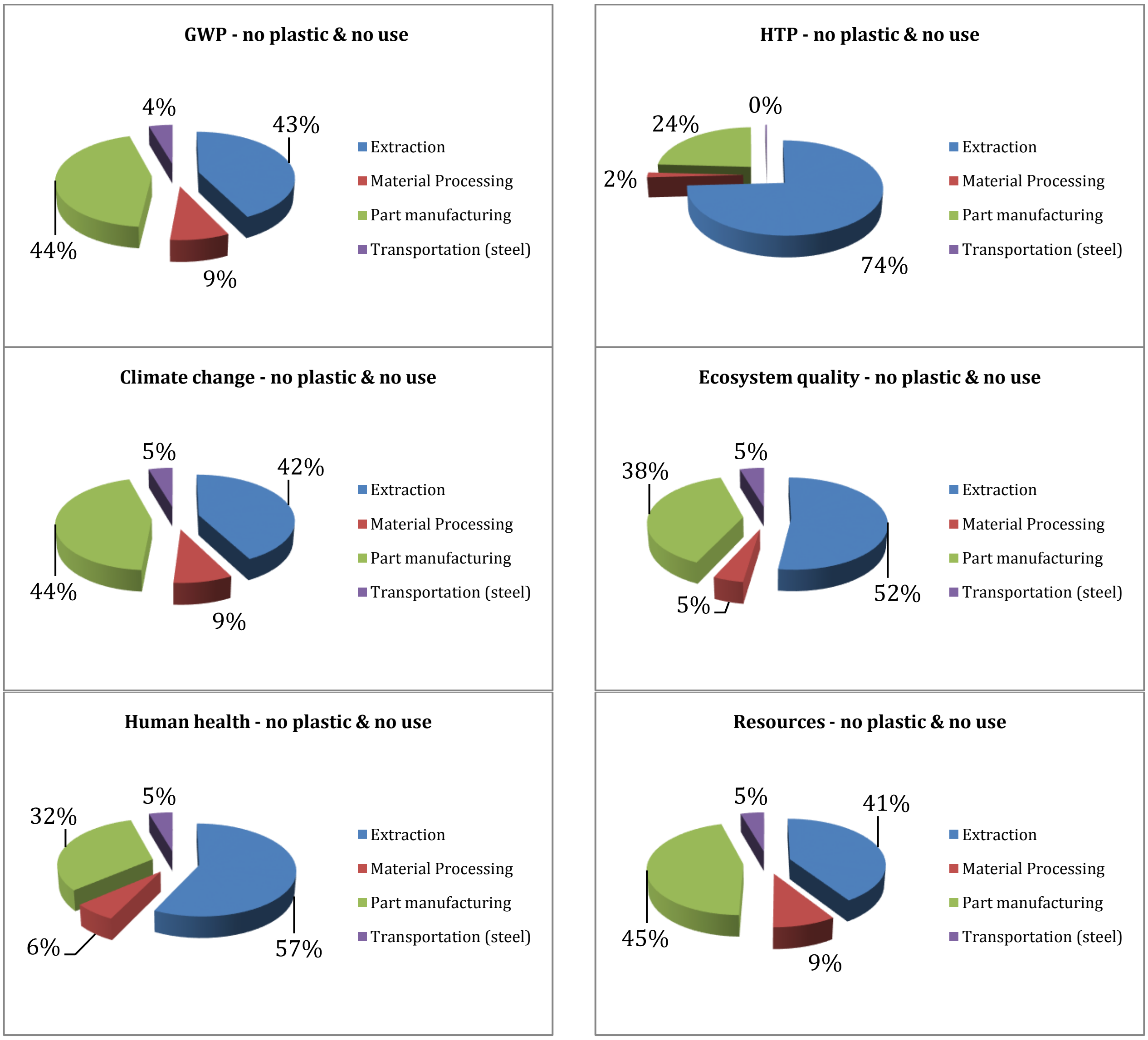


Figure 9: No "use phase" assessment pie-charts

This analysis highlight that the extraction of the steel is the most impacting phase, followed by the part manufacturing (i.e. milling, drilling…) and eventually by the material processing (i.e. the steel rolling) and the transportation. The choice of the steel and of the manufacturing processes used is thus crucial in the determination of the environmental impact related to the mould production.

The results above presented show that the “use phase” is predominant in the lifecycle of a mould. Considering that the choice performed during the mould design can affect not only the mould production, but also the use of the mould, so the injection moulding process, a detailed analysis of the parameter considered by ECOINVENT in the environmental impacts evaluation becomes advisable and is presented below.

As shown by the results of the screening LCA, the analysis and the modelling of the use phase is crucial in order to obtain a reliable sustainability assessment. Even though this behaviour has been shown for the environmental indicators, similar results could be foreseen for some of the economic indicators.

In this context a deeper analysis of the injection moulding phase has been carried out in order to understand which are the elements and the parameters of the process that mainly affect the environmental impacts related. This has been done starting from the analysis of the Unit Process Raw data of Ecoinvent (called UPR) that considers the inputs and the output of the injection moulding process in an aggregated way (i.e. not considering the complete Lice Cycle Inventory data (LCI) of the process).

As a result of this analysis, a more detailed study concerning the energy used by the injection moulding and its forecast is carried out.

Ecoinvent data analysis

Results reported in Attachment 1, §6.1 show the exchange quantities involved in the *injection molding* operation, which are categorized depending on where they come from or go to with respect to the selected process. There are just two domains that can interact with the process: the *Nature* (which represents the environment) and the *Technosphere* (which represents all the technical fields). For each exchange quantity, the table reports their contribution to a set of indicators belonging to the following two Life Cycle Impact Assessment methodologies: *CML2001, IMPACT2002+.*

Conclusions

Results achieved using the “screening LCA” method, even if obviously focussed only on the environmental impacts, allow to identify the most impacting elements and processes of a given target (in the application example: the mould), thus enabling a quick prioritization of the targets to be considered for a sustainability-enhancing projects.

2.3.3 Environmental audits: identification of sustainability challenges for supply chains

Environmental auditing is a practice intended to identify environmental performances of processes of companies related corrective actions. These audits are intended to review the company processes and their environmental performances and usually begin with determining the applicable compliance requirements against which the operations will be assessed.
Benefits of performing such audits vary depending on the objectives and scope of the audit itself. Environmental auditing benefits include:

- Awareness creation;
- Certification of current environmental performances;
- Demonstration of environmental attitude;
- Identification of environmental criticalities and risks;
- Planning environmental impacts improvements projects;

Improving environmental performance is the actual goal why environmental audits are considered here. For these reasons, audits are focused on operational aspects of a company/site, rather than the contamination status of the real property. They rely on protocols, namely a checklist used by environmental auditors as the guide for conducting the audit activities and to assure comparability among the data collected. No regulations are available to define standard protocols, either in form or content. Usually companies or auditors adopt their own protocols to meet their specific needs. Audit firms frequently develop general protocols that can be applied to a broad range of companies/operations.

Application of environmental auditing to a textile supply chain

The here reported investigation aims at performing a preliminary LCA-compliant screening of the environmental impacts of silk and silk-like products manufacturing. Instead of a single company, the target is a supply-chain of several companies. More specifically, just companies located in the textile district of Como, Italy, have been analysed with assessment boundaries going from Yarn twisting to Fabric finishing. 100 kg of output was adopted as functional unit. In literature, no investigations are available holistically addressing the assessment of environmental impacts of silk and silk-like fibers manufacturing.
Actually, fashion brands increasingly ask for product and process environmental compliance even more stringently than regulations in force (see, for example, the “roadmap to zero” initiative[2] proposed by major fashion brands and proposing a list of restricted substances that is far more

[2] http://www.roadmaptozero.com

stringent than the REACH regulation[3]). Textile producers have thus the need to constantly monitor their performances, but neither reliable data nor approaches are available for this purpose.
This study aimed at providing a first insight on the topic, relying on field-data collected from real manufacturing environments and reaching a complete and indicative screening assessment.
Thirteen companies have been interviewed, four of them covering more than one supply-chain phase. The considered supply chain steps are:

1. Twisting
2. Yarns dyeing
3. Weaving
4. Fabrics dyeing
5. Printing
6. Finishing

These processes have been grouped forming three alternative supply chains, resulting in three different product typologies (see table below)

100 kg of Yarn dyed Silk Fabric	100 kg of Open width dyed Silk Fabric	100 kg of Printed Silk Fabric
1. Twisting	1. Twisting	1. Twisting
2. Yarns dyeing	~~2. Yarns dyeing~~	~~2. Yarns dyeing~~
3. Weaving	3. Weaving	3. Weaving
~~4. Fabrics dyeing~~	4. Fabrics dyeing	4. Fabrics dyeing (just scouring)
~~5. Printing~~	~~5. Printing~~	5. Printing
6. Finishing	6. Finishing	6. Finishing

Table 6: The three alternative silk processing chains

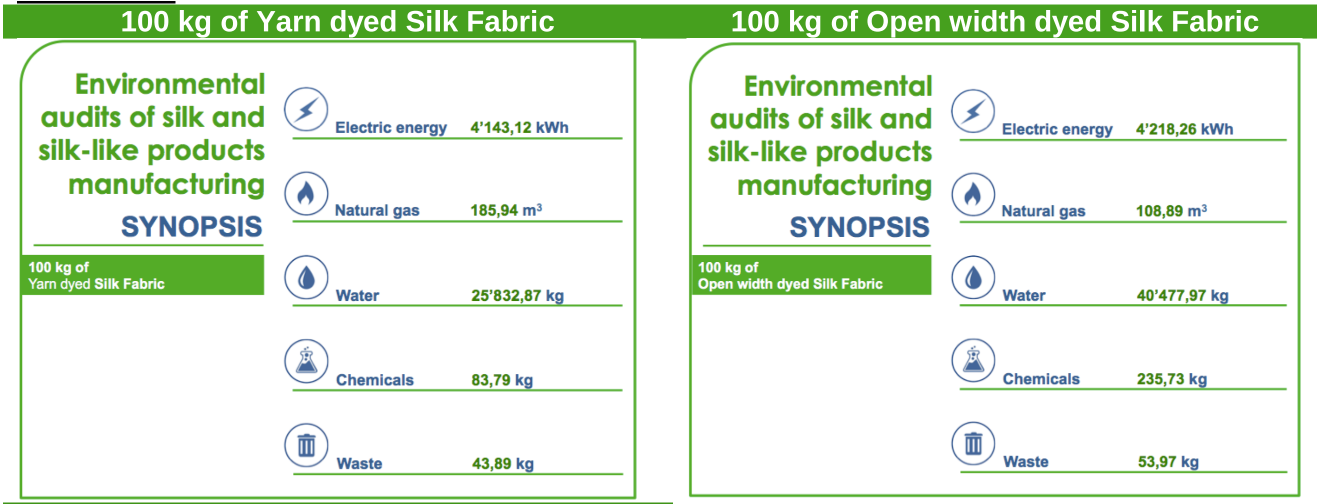
Three examples of finished silk fabrics are described. Environmental impacts of each of them are calculated considering their relevant manufacturing process steps.
Auditing team. For each analysed company, a team of three to four researchers with different background (see below) have performed a ca. 4 hours-long interview, supported by a properly developed questionnaire. Missing data have been usually provided by the company after the audit.
Interviewers had two complementary expertise: (i) at least one person of the team had a solid background on LCA-related issues and auditing; (ii) at least one person of the team had a solid background on textile products and production processes.
Interviewed persons had a solid knowledge of all the company processes. In the event of missing data, further personnel within the company was also involved in pertinent auditing tasks.
Protocol. The adopted questionnaire contemplates two *sheets* to be completed together with the interviewed company, and one sheet to be filled in afterwards, elaborating gathered data:

1. The first sheet, apart from generic administrative data (interviewed person(s), interviewers, date, overall company description) aims at collecting general data related to the company as a whole. These data have been usually derived from utility bills, accounting, declarations as required by law in force. These data have been used to take an overall picture of the company.
2. The second sheet follows a "bottom-up" approach: a *red element* is followed along the company value stream with the goal to gather environmentally-relevant data for each machine, process, manufacturing step.
3. The last sheet aims at providing a synoptic vision of the environmental impacts of the considered functional unit: data from sheet 1 and sheet 2 are compared, analysed, standardized, with the ultimate goal to reach an homogeneous, easy-reading but detailed profile of the target company and to have data ready to be compared with other entities within the supply chain

[3] https://echa.europa.eu/regulations/reach

Indicators. Five indicators have been calculated for each analysed process and for the entire supply chain. These dimensions aim at providing a sufficiently complete picture of the environmental profiles of the analysed entities.

Main results



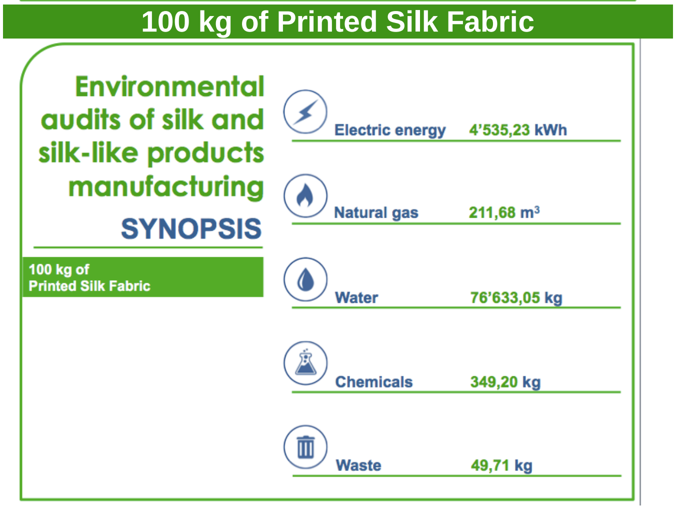


Figure 10: Results of the silk supply chains investigations

- This is an instant picture, but fashion brands ask for evidences on environmental impacts on a daily basis
- A reliable assessment of actual environmental impacts necessarily addresses data directly gathered from different actors along the supply chain
- Alternative technologies used to carry out the same manufacturing task result into really diverse environmental impacts
- The same technology operated by different companies may result into different environmental impacts (due to different procedures, production formulas, used chemicals, …)
- Different batches processed with the same machine may result into really diverse environmental impacts (due to different yarns, different colours or finishing chemicals, need for re-working, …)

The obtained results allowed to define a supply-chain wise environmental-performance improving initiative. Priorities have been identified for each supply chain configuration and proper detailed assessment performed to identify the root causes of each performance.

2.3.4 Proposal for a new sustainability assessment platform

Relying on literature investigation (as outlined in §2.3.1) and experience done with an injection moulding company an innovative platform for sustainability assessment has been developed, establishing a new reference paradigm for operative sustainability assessment and advisory. The tool (called "SAM – Sustainability Assessment in Manufacturing- platform") has been designed and validated in the mould&die sector, but it is easily adaptable to a plethora of manufacturing industries. Previously highlighted limitations of currently available instruments have been worked out resulting in the following characteristics:

- (against 1.i, 2.i, 2.iii, 3.ii, 3.iv, points mentioned in §2.3.1) **targeting two user profiles**: designers and managers. Specific Advisory functionalities have been developed for assisting designers during the design phase. Designers are both decision makers and the best knowledge-holders for technical issues. Awareness-creation and actual support in pondering sustainability performances of alternative solutions are fundamental for designing better performing products. Instead, company managers have a global, high-level vision of products sustainability performances, thus Assessment functionalities of the platform have been developed for enabling strategy-consistent goals setting;

- (against 1.ii, 3.i) 26 carefully selected indicators provide a complete overview on **all the three areas of sustainability**;
- (against 1.iii, 1.iv) the **product is the focus** of assessment and advisory functionalities, covering its whole lifecycle;
- (against 3.iii) the tool has a clear **operative attitude** and is intended to be used in everyday work;
- (against 2.ii) an energy consumption **simulation** integrates the sustainability calculation engine providing accurate, process- and technology- specific estimations of the actually used energy.

Relation to existing theories and work

As mentioned, sustainability performances assessment has been recognized as a crucial element for actual implementation of the sustainability concept within industrial practices [69]. The measurement of appropriate KPIs, indeed, has a twofold operative goal: to check the current sustainability performances of a product/company and to promote sustainability enhancement, understanding where to act effectively. In order to implement the “check and promote” approach, the mere calculation of indexes has to be complemented with tools real-timely highlighting challenges and to capture, analyse, store, search and retrieve data and knowledge [70].

This section focuses on the contextualization of the SAM Platform within the wide spectrum of assessment tools presented in literature and available on the market. First, a distinction between tools, methodologies and indicators is provided since most of the publications tend to confuse them. Then, a classification of the sustainability assessment tools is presented also presenting common and distinctive characteristics of the SAM Platform.

A huge amount of tools enabling the sustainability assessment are cited in literature [71], [72], [73], [74], even though most of the publications tends to confuse tools, methodologies and indicators. A tool is “something used as a means of accomplishing a task or purpose” [75], thus the SAM Platform is a tool. In a trivial way an indicator is “something that provides an indication” [75] and the SAM Platform is meant to calculate a set of sustainability indicators, based on the previous researches presented in [71] and [21]. On the contrary, a methodology is a “procedure and technique in accordance with a definite plan” [75]. For instance, LCA and LCC are sets of methods at product level, while Global Reporting Initiative (GRI) is a referential schema at company level. The SAM platform performs the computation of the indicators relying on well-known affordable scientific characterization methods as the ReCiPe model [76]. The SAM platform is thus an assessment tool similar to already available commercial software dedicated to the analysis of economic, social and, indeed mainly, environmental impacts generated by a product as GaBi, SimaPro or Umberto.

In order to better position the SAM Platform within this wide set of tools, the classification provided by [77] has been considered with only slight adaptations that are presented below. This categorization is meant to classify the assessment tools and methodologies along three axes: i) the integration of nature-society systems, ii) the focus or coverage areas, and iii) the temporal level.

The integration level is meant to evaluate if a sustainability assessment tool is able to measure the performances on all the three dimension of sustainability or only on some of them. The SAM Platform is meant to address all the sustainability dimensions and different areas within the same dimension. Tools as SimaPro or Umberto are specialized in LCA and exclusively dedicated to the environmental evaluation. On the contrary, GaBi allows to assess also the economic and the social dimensions even though only few areas are addressed as LCC and Life Cycle Working Environment.

The coverage areas dimension is meant to evaluate the focus of the assessment: product, company strategies, policies or projects? Just concerning the company or the socio-political context? The focus dimension is also related to the profile of the tool user. When the focus is the product, the user is typically the designer, a project manager or a marketing man, while the company CEO is more interested on the company as a whole.

The SAM Platform focus, as already presented also in [78], is the mould but it is meant to support the decision making process of both designers and managers. The lifecycle perspective and the

tools developed allows to define company strategies and policies related to the moulds design, its manufacturing processes, the moulded products design, the injection moulding press to be purchased, the end of life policies related to the mould, the waste management of the scraps generated during injection. LCA solutions currently available in the market focus on the product but have been developed more specifically for LCA experts rather than for designers or company managers. In fact, these tools have not been developed in order to use the same language of the designer since they are typically process-based rather than Bill of Material (BOM)-based. Moreover, managers rarely use them since they do not allow evaluating aggregated data and comparing alternatives.
Finally, the temporal level dimension evaluates when the assessment is performed, distinguishing between tools allowing ex-post or ex-ante pondering. In the first case, concerning the product, the assessment is performed after the design, often also after the production of the item. These tools are meant to provide a static view of the sustainability performances of the product that can be used for certifications or marketing needs. Conversely, ex-ante assessment allows the calculation of sustainability indexes during the design of the product or even during the concept development. The SAM Platform allows both these kinds of evaluations enabling the real-time assessment during the design of the mould, and the ex-post evaluation of the mould in comparison with other references. GaBi, Umberto and SimaPro are more ex-post oriented since the assessment is not provided real-timely and they are not equipped by specific forecasting tools to simulate the use and maintenance phases (just sketched in the design step).
The classification of the SAM Platform along the proposed dimensions indeed highlights some of the tool characteristics that have been already considered during the requirements collection phase, together with the lifecycle approach, the need to simultaneously assess product, process and supply chain, and the envisaged response of the Platform (as presented in [78]). All these elements have been used as the basis for the tool design and implementation that is presented in detail in the Findings section.

Research approach

Being the SAM platform the main outcome, a typical software development process has been followed to structure, plan, and control the research initiative. A wide variety of software development frameworks have evolved over the years, each with peculiarities and preferred application contexts: some rely on more carefully pre-defined processes, while others take a more incremental approach, where software evolves as it is developed. The selected approach consists of four main steps managed using a waterfall (almost stage-gate) model, while something similar to an agile development model [79] has been used within each of the four steps.

1. Requirements collection and formalization

Two major sources of requisites have been taken into account as major stakeholders: the platform final user (the mould&die company involved in the project) and the team of researchers expert in sustainability issues. Functional and non-functional requirements have been devised based on properly represented “as is” and “to be” industrial scenario, thus identifying available data and data sources, product and process characteristics, platform users capabilities, expected result. A careful investigation on existing sustainability metrics ([21]) and on adaptation/revising needs (already explicated in [78]) has been the researchers-driven task. A smart combination of such indications and constraints resulted into a list of requirements (then translated into specifications, see §3 of [78]) for the whole platform.

2. Platform design

An evolving design of the whole platform has been proposed by software developers and modified by both the groups of stakeholders. Two major challenges were confronted during the design process. The first one was concerned on how to allow the user to design the mould lifecycle through the editing functionality of the platform. A thoughtful and detailed modelling of the mould lifecycle is crucial to its accurate assessment, but it is often a very time-consuming and difficult task for the designer that, in our concept, has not to be supported by dedicated professional profiles.
Two radically different mould lifecycle design paradigm were considered:

- Process centric design: The product lifecyle is modelled through a graph of interconnected processes, each one describing its characteristics, its input and output commodities and its role in the whole picture. This approach allows to describe the lifecyle in a way which is close to the typical data model on which the sustainability assessment is performed. Its downside is the distance from the way designers are used to formalize the product which is usually component-wise.

- BOM centric design: The product lifecycle is organized upon its components and assemblies, which are placed on a tree-structure. The modelling of the lifecycle of the product is therefore down-casted to the modelling of the lifecycle of its parts. This approach is close to the way product's designers are used to work, but the semantic distance from the typical assessment data modelling makes it prone to data-gaps and data redundancy.

Keeping a high regard for time-constraints and zone-of-comfort of the product designer, a major effort was carried out in order to still allow a BOM-centric design approach, while mitigating as far as possible its disadvantages. In order to do so, three main addition to the standard BOM-centric paradigm were adopted:

- The lifecycle of each component was chosen to be designed as a linear temporal sequence of operations.
- The concept of operation was made more broad from the typical manufacturing process, as to include concepts such as logistic transportation or economic transaction.
- The history of each component, as a temporal sequence of operations, was exploited to derive and keep track of useful data (weight, ownership, physical location, etc.) in order to minimize data entry and redundancy.

This approach made the platform somewhat unsuited for modelling non-structured products (chemical industry for instance), but still adequate for the specific context of the mould&die industry.

The second challenge of the design process was to allow a high degree of modularity since, especially in the development carried out in research projects, new functionality and constraints tend to arise quite often as opportunities and issues are encountered. Therefore the application was designed with a central core module, holder of the live data model and basic listening capabilities (event-driven programming). Every other module was made to be dynamically pluggable in order to obtain the functionality it's responsible for. For instance, a persistency module was made responsible of ensuring the saving and loading capabilities of the software via the file system. While still allowing to be interchanged with a new module with cloud or database-based persistence should the necessity occurs. Moreover the modules where allowed to have dependencies relations between each other. For instance, the module responsible for assessment calculation was made dependent on the outputs of the injection moulding simulation module.

The modular design of the SAM platform made it robust against past, present and future maintenance necessity and changes in requirements with a reasonable effort demand.

In this perspective, the design of the solution has been presented through a set of Component diagrams obtained using the UML 2.0 notation. Both the overall architecture and the role and functions of each constituting block evolved through a strict interaction between developers and users. A final version have been approved and saved as a reference (see §4 of [78]).

3. Software development

The designed modular architecture allowed to minimize the initial effort: a common, flexible and general-purpose GUI structure was the only task performed at the beginning, while each module of the platform followed a specific development path. The software developer proposed sets of alpha-versions for internal (researchers’) test and modification requests gathering. Third party (industrial) test followed once a consolidated and robust version of the module was achieved. Proper bug reporting and functionalities requests documentation was adopted and used also for internal validation purposes.

The starting ground of the development was a pre-existing proprietary framework which provided a GUI infrastructure for generic editing functionalities and a backend skeleton well-suited for the development of a modular software.

The chosen language for the development was Java. Its object-oriented features were widely exploited to minimize the development time and maintainability burden. Moreover the fairly low computational requirements of the assessment and the injection moulding simulation made it not necessary to adopt a native language (such as C++) even for the more CPU-intensive tasks.

The front-end development was based upon Swing, allowing advanced user interactions such as drag&drop, multi-selection editing, shortcuts, etc., to help increase the designer productivity. Moreover it made possible to create a direct bridge between the live data model and the GUI elements, via event-driven programming, in order to minimize the chance of synchronization or concurrency-related issues.

4. Software deployment and functional validation

At the moment, the final step has been planned and just partially performed. The beta version has been released after an internal (white box) test performed by the software developers. Beta phase started as soon as the platform has been considered feature complete. Properly selected groups of accustomed and non-accustomed testers have been arranged and beta-versions of the platform shared, testing&validation protocols prepared for a formal and traceable process. Two groups of testers have been selected: three sustainability experts are focussing on bugs finding in the assessment engine through a three-level control process planned to verify the consistency between indicators value calculated by the software engine and: (i) manual computation of the formulae; (ii) output of other sustainability pondering software (esp. GaBi); (iii) (especially for economic indicators) values calculated by the industrial partner using its consolidated accounting software. As today, just minor calculation bugs have been identified and promptly fixed. Five mould designers and product managers form the second group of testers. A proper bugs-collection-template has been developed intended to organically gather users' feedback especially related to usability.

Findings

The starting point for the mould design is the draw of the plastic product to be injected and its specifications. Following the path performed during the design of the mould, the different functionalities and modes of the SAM Platform are presented. The first mode introduced is the *Company Specific Data Editor*, an essential component to rapidly perform the sustainability assessment since it avoids repeating the insertion of data common to the different projects (moulds). Then the *Mould editor and Advisory Mode* is presented as the core one since it directly supports the designer in the development of a sustainable product. Eventually the decision support system for the company management, i.e. the *Diagnosis Mode,* is described.

The Company Specific Data Editor Mode

This mode allows to edit the data needed for the sustainability assessment that concerns all the members of the addressed supply chain involved in the mould life-cycle. This data, such as sales turnovers, R&D investments, number of injuries, average worked hours, are not mould-specific, so they can be inserted into the platform once and exploited every time is needed. This avoids repeating, for each new mould project, the data-entry process of company-specific information.

It is also possible to introduce new data (e.g. adding a new supplier to the supply chain) or update the existing one (e.g. in case the sales turnover of the company is changed).

Moreover, the company-specific data editor has been designed to provide the possibility to define "strategic indicators" that can be obtained through a custom-weighted combination of the environmental, economic and social indicators.

The user of this mode can be either a designer or a manager of the main company.

Mould Editor and Advisory Mode

As already stated, the designer is the first direct user of the SAM Platform. He receives the blueprints of the product to be moulded and he traditionally starts the development of the mould considering the plastic parts characteristics and launching the CAD. In order to support the design of a sustainable mould, the designer could activate the *Mould Editor and Advisory Mode* of the SAM Platform (Figure 11). This mode can be considered as the main one since it directly supports the design of the mould, and it can be used both in parallel with the CAD or in substitution of it during the concept design. Moreover, this software component is meant to provide advisory functionalities by calculating and showing the sustainability performances in real time during the design of the mould. Through the Editor, the designer starts collecting the needed data for a complete sustainability analysis:

- describing the mould structure, the BOM and the components characteristics in terms of materials types and weights (see the upper-right part of Figure 11);
- defining all the processes needed to produce the components and assemblies included into the mould (see the lower-left part of Figure 11);
- specifying the parameters characterizing the remaining mould lifecycle phases as: the use phase of the mould (injection temperature, cycle time…), the maintenance, and the end of life (see the lower-right part of Figure 11).

This mode thus allows the user to create or completely edit a new or an already existing project (i.e. mould). In order to rapidly gather the information needed to perform the sustainability assessment, the Platform enables the designer to describe the mould from a pre-defined Library (see the upper-left part of Figure 11) or importing an initial set of information concerning the mould BOM taken from CAD (a function available on the “File” menu). The user can choose from the Library components, assemblies or a complete mould and then drag and drop them into the Project window where the BOM structure is built and presented (as already stated, the upper-right part of Figure 11). It has been directly experienced by the implementation company that the use of the Library may foster the born of a “product platform” so that it is possible to built each mould as an instantiation of a standard one that is included into the Library. This is a completely new way to develop a mould for the industrial partner that will be further investigated and presented in future publications. As an alternative to, if the designer has already defined at least a first draft of the CAD draw of the mould, it is allowed to import an Excel file obtained from a CAD exportation that contains the list of components and assemblies, their raw mass, their final mass and the materials constituting them.

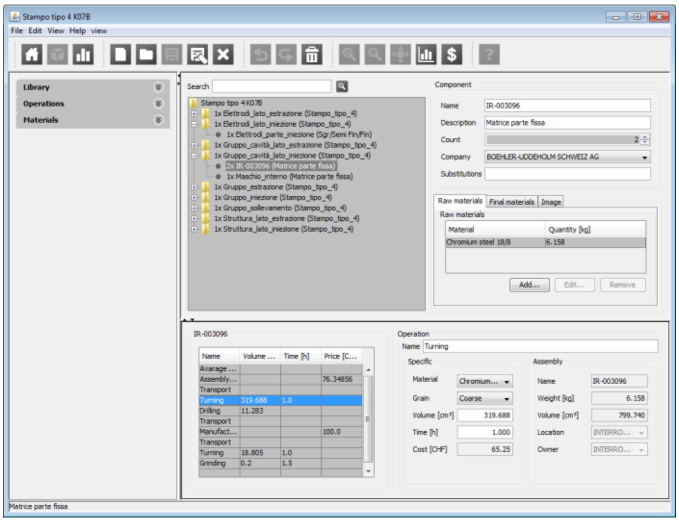


Figure 11: The Mould Editor mode

Actually the SAM platform is configured to load data from a specific Excel template created within the SAM project that is meant to be shared also with the company suppliers. In this template, the information obtained from CAD is completed with the cost of the purchased components and the identification of the supplier.

After the use of the Library or of the importer, the complete BOM of the mould can be rearranged into the *Project windows* (see the upper-right part of Figure 11). In order to complete the data needed to run the assessment, the *Timeline Editor* (see the lower-left part of Figure 11) allows the designer to describe for each mould element, with a temporal sequence, all the manufacturing and economic processes needed to build the mould. The timeline assign to each operation its positioning time relative to each other. Time sequence is exploited in order to avoid redundancy in the data needed for the sustainability assessment. For instance, knowing the raw weight of a component and a list of material removing operation carried out on it, it is possible in each instant to deduce the weight of the component that is needed to evaluate the impact of possible transportations performed, without specifying the weight of the component for each transportation. The *Timeline Editor* enables to detail the information concerning all the processes performed during the lifecycle of the mould and its components as the manufacturing operations (e.g. milling, electro-discharge machining (EDM) and drilling), the purchasing of components or assemblies, the transportations, the injection moulding operation, and the operation carried out during maintenance and the end of life (see the lower-right part of Figure 11). Through the proper GUI presented in Figure 11, the designer is able to complete the project description inserting all the data needed to assess environmental, economic and social impacts.

Considering the extend of the assessment in respect to the sustainability dimensions, many diversified data has to be collected as, for instance, the mould constitution in terms of materials and weights, the parameters characterizing the manufacturing process (e.g. the material removed and the time spent for the specific operation), the purchasing costs of components and processes, the sequence of the transportations occurred, the moulded product geometrical characteristics and so on.
A brief digression concerning the use phase and the maintenance one is here needed in order to fully understand the potentialities of the Platform. These two phases in fact are those more related to the forecasting potentialities of the SAM tool since, during the design phase, the designer can for instance easily access to the weight of the components or the quantity of the material removed during the manufacturing operations, but has not the right tools in order to characterize the injection moulding and the number of the maintenance operations on average needed by the mould during its functioning time. The calculation of the energy consumed during the melted polymer injection into the mould is a crucial element determining economic and environmental impacts [80] and [78]. For this reason the engine of the sustainability assessment has been equipped with a module that is meant to calculate the energy needed starting from the following data: the product geometry to be moulded; the injection moulding process parameters; the injection moulding material; the injection moulding machine used during the process; the main mould characteristics (assumed number of cavities, runner type,…).
This module has been developed through semi-empirical calculations and DoE techniques. Similarly, concerning maintenance, the assessment engine has been equipped with a module that, through a statistical approach based on the Naïve Bayes Classifier, provides a forecast of the maintenance operations needed during the mould lifecycle. In this case the engine module uses some mould characteristics identified to be crucial in maintenance (e.g. the number of the cavities, the injection type (hot or cold runners), the number of version changes and the number of pieces moulded) and then provides a forecast of the maintenance operations to be performed thanks to statistical data concerning already existing moulds that relates mould characteristics and the maintenance operations actually carried out on them. Similarly to the other manufacturing processes, this detailed information concerning both injection moulding and maintenance can be inserted into the GUI panel represented into the lower-right part of Figure 11.

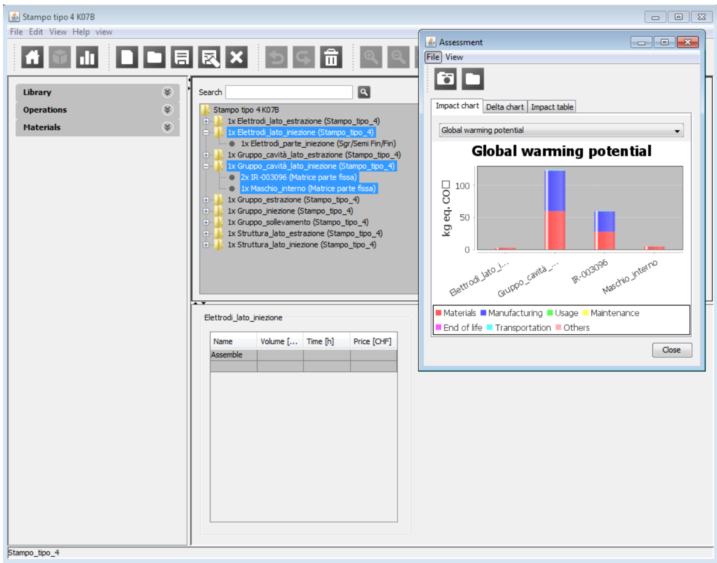


Figure 12: The Advisory Mode window

When the insertion of the data concerning the mould is completed, the new project created can be included as a new element of the library. The library thus include not only the BOM of the mould, but also all the other information needed for the assessment even though the Platform allow to save and also assess projects that have not been completed.
The *Advisory Mode* is indeed an integrated component of the Editor Mode since it enables the real-time sustainability assessment of the open project, reporting in a dedicated window the values of a set of environmental, economic and social indicators. Figure 12 shows how the Advisory window is displayed: it can be maintained into the screen while the designer modifies the mould design both in term of components and operations. Figure 13 provides a detailed view of the Advisory window, showing for the group of mould components that has been selected into the Project window in Figure 12 the value of a certain sustainability indicator. During the design of a mould the end user is provided with information useful to modify it. The Advisory window is indeed separated into three sub-windows such as the Impact chart, the Delta Chart and the Impact table

(see Figure 13). In the Impact chart it is possible to visualize as histograms the indicators concerning the whole open project (i.e. the mould) or the indicators concerning single assemblies, single components or group of them (as in the case of Figure 13). In this visualization mode it is possible to display the indexes values one-by-one. The Delta Chart is on the contrary dedicated in displaying the project indicators histograms compared with those of a benchmark project. The need of a benchmark is basically related to the fact that, from the sustainability point of view, there is not a "sustainable" mould, but just a "more or less sustainable" one.

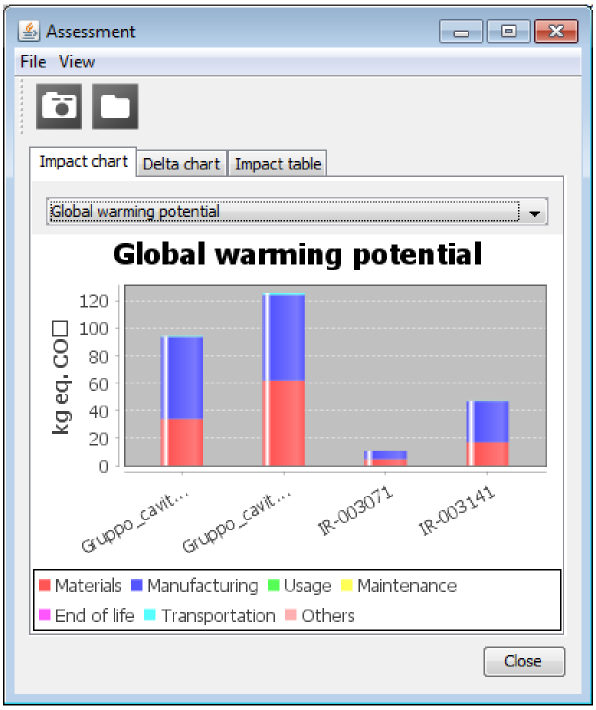


Figure 13: The Advisory window in detail

Currently it is possible to define two typologies of benchmark within the Advisory Mode. The first one is the so-called "Previous configuration" that concerns the last mould configuration obtained, before the mould is modified. The designer can save the impacts related to a mould configuration, then modify it and verify if the modifications operated affect positively the sustainability level of the mould. The second benchmark type that can be defined is the "Saved mould" benchmark that is the possibility to charge a benchmark the sustainability indicators of any project built with the SAM Platform. Moreover the Delta chart allows to perform the comparison on the complete set of the indicators or on a partial one (that is customizable by the user) since the use of few indicators may allow a quick overview of the projects impacts. Additionally he can analyse in a more detailed way a single indicator in order to understand how the lifecycle phases contribute to the indicator value.
Eventually the Impact table summarize the information provided by the visualization mode mentioned in a table format.
How the Advisory Mode can be exploited? A first possible application, indeed already sketched, is the real-time sustainability improvement of a mould. The user is interested in develop a sustainable mould directly during its beginning of life phase. During the design, the designer can constantly visualize the sustainability values indicators of the open project, as shown in Figure 12. He can identify the "hot spot" of the project (e.g. assemblies, lifecycle phases) that generate the main impacts, or evaluate different possible configurations fixing at its choice the appropriate benchmarks. In this way the user can modify the selected project trying to understand where its weak points are and how to face them: this process could be reiterated until the desired target is achieved or the resulting output is no more improvable. A second use scenario is the comparison of two moulds very different in size (i.e. with a substantial difference in the number of cavities) but producing the same set of items. This is the case when already existing moulds has to be replaced or supported by new ones for production needs. In this scenario the existing mould can be defined as benchmark in the Advisory Mode so that the design of the new mould can be rapidly assessed in each step of its development.
When the design of the mould has been completed, the project can be saved for future evaluations. For instance when the mould will be actually built, the project can be recalled and modified using real data rather than the forecasted one. After the design phase the *Diagnosis Mode* can be activated so that the management can compare the new mould with already existing one or add it to the evaluations already performed.

Diagnosis Mode
This mode allows the end user to select from all the existing moulds available in the company, a subset by means of filtering utilities. Moreover it allows to define groups of moulds and to make sustainability comparisons between single moulds, mould groups or single moulds with mould groups.

The user of this module, as already stated, is typically a manager of the company that could be interested in strategic decision-making or in marketing and external communication. The Diagnosis user can analyse selected groups of moulds or moulded products in order to obtain a high-level perspective of the company sustainability performances. In order to perform this analysis, the manager can interact with this software module through a GUI layout composed by i) the *Filtering window*, ii) the *Database window* (both shown in Figure 29) and the *Selection window* (Figure 29). The *Database window* (upper-left part of Figure 29) visualizes all the available SAM platform projects that are stored in a defined directory.

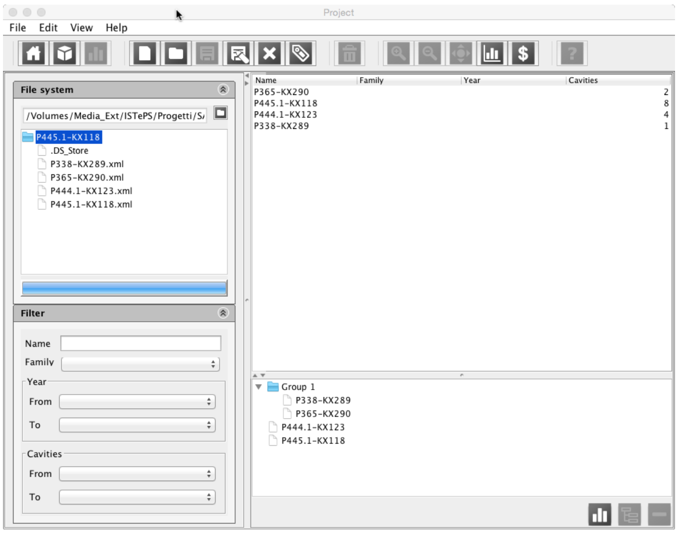


Figure 14: The Diagnosis Mode

The *Filtering window* (lower-left part of Figure 29) allows the user to create one or more filters to ease specific searches. The items in the Database window can be selected and added to the *Selection window* (right part of Figure 29) as single items or groups: here they can be evaluated and compared from the sustainability point of view. For instance the manager could be interested in analysing the trend of the sustainability performances of the mould produced during the last year. He can add a set of moulds in the *Selection window*, selecting them from the *Database window* in order to compare their sustainability level. The selection is performed through the *Filtering window* that helps him to quickly identify the moulds of interest. Eventually the selected mould can be introduced to the comparison as single entities or grouped together if the management is interested in comparing the moulds produced into two different years.

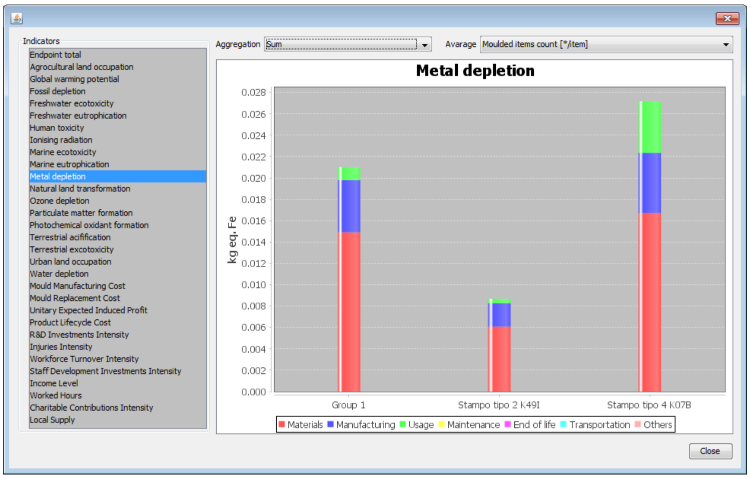


Figure 15: The Diagnosis Mode – The Comparison window

The results of the sustainability assessment and comparison are then displayed in the *Comparison window* (Figure 15) as histograms and tables and the set of indicators to be shown is fully configurable by means of a filtering menu, visible in the left part of Figure 15. Moreover the user can also choose how to define the mould groups indicating the aggregation procedure to be applied (i.e. sum or average) and the type of average (e.g. average on sales turnover, on moulded pieces…). This is done through the menu shown in the upper-right part of Figure 15. In our example the user can chose to group the mould produced in 2014 as a single entity that is defined considering the average impacts of the 2014 moulds, average based on the moulded pieces produced by the moulds.
This kind of analysis allows determining the sustainability trends of the company products and enables the identification of possible strategic areas of intervention in order to improve the overall company performances.

Conclusions

An assessment and advisory software tool has been developed intended to support the actual implementation of the sustainability paradigm in everyday work. Thanks to a closed interaction between researchers and industrial users, the resulting platform is a valuable compromise between usability and accuracy. In fact, the SAM software has been designed with the goal to integrate and complement the traditional product design process requiring the users to possess just a minimum knowledge on sustainability topics. And here is the most innovative element of the presented solution: real decision makers (product designers and product managers) have been given an unmediated access to the sustainability body of knowledge; they can sustainability-wise ponder, compare, and rank alternative products, elements of a product, technologies, suppliers, energy sources, transportation means… with the final goal to increase corporate awareness on sustainability performances and, leveraging their competences on product- and process- related technical issues, identifying the most promising and effective improvement paths. The platform is now undergoing the beta-version test campaign already described both to gather quantitative measurements on achievable results, and to identify procedural drawbacks for improving the current product design process. To date, major criticalities turn out to be: (i) lack of integration with existing CAD software. To start using the SAM software, users can import the BOM generated by the CAD (but that's a mere list of components, without parent-child relationships explicated) or directly editing within SAM the components of the mould. In both cases, a reasonable effort is required and there's a lack of connection with the CAD; (ii) need to re-think the new product design process. Interestingly, designers have started stressing the need for a more linear, protocol-based, and also platform-oriented approach towards new product development, including a deep re-use of existing components and assemblies, the introduction of a preliminary sustainability screening functionality, a continuous comparison with past projects; (iii) a careful design of the sustainability label to be assigned to each mould: how to explain indicators, how to define classes, how to define the thresholds among classes.

In the medium term, a more extensive validation campaign is advisable in order to size the efforts required for a sector-wise customization.

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3 Sustainability-driven innovations

3.1 Introduction

Innovation in manufacturing contexts may derive from and result into changes ranging between small, incremental adjustments to multi-layer multi-disciplinary disruptions. Traditionally, the great part of innovation initiatives addressing manufacturing are triggered by economic and financial goals, even if, in recent years, some methodologies and approaches emerged aimed at integrating all the three sustainability dimensions [81] into innovation-related decision making. This is a result of an increasing pressure from the market on including (also) environmental and social elements in business model evolution. In general, as each sustainability issue gains relevance in the strategy of a company, more extensive changes of the company have to be performed [82] including wider, multi-layer, integrative approaches to innovation as more extensive opportunity for a sustainable development.

Experiences from the manufacturing world suggest that the more extensively the corporate business model blocks are innovated using a sustainability-driven approach, the greater the envisaged sustainability impacts according to the triple bottom line are. The proposed empirical point of view is reasonable as far as: (i) different scenarios can be derived from a unique business context that (radically) innovated over a medium-term time horizon modifying product, process and supply-chain (at least, a single-dimension change is contemplated in the wider multi-dimensional); (ii) all the three aspects of sustainability are relevantly represented; (iii) standardized and measurable metrics can be applied to reliable input data for an effective comparison of the selected scenarios.

Several literature sources discuss *available* means to improve sustainability performances of a manufacturing company, but they don't arrive at a common classification. Some authors (e.g.: [83]; [84]) consider a lifecycle point of view and focus on the product. Potential sustainability-enhancing opportunities may arise in one of the lifecycle steps among product design, manufacturing by-products, by-products produced during product use, product life extension, product end-of-life, and recovery processes at end-of-life.

Other authors focus on the sources of (environmental) unsustainability and measures to properly manage them: energy-saving production technologies, reduction of emission of greenhouse gases, limited generation of waste, avoidance in use of non-renewable or toxic materials ([85]).

Smith and Ball ([86]) and other authors suggest a three-levels approach with a focus on technical-related elements on different scales (process, system, plant, supply chain, etc.) that can facilitate sustainable manufacturing.

According to 2011 annual series of Global Conferences on Sustainable Manufacturing (GCSM) sponsored by the International Academy for Production Engineering (CIRP), innovation initiatives potentially improving the sustainability performances of a business can be due to the following areas:

- Sustainable Manufacturing through high-performing manufacturing processes and equipment
- Revised manufacturing paradigms enabling optimized management of resources (e.g.: Lean Manufacturing for sustainability, Integrated development of product-production system combinations)
- Advanced diagnostics and assessment for awareness creation and decision support
- Remanufacturing, Reuse and Recycling
- Product design for resource efficiency and effectiveness
- Innovative energy storage and conversion technologies
- Green supply chain and efficient transportation
- Education and training for sustainability
- Business model for sustainable development

Probably one of the most interesting works on the topic was proposed in the 2014 review by Bocken, et al. ([87]) Authors suggest that the kind of innovation/investment you focus on when starting a sustainability-enhancing project varies in accordance to the business archetype you consider (see figure below).

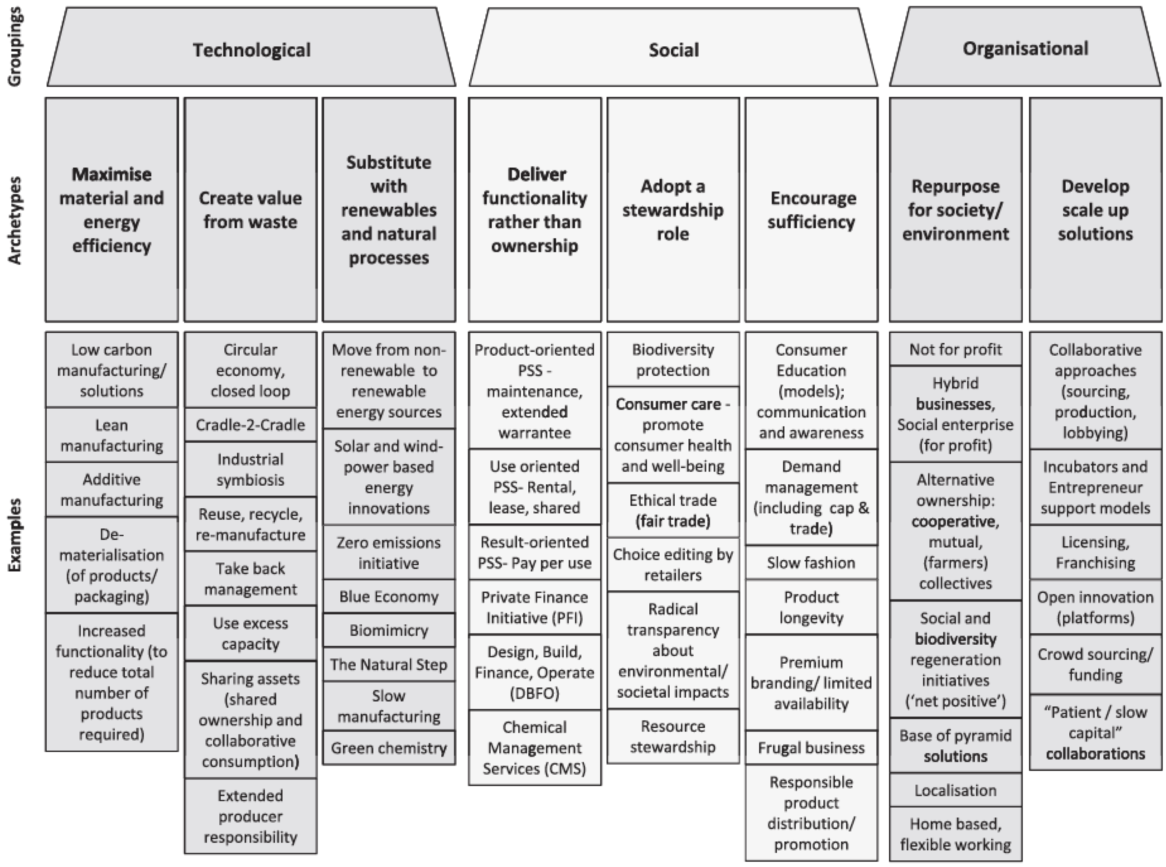


Figure 16: Business archetypes in accordance to Bocken et al.

Finally, other authors ([88]) focus on the stakeholders and on the role each stakeholder should have in promoting sustainable manufacturing. This brought to the identification of seven potential contributor typologies, as depicted in the schema below.

Figure 17: Stakeholders influencing sustainable manufacturing practices

According to this vision, authors identify the following contexts where to act in order to improve the sustainability performances of a company:

- Sustainability-aware manufacturing processes and technologies
- Sustainability-driven product design and development tools and methods
- Remanufacturing, re-use and recycling methods and technologies
- Renewables and resource utilizations
- Sustainability assessment
- Logistics and green supply chain management

Combining all these inputs, we can identify the following areas of potential intervention for entrepreneurs aiming at improving their sustainability performances:

1. Tools for sustainable design of products and processes
2. Methods and tools for sustainability assessment
3. Sustainability-aware manufacturing technologies
4. Remanufacturing, re-use and recycling methods and technologies

5. Environmentally-conscious energy and resource management practices and technologies
6. Optimized logistics and green supply chain management
7. Sustainability-conscious business models

As mentioned in the initial chapter, a successful sustainable business model has to smartly deal with **appropriability** of public benefits, i.e. positive social and environmental externalities, by private entities (namely: manufacturing companies investing in one –or more– of the points above). This is why companies compete in markets where they are (usually) paid only by customers and, thus, for the value they provide to these paying customers. In the face of increasing awareness about business-society interrelations and moral and ethical concerns, companies strategies started to consider simultaneously customer value and public value ([89]). This means that to justify value propositions to their customers, manufacturers have to combine public value propositions (thus resulting in *green* or *sustainable* solutions). This is ok as far as customers are willing to pay for this added (public) value. Problems arise when:

- Customers are not made aware of the increased public value the solution offers in comparison to competitors';
- Customers are not willing to pay for this public value.

Two further elements have to be added to the list above in order to deal with these two issues:

8. Labelling and other methods intended to communicate the enhanced sustainability performances of a company/solution. This is the way to create awareness in the customers and, thus, to exploit the mentioned attention towards environmental and social performances of the products in the market.
9. Sustainability accounting and other sustainability-related taxations, regulations, … intended to force producers to adopt sustainable production measures and/or to reward companies investing in environmentally- and socially- conscious initiatives.

Therefore, the here proposed vision includes nine blocks forming the **sustainability-driven innovation palette**.

In this work, we present some findings we achieved concerning four of the points above:

- Sustainability assessment. The Sustainability Assessment tool has been already presented in §2.3.4.
- Remanufacturing, re-use and recycling methods and technologies. Two patented processes/technologies will be here presented as examples showing smart ways to exploit wastes and by-products of the silk production process.
- Sustainability-conscious business models. A proposal will be here reported for a sustainability-centred business model to be adopted by manufacturing clusters and industrial parks interested in adopting symbiotic production behaviours.
- Labelling. A voluntary labelling method has been developed for an injection moulding company in Switzerland interested in communicating to its stakeholders the sustainability performances of their products. This will be presented in §4.2.

3.2 Sustainability-enhancing technologies

3.2.1 Exploiting textile production wastewater

Silk is widely used for the manufacturing of high quality and comfort garments, and luxury furnishing textiles. Silk is a textile fiber of animal origin, obtained from the cocoon produced by silkworms (mainly of the Bombyx mori species). Silk fibers are made of two proteins: a double-stranded internal structure of fibroin wrapped by a sheath of sericin.

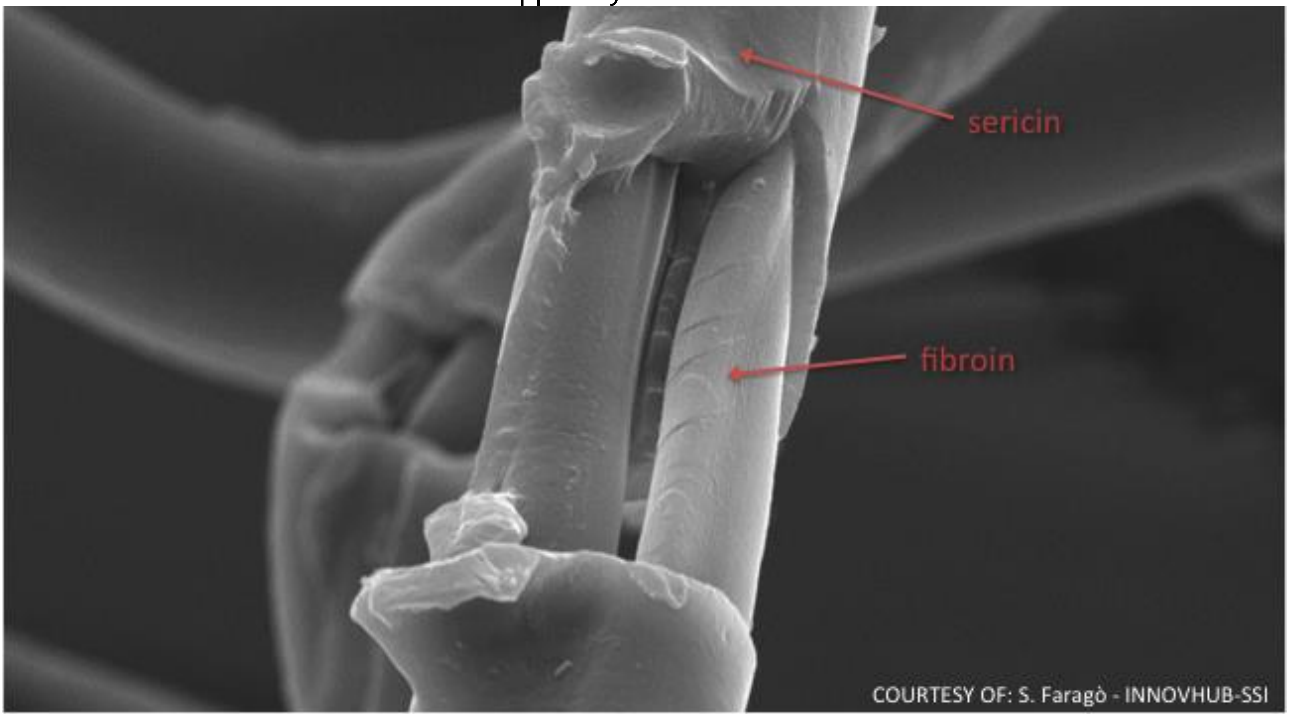


Figure 18: Silk proteins viewed through an electron microscope

Fibroin is the only component used in the textile industry. On the contrary, sericin has an amorphous structure, it's highly hydrophilic and it is eliminated during the textile manufacturing process, although it represents more than 20% of the native fiber weight.

In particular, the so-called "degumming" process is performed by means of water solutions (at 95°C - 98°C) and soaps for an average time of three hours. Thanks to this treatment, sericin is removed from the fiber and disposed through wastewater. This process generates effluents with a high content of organic matter (BOD5 equal to about 30,000-50,000, high COD) leading to the production of nitrogenous substances and odors in wastewater. Consider that around 2,000 tons of silk are produced just in the Como district on a yearly basis, with over 400 tons of sericin discharged into wastewater as pure waste.

Some data of the degumming effluents are reported below.

DEGUMMING EFFLUENTS CHARACTERISTICS
BOD5 (mg/l): 30'000-50'000
COD (mg/l) > 2'000
SST (mg/l) >1'000
• 25% of animal-produced material actually wasted
• Energy used to heat the water
• Co-formulants of the degumming moisture: soap, detergents, emulsifiers
• Water depletion
NUMBERS OF THE COMO SILK DISTRICT
• 2'000 tons of silk manufactured on a yearly basis
140'000 mc of depleted water
> 7 mln kg of steam
300'000 kg of co-formulants
… to produce 1'500 kg of silk to be used (fibroin)
… and 400-500 kg of sericin to be discharged

Table 7: Effluents of the silk degumming process

Sericin is thus considered as a waste in textile, but it is indeed a really valuable material for other applications. For example, sericin can be added in cosmetics to beauty creams, shampoos, wipes, … as it inhibits skin aging and promotes skin protection and hydration.
Therefore, although sericin is a by-product of the textile industry throughout the world and is produced during the processing of raw silk cocoons, sericin potential utility ranges from cosmetics to biomedical products, which includes its use in anticancer drugs, anticoagulants, cell culture additives and for its antioxidant properties in pharmacological and biotechnological applications.
In particular, low-molecular-weight sericin is used in various blends for cosmetic, medical and pharmaceutical applications since it helps to enhance the elasticity of skin and has anti-wrinkle and anti-aging effects. Sericin enhances the light-screening effect of UV filters like triazines and cinnamic acid esters. Sericin has also many medical applications. Study of the macrophage response of silk protein concludes that sericin usually does not manifest inflammatory activity when present in soluble form.

The recovery and recycling of sericin by-products could results in a significant environmental, economic and social benefit.

Nowadays, sericin produced for cosmetics derives from ad-hoc processes, where (second-choice) silk cocoons are processed in autoclaves by means of hot water and chemical additives. The obtained solution is then dehydrated by lyophilization or oven (both of them energy-consuming) and the resulting powder is sold at very high prices (200 €/kg).
In fact, in the degumming water, the low concentration in sericin induces its aggregation and precipitation at room temperature. To avoid this drawback and to prevent material decomposition, sericin solution must be lyophilized.
However:

- lyophilized sericin is less soluble in water (about -60%), due to conformational rearrangement after water removal,
- the lyophilization process is relevantly energy- and time- consuming.

With some partners from the silk industry, we developed a new technology aimed at sustainably recovering sericin from the textile wastewater and to derive a really valuable and sterilized ingredient intended for cosmetics and pharmaceutical applications. The developed technology (currently shaped in a lab-prototype size) starts from sericin in solution directly taken from the degumming process. This solution is added with minimum chemicals and then ultra-filtered using a patented process (details below). The output is a 10%-rich sericin gel, completely free of impurities and not chemically modified by the degumming process. Modulation filters also allow the elimination of other pollutants. The gel is ready to be used in cosmetics, and its production cost is less than ¼ of the ad-hoc process.
Moreover, the technology allows to eliminate the BOD5 pollution of silk manufacturers' wastewater (and the deriving treatment costs).
With respect to lyophilisation, benefits are:

- ½ energy consumed
- Improved sericin quality
- -40% production costs

Our prototype is based on a ceramic-filtering ultrafiltration that allows:

- Elimination of contaminants
- Sericin solution concentration

Through:

- Ceramic membrane with cutoff 15kDa
- Cavity pump with flow-rate 2400l/h
- Working temperature around 40°C

The technology is currently at a pilot level and it has to be scaled-up. With the resulting material, it would be possible to design and develop a wide range of cosmetics and pharmaceutical applications based on sericin, and intended for different application areas:

- sericin as it is, to be used by cosmetics and pharma companies as a co-formulating ingredient for their products;
- high-level (cotton-based) cleaning wipes and cleansing diskettes added with sericin with improved bacteriostatic, bactericidal, moisturizing functionalities;
- cosmeceutical products properly developed for skin treatment and based on sericin combined with properly selected co-formulants (silver, cuprum, alginate,…)
- medical, such as advanced bandages used for the treatment of major diseases of the skin (psoriasis, bedsores wounds), and (also implantable) scaffolds based on natural bio-compatible materials for tissue engineering with applications in the field of dermatology and surgery.

Figure 19: The degumming wastewater processing prototype

A patent has been obtained for the process (initially intended to process the solubilized fibroin, but perfectly working with minimum modification to process the sericin):

ID: MI2013A001563

TITLE: METHOD AND APPARATUS FOR PREPARING FIBROIN DERIVED PROTEIN MATERIALS, IN PARTICULAR FOR MEDICAL AND COSMETIC USE

Verbale di Deposito Domanda di Brevetto per Invenzione Industriale
numero domanda: MI2013A001563

CAMERA DI COMMERCIO MILANO

Camera di Commercio Industria, Artigianato e Agricoltura di MILANO

Verbale di Deposito
Domanda di Brevetto
per INVENZIONE INDUSTRIALE

Numero domanda: MI2013A001563
CCIAA di deposito: MILANO
Data di deposito: 23/09/2013

<u>Claims</u>:

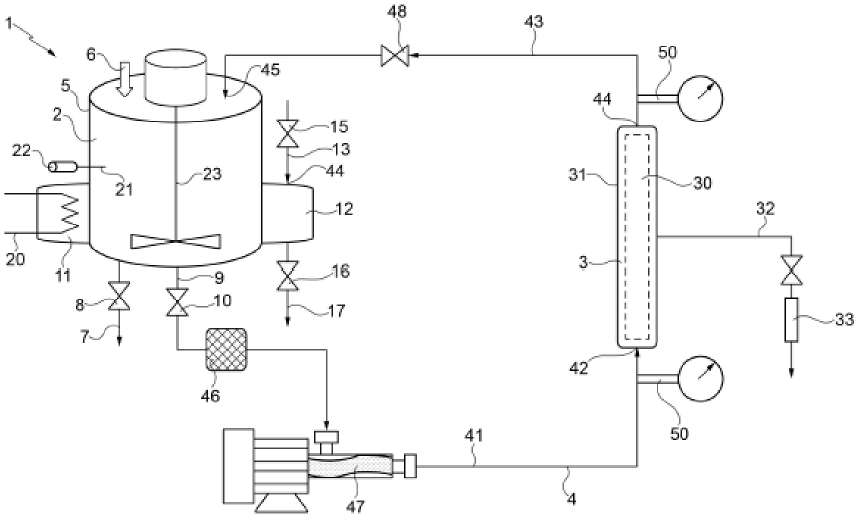
1. A method for preparing fibroin derived protein materials, in particular for medical and cosmetic use, comprising:
- a solubilization step, in which fibroin in fibrous form is solubilized in a solvent mixture containing formic acid and at least one phosphoric acid and, optionally, water, for forming an acid solution of fibroin;
- an ultrafiltration step, in which the acid solution of fibroin is subjected to an ultrafiltration process for removing from the acid solution of fibroin said formic acid and at least one phosphoric acid and replacing said acids with water, so as to obtain a solution of fibroin in water.

2. A method according to claim 1, wherein the solvent mixture contains water, present in the formulations of the acids or added, in a total amount less than 20% v, preferably less than 15% v and more preferably ranging between 0,5 and 5% v.

3. A method according to claim 1 or 2, wherein the solvent mixture contains:
- 40÷80% v, preferably 50÷80% v, of a phosphoric acid having a concentration of 85÷99% w in water or pure (100%);
- 20÷60%, preferably 20÷50 v, of formic acid having a concentration of 95÷99% w in water or pure (100%);
- 0÷15% v, preferably 0÷10 v, of added water.

4. A method according to one of the preceding claims, wherein the solvent mixture contains, in terms of pure components:
- phosphoric acid: 40÷80% v;
- formic acid: 10÷50% v;

- water: 0,5÷20,0% v.
5. A method according to one of the preceding claims, wherein the fibroin is added to the solvent mixture in such an amount to have a concentration of about 2÷10% w/v and preferably of about 4÷6% w/v.
6. A method according to one of the preceding claims, comprising a step of selection of operating parameters of the solubilization step and/or the ultrafiltration step for varying the properties of the fibroin obtained, by changing one or more of the parameters: composition of the solvent mixture, in particular relative amounts of formic acid, phosphoric acid and water and/or concentration of phosphoric acid and formic acid in the solvent mixture; initial concentration of fibroin in the solvent mixture; temperature and time of treatment of the solubilization step; pressure, rate, temperature and time of treatment of the ultrafiltration step.
7. A method according to one of the preceding claims, comprising, after the solubilization step and before the ultrafiltration step, a step of first dilution, in which an amount of water substantially equal to the volume of the acids present in the acid solution of fibroin is added to the acid solution of fibroin and a water diluted acid solution of fibroin is formed, which is fed to the ultrafiltration step.
8. A method according to one of the preceding claims, wherein in the ultrafiltration process the acid solution of fibroin tangentially runs through a ceramic membranes tangential filter (30), in which the acid solution of fibroin separates in: a permeate, that passes through the pores of the ceramic membranes and is removed; and a retentate, that is retained by the ceramic membranes and remains in the solution; the filter (30) having ceramic membranes with pores such as to allow passage in the permeate of said formic acid and at least one phosphoric acid, and retain fibroin in the retentate.
9. A method according to one of the preceding claims, wherein the ultrafiltration step comprises repeated ultrafiltration passages, carried out in the same filter or in a plurality of filters, in which the retentate of each passage is replenished with an amount of water substantially equal to the amount of permeate removed in the same passage, so as to maintain substantially constant the volume of fluid processed in the various passages.
10. A method according to one of the preceding claims, comprising a step of total or partial removal of water from the solution of fibroin in water, and/or a step of stabilization of the solution of fibroin in water, for obtaining fibroin in a specific use form.
11. An apparatus (1) for preparing fibroin derived protein materials, in particular for medical and cosmetic use, comprising: a mixing unit (2), in which a solvent mixture of formic acid, phosphoric acid and optionally water is prepared, and a solubilization process of fibrous fibroin in said solvent mixture is carried out; a filtration unit (3), for carrying out an ultrafiltration process of the solvent mixture containing fibroin and preparing a water solution of fibroin; and a circuit (4) that connects the mixing unit (2) and the filtration unit (3).
12. An apparatus according to claim 11, wherein the filtration unit (3) comprises a ceramic membranes tangential filter (30), provided with ceramic membranes columns defining semipermeable membranes and having pores of dimensions such as to allow passage of formic acid and phosphoric acid, but retain fibroin.
13. An apparatus according to claim 11 or 12, wherein the mixing unit (2) comprises a process tank (5) and a temperature adjusting device (11) for adjusting the temperature of the fluid contained in the tank (5).
14. An apparatus according to claim 13, wherein the temperature adjusting device (11) comprises: an outer jacket (12) positioned around at least one bottom portion of the tank (5); a cooling circuit (13) that circulates cold water in the jacket (12); a heating element (20) housed in the jacket (12) for heating the water in the jacket (12); a temperature sensor (21) associated with a control module (22) that controls the temperature adjusting device (11).
15. An apparatus according to claim 13 or 14, wherein the circuit (4) comprises a delivery branch (41), that connects an outlet (9) of the tank (5) to an inlet (42) of the filtration unit (3), and a return branch (43), that connects an outlet (44) of the filtration unit (3) to an inlet (45) of the tank (5), for recirculating to the tank (5) the fluid passed through the filtration unit (3).
16. An apparatus according to one of claims 11 to 15, wherein the circuit (4) further comprises: an auxiliary filter (46), arranged upstream of the filtration unit (3); a circulation pump (47); a control valve (48), for example a membrane valve, positioned downstream of the filtration unit (3) and adjustable to maintain a preset filtration pressure in the filtration unit (3).



3.2.2 Exploiting textile production wastes

As mentioned in 3.2.1, silk is usually known as a natural fiber used in textile, however it is, first of all, a bio-material. Silk is composed of two proteinic molecules, i.e. fibroin and sericin, both produced by the glands of silkworms Bombyx Mori reared in captivity. Sericin is an amorphous protein, it is separated from fibroin using a process called degumming. On the other side, fibroin is the protein that constitutes the fibrous part of the silk and is characterized by high physical-mechanical properties, high chemical stability, high level of bio-compatibility, high level of cellular adhesion (resulting into great performances in cellular cultivation and preparation of scaffolds), filming and skin-protection functions, easy miscibility with other natural and synthetic polymers, easy miscibility with other substances (anti-bacterial, anti-fungal, antibiotics) also stimulating healing and epithelisation. All these properties make fibroin suitable for the preparation of fibrous, colloidal, idrogel and spongy supports and of micropowders structured in microspheres or micro-capsules (both pure or in blends with other polymers), promoting a positive therapeutic action in

the treatment of ulcerative pathologies and many affections of the skin.
The market of solution for the treatment of skin pathologies is highly heterogeneous, ranging from pharmaceutical products to cosmetic compounds, and a clear estimation of the overall market size is difficult to be performed. Despite the effectiveness of the preventive actions, the number of persons affected by skin pathologies is increasing yearly. This is mainly due to the increasing of aged population and from a growing incidence of diseases like vascular, obese, diabetic pathologies, … causing bedsores.
Instead of using raw silk yarn, it is possible to exploit silk production wastes coming from throwing and twisting companies. These by-products amount for several tons per year, far more than the amounts required for producing fibroin-based medical devices for bedsores treatment.
An initiative was set up together with industrial and research partners from the textile industry aimed at developing a new process intended to process the silk by-products gathered from selected silk manufacturers.
The scraps of 100% raw silk coming from twisting companies are really similar to the raw silk yarn coming from the reeling of cocoons or to the fibrous material coming directly from the barks of the cocoons. During weaving, instead, the material can treated with oiling substances, anti-static and transient colorants. The oiling and anti-static agents are applied to the raw silk thread to favor smoothness (reduction of friction coefficient) and, therefore, the workability in machining of twisting and weaving. The antistatic substances favour the dispersion of the electrostatic charge, which is produced by rubbing of the wire on the mechanical parts of the twisting machines and weaving, while the dyes primarily serve to distinguish the direction of twist (S or Z), imparted to wires in the twisting, and distinguish, also, the various types of twisting procedure (frizzy, the organzines, hair, etc.). They are called "fleeting", because they do not attach to silk as the dyes used in the dyeing and printing, as they must be completely eliminated in the degumming process of silk, as would otherwise interfere with the color of the dye. Pursuing the purposes of obtaining silk fibroin good for medical devices production, the raw silk waste must be degummed process to remove sericin and other soluble natural substances (contaminants). The currently used industrial methods for degumming are based on the use of a Marseille soap bath with bath ratio of 1:20 to 1:50 for one or more hours at 98 ° C. To completely eliminate the soap from the degummed silk, avoiding the hydrolysis and precipitation as calcium salts, it is hot-washed with an ammonium-based bath. A second method contemplates the usage of synthetic surfactants in place of the soap, with addition of alkali as the high pH favors the degumming and the elimination of oiling, however, if it exceeds pH 9.5 to 9.8 degradation of the solubilized fibroin is caused, with loss of the mechanical characteristics of the wire.
An alternative method used to burn rubber yarn is to treat them in an autoclave under pressure (about 1.4 bar) at a temperature of 120 ÷ 130 ° C for about one hour. In these conditions the sericin solubilizes, the oiling however are not completely eliminated and, therefore, it is preferred to add the surfactant and alkali to also eliminate these substances. These degumming processes have been also studied in an acid environment or with enzymes, but these alternatives are not as effective as those with surfactants and alkalis. The ideal degumming process to preserve the fibroin and to eliminate other contaminants is, therefore, to process the silk only with water at high temperature ± 125 ° C (5 ° C). Making two 30-45 °C treatments by changing the bath and by performing one or two rinses with warm water is obtained with the fibroin sericin residues of less than 1-2%. For the scouring of the scraps treated with oiling and odorants fleeting the best process, identified after a careful study, is to always drift with two cycles at 125 ° C ± 5 ° C, but raising the pH to 9.8 with 2 g / l of sodium bicarbonate and 2 g / l of sodium carbonate. These alkali form a buffer that maintains constant the pH during the entire cycle and are almost completely eliminated by thorough warm washing, and a final rinse. The only sodium bicarbonate provides, instead, only a pH of 8.6, insufficient to purge completely to the bottom. At the end of the process of degumming the silk pH (now almost all fibroin) it is 7.5 ± 8.5 and extractables in solvents is ≤ 0.2%. It is important that the raw silk has not been treated with substances that make sericin no more soluble (e.g.: aldehydes), otherwise it is not eliminated by the degumming processes. The loss to the degumming is ca. 25% by weight with respect to the initial raw silk for the only sericin. When the silk scraps are mixed with other fibers (polyester, cotton, etc.), the degumming process is no more able to result in pure fibroin silk.

The fibroin obtained after treatment of degumming and eventual mechanical weakening by the hydrolysis of native silk Pad, or from cocoons or raw silk thread is to be conveniently milled into particles less than a millimeter before undergoing subsequent micro milling (with any other components) to achieve the final formulation of the product.

The burr serum present in the cocoon (and hence in the pad or in the raw silk thread) is formed by two filaments of fibroin, which are separated following the removal of the sericin that agglutinates them, in the treatment of degumming. The fibroin yarn has triangular section and transverse dimension of 8 to 12 pm, while the longitudinal dimension is to be considered infinite (hundreds of meters).

The title of the single yarn is 1 to 1.5 dtex and his tenacity, and when it is not weakened, it is at least 3 cN / dtex. The high ductility (≥20%), formability and plasticity even at extremely low temperatures make silk not weakened mechanically, impossible to shred or grind with a crushing systems, while it may only be shredded with a knife / cutting system.

To grind the silk for our purpose, it is adequate the use of a laboratory mill. Grinding takes place in a circular chamber (diameter of about 13.5 cm and depth 9.5 cm) where the fibroin coarsely cut with scissors in clusters of 2-10 cm is loaded by gravity into the grinding chamber through a hopper, while the unloading of milled fibers takes place from below through a semi-circular grid also in ST 1.0353 steel with light mesh 1 or 0.25 mm.

The dry fibers after a first cutting / tearing at the entrance of the grinding chamber create into small balls, but undergo subsequent cuts as they are pushed by the centrifugal vortex generated by the rotation of the inner rotor (optimum speed for silk 1500 ÷ 2000 rev / min), on the walls of the room and gradually affected by the sharp blades of the rotor and the fixed counter-blades in the chamber.

When the fiber fragments have reached similar lengths in the light of the mesh of the grid, they manage to escape from the grinding chamber and fall by gravity into the collection bin.

At the end of the ground it is collected in food-grade polyethylene bags, sealed by knotting before eliminating the majority of air. The dry fiber milled and packaged is kept unchanged for an extremely long time (years) in a cool, dry place, away from light.

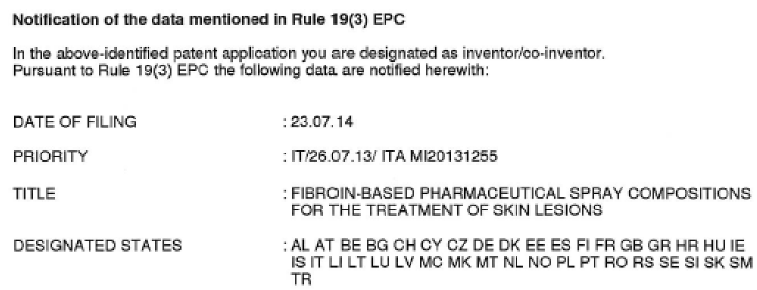
Using this processed fibroin as a raw material, an innovative medical device has been designed and patented as described below.

ID: MI2013A001255

TITLE: FIBROIN-BASED PHARMACEUTICAL SPRAY COMPOSITIONS FOR THE TREATMENT OF SKIN LESIONS

Claims:

1. A composition nebulizable from pressurized canisters, comprising fibroin co-micronized with an alginic acid salt, a micronized calcium salt and a silver and/or copper source.
2. A composition according to claim 1 wherein the alginic acid salt is selected from sodium alginate and calcium alginate, preferably sodium alginate.
3. A composition according to claims 1 - 2 wherein the calcium salt is selected from gluconate, ascorbate, glucoheptonate, dobesilate, glucobionate, levulinate, lactate, lactobionate, pantotenate, ketoglutarate, borogluconate, preferably calcium gluconate.



Notification of the data mentioned in Rule 19(3) EPC

In the above-identified patent application you are designated as inventor/co-inventor.
Pursuant to Rule 19(3) EPC the following data are notified herewith:

DATE OF FILING	: 23.07.14
PRIORITY	: IT/26.07.13/ ITA MI20131255
TITLE	: FIBROIN-BASED PHARMACEUTICAL SPRAY COMPOSITIONS FOR THE TREATMENT OF SKIN LESIONS
DESIGNATED STATES	: AL AT BE BG CH CY CZ DE DK EE ES FI FR GB GR HR HU IE IS IT LI LT LU LV MC MK MT NL NO PL PT RO RS SE SI SK SM TR

4. A composition according to one or more of claims 1 to 3 wherein the preferred dimensional range for silver and/or copper is nanometric.
5. A composition according to one or more of claims 1 to 4, wherein the silver source is metal silver or silver phosphozirconate.
6. A composition according to one or more of claims da 1 a 5 wherein the fibroin to alginic acid salt weight ratio ranges from 1:9 to 4:1.
7. A composition according to one or more of claims da 1 a 6 wherein co-micronized fibroin and alginic acid salt amounts to 80 - 97.5%, preferably 90 to 95% on the composition total weight, the calcium salt weight percentage ranges from 2 to 20% and the silver or copper source weight percentage ranges from 0.05 to 0.5% on the composition total weight.
8. A composition of the above claims for use in the treatment of vascular ulcers, skin lesions, bedsores, psoriasis, dermatosis and burns.

9. A process for the preparation of the compositions of the above claims, which comprises the following steps:
   a) micronizing fibroin previously degummed, destructured and ground;

b) co-micronizing fibroin from step a) with an alginic acid salt;
c) adding a calcium salt and a silver and/or copper source previously micronised mixture to the co-micronized fibroin and alginate product;
d) adding optional excipients and distributing in pressurized canisters with a gas propellant.

10. A process according to claim 9 wherein step a) is effected in a gas jet micronizer, where the gas is typically nitrogen, with pressure of 5 to 15 bars.
11. A process according to claim 9 or 10 wherein step b) is effected in a gas jet micronizer, where the gas is typically nitrogen, with pressure of 5 to 15 bars.

3.3 Business modelling for sustainability and sustainable clusters for industrial symbiosis

Within a EU-funded project (Horizon 2020) called Symbioptima, a new business model has been defined intended to be adopted by clusters of process industries. In this paragraph, business models adopted in eco-industrial parks have been examined and a proposal for a symbiotic approach exploiting sustainability potential is described.

3.3.1 Current industrial agglomeration approaches

Since the middle of the 19th century, various experiences are reported of industrial activities grouped in specific industrial areas, estate or parks, with varying agglomeration sizes. The number of this clustered assets is still steadily increasing worldwide and many of them are being planned, built and managed with various scopes, ranging from effective service provision, economies of scope, concern for resource efficiency and their impact on the environment.
Various studies addressed this phenomenon, also with the goal to reach a classification of these different forms of companies cooperation and agglomeration approaches, namely collaborative patterns. Proposed taxonomies rely on different dimensions: size of the agglomeration, scope, kind of governance, trigger of the initiative, etc.. In fact, cooperation may be motivated by environmental policies or specific problems such as waste management ([104]) it can occur spontaneously, as in Kalundborg (Denmark), where each business connection has been negotiated as an independent deal ([97]), or prompted by the government. As a result, collaborative patterns in industrial areas have been identified using different names such as eco-industrial networks, industrial ecosystems, environmental parks, and others, which will be discussed later in this chapter.
In parallel to these taxonomy-searching analyses, many studies have been performed in the last two decades in order to both understand and support the establishing of networking platforms of manufacturing companies. In particular, in 2010 the ERA-Net ECO-INNOVERA initiative was launched to support the creation of eco-innovation parks in Europe. Also the Swiss Federal Office for the Environment performed a study analysing existing industrial parks worldwide that develop integrated solutions to improve their environmental and socio-economic performances (a number of 168 parks among more than 300 have been selected according to this criterion).

Different types of industrial agglomeration are presented below and briefly described according to ([99]) and ([108]). The description has been focused on the peculiarities of each instance: no univocal taxonomy or description scheme has been found in literature, thus the main characteristics of each agglomeration are here reported in order to be easily analysed.

Industrial park	
Cooperation among legally independent enterprises which share different infrastructural facilities such as sewage system, wastewater treatment plant, pipeline network, …([103]). Within the park, a park managing company provides several services such as site security, logistics and maintenance, and infrastructure such as roads, pipelines, water supply and energy. The industrial park is formed by multiple suppliers of usually one single customer. Its development is pushed in a planning manner by the site developer and local municipalities.	Cooperation among companies Facilities sharing No exchange of resources Interest in new opportunities of improvement of the profitability of the existing companies Improvements of companies' economic benefits

Industrial cluster - industrial district	
An industrial cluster is a regional agglomeration of independent companies belonging to a specific sector ([95]). The main element of an industrial cluster is the anchor industry that forms the cluster and push the other grouped companies to collaborate. The most important difference between industrial cluster and industrial park is that the cluster has no integrated planning or collective objectives. Moreover, inside the cluster infrastructure or facilities are not shared. Similar to the cluster, the district is a geographic area developed by municipalities formed by companies coming from different sectors, without establishing business relationships between them.	Cooperation among companies No sharing of facilities No exchange of resources No interest in sustainability improvements
Industrial estate	
The industrial estate is a large tract of land, subdivided and developed for the use of several firms simultaneously, distinguished by its shareable infrastructure and the close proximity of firms ([93]). The industrial estate is developed by an external manager that provides the necessary infrastructures such as roads, transports and public utilities. Moreover, the zone manager is responsible for site planning and development, approval and supervision of tenant companies. The industrial estate is developed following a specific plan based on environmental aspects and performance standards.	Infrastructures sharing Optimization of economic benefits Improvements of companies' economic benefits No cooperation among companies No exchange of resources
Free economic zone	
The free economic zone is a restricted area developed in order to realize economic and political objectives. The zones are focalized on economic activities for one or more sectors and designated by trade and commerce administrations. The free economic zones can be divided into enclave and open zones. The first ones are characterized by closed customs supervision, the second ones, instead, are separated areas and follow special but not closed customs supervision policy ([100]).	Cooperation among companies Improvements of companies' economic benefits Interest in new opportunities of improvement of the profitability of the existing companies No facility sharing No exchange of resources
Industrial ecosystem	
Web of interactions among companies where the residuals of one facility become feedstock for another. Industrial ecosystems aim to minimize inefficiencies and the amount of waste created by mimicking natural ecosystems in industrial systems ([98]).	Cooperation among companies Exchange of resources and by-products Facility sharing Improvements of companies' economic benefits
Eco-industrial park	
An eco-industrial park (EIP) is a community of manufacturing and service businesses seeking enhanced environmental and economic performance through collaboration in managing environmental and resource issues, including energy, water and materials ([98]). By working together, the community of businesses seeks a collective benefit that is greater than the sum of the individual benefits each company would realize whether optimizing only its own performances. The goal of an	Cooperation among companies Exchange of resources and by-products Facility sharing Optimization of environmental and economic benefits Interest in new opportunities of improvement of the profitability

eco-industrial park is to improve the economic performance of the participating companies while minimizing their environmental impacts. Components of this approach include new or retrofitted design of park infrastructure and plants, pollution prevention, energy efficiency and inter-company partnering. Through collaboration, this community of companies becomes an industrial ecosystem. Similar to this park is the integrated EIP, whereas the term integrated refers to cogeneration, energy cascading and recycling opportunities through inter-firms collaborative patterns.	of the existing companies
Eco-industrial network – Industrial Symbiosis	
The term "eco-industrial network" [EIN] describes a resource exchange network (often structured as an EIP) at regional scale that does not strictly require geographical proximity and allowing the implementation of Industrial Symbiosis (IS). Given that IS is the distinguishing characteristic of EIN, this kind of networks is synecdochely identified as "IS". The term IS has been coined in 1989, when Valdemar Christensen, production manager at the Asnaes Power Station (Denmark), used it to describe this particular behaviour in the Kalundborg eco-industrial park. IS focuses on the flow materials and energy from local and regional economies. IS traditionally engages separate industries in a collective approach to a competitive advantage involving physical exchange of materials, energy, water, and/or by-products as well as services and infrastructures shared at the industrial park scale to reduce environmental impact and overall production cost. The key factors for IS are collaboration among actors and the synergistic possibilities offered by geographic proximity ([91]). The exchanges among companies could also include exchanges of knowledge and other resources and on the shared utilisation on infrastructure and logistical elements ([102]).	Cooperation among companies Exchange of resources and by-products Facility sharing Optimization of environmental and economic benefits Interest in new opportunities of improvement of the profitability of the existing companies

Considering such concepts, the presented study will mainly focus on the analysis of EIP and EIN/IS real cases. These ones are characterized by at least the following factors:

- cooperation among companies;
- physical exchange of materials, energy, waste, and by-products;
- exchanges of knowledge and shared utilization of infrastructures;
- possible optimization of the environmental and economic benefits;
- possible improvement of the profitability of the existing companies;

that are all requirements for a symbiotic implementation scenario, where the results are applied to a network of companies interested in optimization of resources.

The analysis of existing industrial parks suggests that EIP usually pursues profitability growth, reduction of environmental impacts and improvement of social performances over three levels: for the single company, for a network of companies and for the community. A deeper analysis of EIP has covered the last decade exploring alternative approaches to design EIPs, to simulate their behaviour, to evaluate existing IS and to identify enabling factors for the successful development of EIPs. Also different optimization approaches have been studied in these last few years, focused on finding the by-product exchange networks in EIPs that maximize economic and environmental performances. A recent review of such approaches has been presented in [96]. Considering these elements, in order to provide a comprehensive but still simple describing approach, developed a first framework intended to describe the EIP constituting elements (Figure 21) and their relationships and a second one focussing on the possible IS relationships (Figure 20).

The EIP (Figure 20) is characterized by positive economic, environmental and social performances (with respect to companies operating autonomously). Such features can create value for different stakeholders, that are companies, local government, local community, social groups interested in environmental performances. For this reason, all these actors are interested in the development of the EIP, in particular in its value creation, and can affect EIP depending on their ownerships, power and specific interest. They have different relationships one with the others (competing, cooperating, or indifferent - collaboration between companies is a prerequisite) and can exchange value (financial, goods and services). The EIP can have a governing body that oversees the EIP development and operation and usually consists of EIP company members. Another element that influences an EIP development is the location of the park, addressed by the "Geography" block of the scheme. In fact, it influences the costs of infrastructures, depending on the topology of the land, the presence of pre-existing industries with qualified personnel and established transportation infrastructures, and the ownership of lands. Moreover, EIP development activities can be financed by third parties using alternative debt and equity financing schemes ([101]).

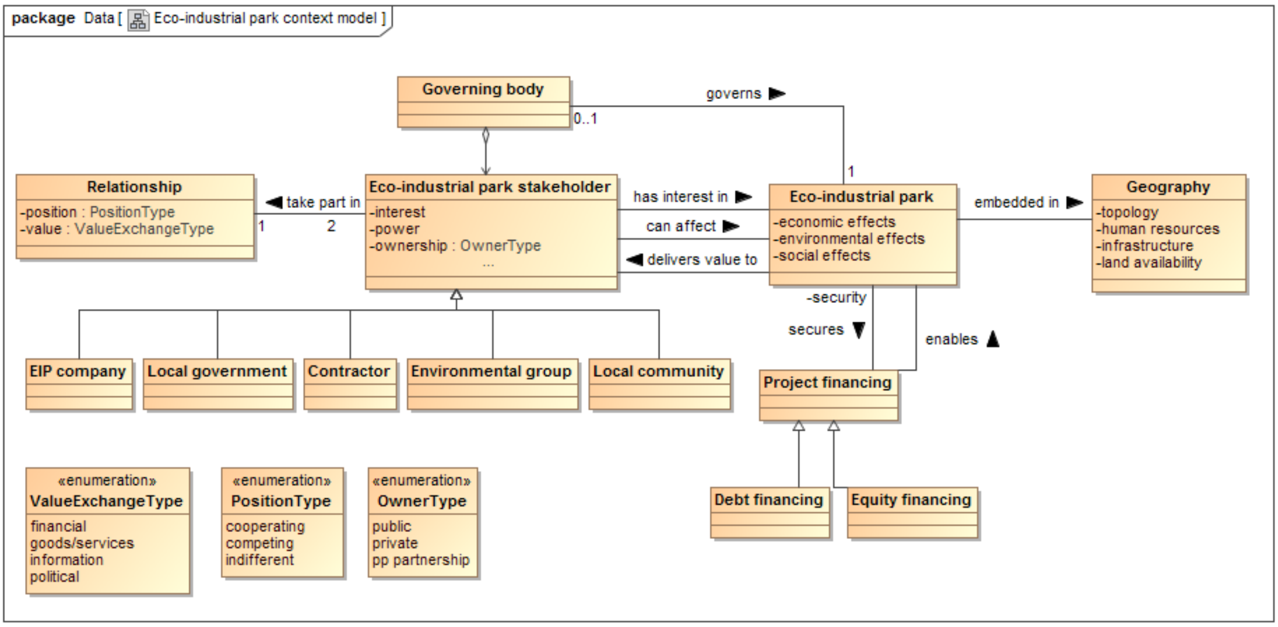


Figure 20: EIP context model

As mentioned, IS is a possible feature of a network, namely one of the possible exchange relationships among stakeholders that is able to generate value for stakeholders. A proper IS describing scheme has been developed (Figure 21) with the goal to highlight IS characteristics. Thinking about IS means focussing on a by-product exchange flow: thanks to IS, scrap or waste flows are qualified, thanks to a recovering scheme, by one of EIP/EIN partners, that gains values thanks to this action. To share this benefit with the supplying agent, the receiver can provide some form of compensation, for example informational, financial, political. Similarly to what happens with the EIP development, the creation of symbiotic flows may result in new costs for the construction of exchange infrastructure. Such investments can be funded by project financing methods and establishing public-private partnerships.

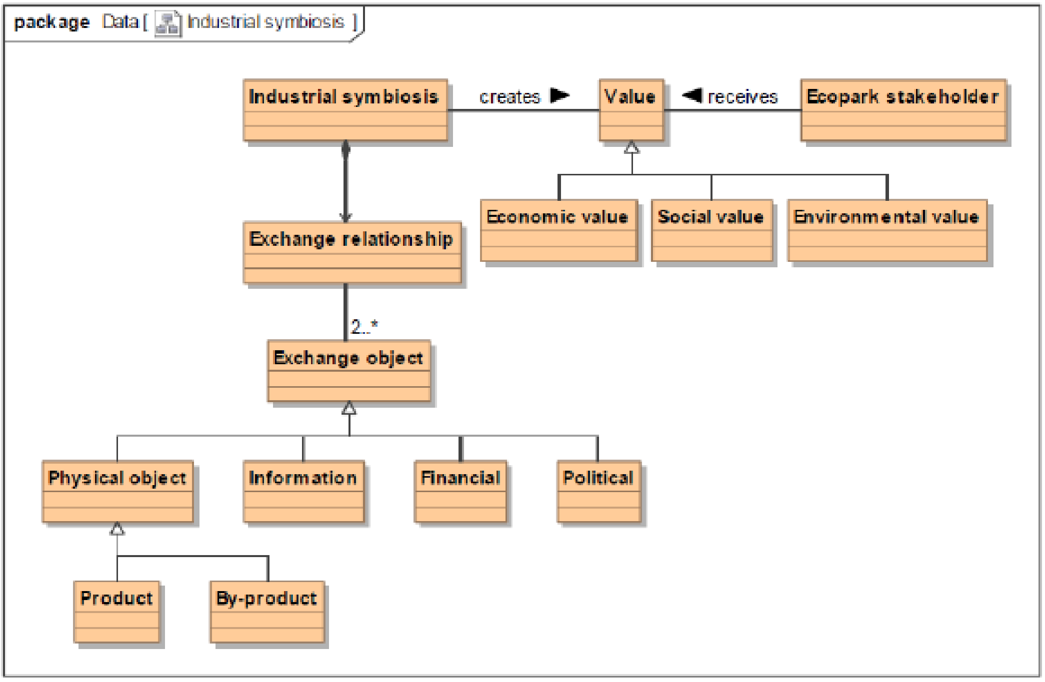


Figure 21: The IS model

The study of EIP and its relationships models allowed the identification of the main elements to be considered when analysing a collaborative pattern: actors such as the governing body, stakeholders and tenant companies; the elements constituting the park and necessary to enable flows and the creation of relationships such as the IS, financial schemes to fund the park investments, and the values that characterize the park. In Figure 22 a conceptual framework has been depicted, gathering in one single canvas all these elements. This framework is also suitable for describing all the agglomeration types mentioned before, since its constituting blocks allow to highlight the differences in terms of both aggregation and cooperation.

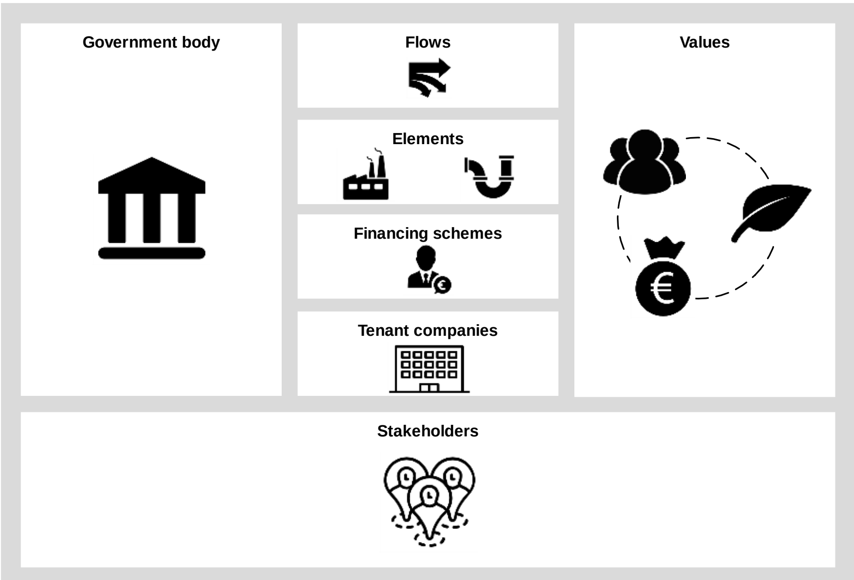


Figure 22: General conceptual framework for industrial agglomeration

Elements forming the canvas are here described.

Government body: it is responsible for the management of relationships among stakeholders. It can be: (i) a council of tenant companies, (ii) an external service provider, or (iii) the (local) government. Their main roles may vary in terms of pervasiveness, degree of ownership (of flows and infrastructures), bestowed decision power. At a high level, this entity is usually responsible of the construction of new infrastructures (at least of commissioning and controlling), searching investors, and managing the collaboration between companies. If the government body is composed by a council of tenant companies, the EIP could be generally described as a self-organized park, where companies decide and contribute together to the benefits of the park. If the park is under the control of a third company (which often provides land, infrastructures, roads, pipelines, etc.), this actor manages the collaboration and communication among the different tenant companies settled in the park, being also in charge of searching for new investments and new companies to be included in the park. When the government body is represented by local government, the situation is quite similar to the previous one, with a variation in the pursued scope: local authorities are usually interested in promoting the non-economic elements of sustainability (e.g. boosting local communities and environmental performances).

Tenant companies are groups of manufacturing firms, supply and treatment companies or service providers, participating in sharing facilities and exchanging resources. Their objectives are to increase personal profit, reduce the cost related to waste production, transport and warehouse, and create synergies with other companies. The role of tenant companies depends on the relationships established with the park governing authority. Tenant companies are usually customers of the park management entity (represented by the government body), even if they sometimes hold shares of it.

Stakeholders: different types of (other) stakeholders need to be considered when analysing a collaborative pattern. In particular, each actor directly or indirectly involved in the initiative can affect the achievement of the park goals. For the development of collective goals and strategies as well as network structures, it is important to understand the different roles and interests of all the most important stakeholders. Examples of stakeholders are: local community, banks, science and technology institutions, local government, universities, municipalities, etc..

Flows are the core of industrial cooperation initiative, especially ones addressing IS . They could be flows of general resources (energy, information, knowledge, etc.), by-products, wastes, and other kinds of material. Flows are instances of links between different companies within the park, regardless of the sector the play in or the product they produce. Flows also are the main reason of environmental, economic and social impacts production.

Elements: they permit to transport flows from a company to another one. Elements could be in general infrastructures such as pipelines, roads, railway, buildings, wastewater treatment systems, electricity grid, incinerators, power plants, by-products revalorization plants, and so on. They could be acquired and managed by the single tenant companies or by government body.

Values are the created environmental, economic and social benefits. Environmental values are, for example, related to a reduction of wastes and emissions caused by a by-product valorisation. Economic values are usually the result of a decreasing of production costs or of an increasing of profits. Social values include the involvement of the local community, generating, for example, new job opportunities thanks to the creation of exchanges between companies inside the park.

Financing schemes are the financial investments that allow a park to grow through new infrastructures, sustaining by-product and resources exchanges, etc.. Possible financing schemes could derive from the government, national and international actors, internal companies, banks, etc..

3.3.2 Methods and tools for symbiotic Business Models implementation

Exploiting the results of the conceptual framework developed and validated above, a further step towards the objectives of the task is performed. The questions we want to answer are: how does environmental park business model may include symbiotic approaches? How do they interact with, influence and modify the mapped components?

Actually, the symbiotic concept goes beyond the current approach to IS. Current IS development occurs spontaneously and such an approach is not sufficient (nor compatible) for the symbiotic park implementation.

Due to their hierarchical decentralization, none of the companies Production Units (PUs) has the chances to impose actions on other PUs: PUs are the controllers (decision makers) of their own behaviour. This opens the approach of symbiotic clusters, where decentralized decision making for the whole park is targeted towards an optimizing global behaviour.

For this reason, the exchange of flows must be governed by a (external) coordinator in order to obtain an overall optimization of the performances. As shown in Figure 23, the symbiotic behaviour of symbiotic clusters addresses an improvement of the overall sustainability performances of the adopting cluster. The main difference with the current approaches doesn't regard the number of companies involved in every flow, but the number of companies required to identify the different opportunities of symbiosis and the different approaches for the flows evaluation. In fact, flows are evaluated considering the overall network and not individually.

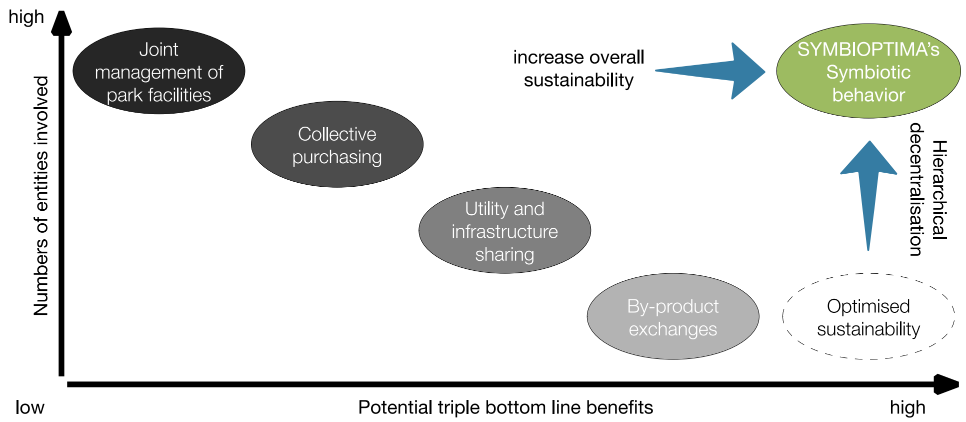


Figure 23: Collaboration levels and positioning in the graph of the "symbioptimized" behavior

Two different time levels are considered for optimization: in a first step, the optimization tool identifies all the possible matching flows considering a static condition guided by: an integrated approach to optimization; a multi-objective optimization strategy considering energy and flows of resources; the management of demand-responses aspects; the supply chain management.
In a second step, the tool manages all the flows in a dynamic way, considering all possible variations and changes along time (quantity, price, emissions, etc.). The continuous time monitoring and decision making are crucial aspects.
The static optimization must take into account this aspect through forecasting of: consumption of resources (raw materials, energy, water, steam etc.); price of resources.
The most important variations could be the availability and the demand of by-products, or the variation of energy consumption. On the one hand, the static optimization identifies the possible optimal links; on the other hand, the dynamic optimization adapts the flows in order to achieve the optimum in every time unit, characterized by different demand and supply attributes.
Another criticality regards the availability of information. Considering the environmental and social KPIs, they do not usually use companies' sensitive information. Regarding economics KPIs, every company flow has its costs, quantity and source. To build the optimal scenario, all this information needs to be available and collected.
In a collaborative planning, information asymmetry can be a problem during the negotiation process. For example, in a by-product exchange, the buyer might be reluctant to share the raw material price with by-product supplier in order enforce its position. In the same way, the supplier might be reluctant to share its disposal, treatment and storage costs with the buyer for the same reason ([90]).
The same situation could happen for every sharable flow with its relative costs. To handle this kind of problem, **a coordinator is fundamental**, as represented in Figure 24.

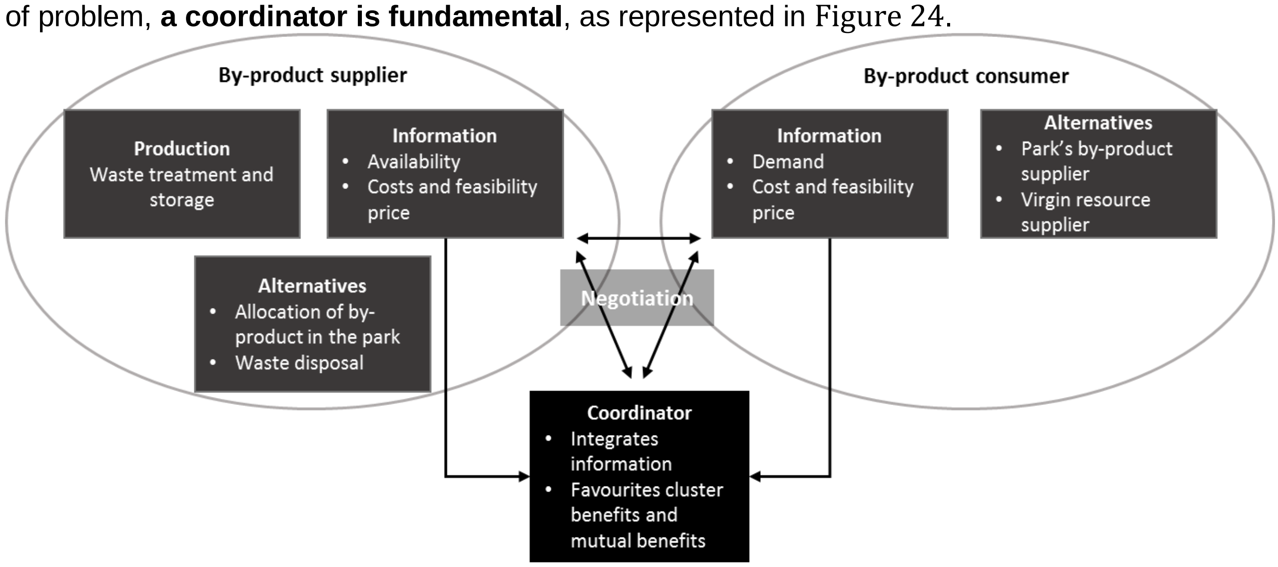


Figure 24: Role of the coordinator in information sharing

Other issues regarding economic aspects are critical. The optimization tool calculates the best scenarios of flows configurations and selects the optimal one considering sustainability performances (environmental, economic and social). A possible symbiotic cluster optimized solution may foresee flows that are not all sustainable from the economic point of view, if they are considered individually.
To better understand this issue, that is one of the most intriguing founding principles of the proposed approach, let's start with an example. The sustainability optimization tool suggests the deployment of a material flow between company A and company B, since it improves the overall sustainability performances of the park. Unfortunately, due to high infrastructure costs, this flow doesn't provide an economic advantage for both company A and B. If we rely on approaches towards IS that have been described above (spontaneity of aggregation, independence of each flow and economic benefits for companies involved in the IS), none of the involved actors would activate such a material flow: a sustainability-improving stream would be dropped. How should we force someone in the ecosystem to implement such an investment? Who pays for it? None of the examples reported in literature provides an answer.
In fact, when we want to quantify the sustainability performances of a flow, we need to "sum up" in a selected way KPIs measuring environmental, economical and social performances. The KPIs evaluated when calculating the optimal scenario must be tuned by weights that can be pre-defined or defined during the optimization by the coordinator entity. These weight values are assigned according to the network objectives (whether the main objective is to improve social impacts of the overall network, social KPIs will contribute with a higher impact than economic and environmental ones on the identification of the final solution). Actually, this means that a decision maker has to express how many kilograms of CO_2 emissions are equal to 1 job creation. This means that the optimization tool suggests to implement a set of flows, streams, interactions that optimize this indicator, also at the expense of economic benefits of some of the involved actors.
Actually, the integral and rigorous approach of overall optimization is not feasible if we don't modify the park business model: regardless of the overall sustainability performances, companies would not be interested in joining the network if they would derive economic loss.

3.3.3 Approaches for successful symbiotic principles implementation

The increase of overall sustainability proposed by our proposal encompasses environmental, social and also economic aspects. In this sense, the optimal configuration scenario must not select solutions that worsen one of the three aspects. Anyhow, in order to build a BM that fosters cooperation among companies, it is necessary to give particular attention to the economic aspect (competition of each company in their respective market is actually based on economics and financial elements).
The constraint that makes the Symbiotic BM feasible and allows an acceptable scenario for all the involved partners is:

The economic balance of N companies inside the IS network must be ≥ 0

that can be translated in the following equation:

$$\sum_{n=1}^{N} (Rsym_n - Rasis_n) - (Csym_n - Casis_n) \geq 0 \qquad \text{Eq. 1}$$

where:

n	Company involved in the symbiotic network	
With centralized symbiotic network optimization	$\mathrm{Rsym_n}$	n-company's gain obtained from all changed flows through sustainable optimization. It could come from: • New or changed by-product flows
	$\mathrm{Csym_n}$	Costs derived from all changed flows through the optimization. They could come from: • By-product purchase costs (they should be lower than raw material costs) • Energy costs (they should be lower than as-is scenario thanks to Smart grid tool and collective

		purchasing) • Instalment costs if a loan is necessary for an infrastructure investment • Disposals/emissions taxes (they should be lower than as is scenario thank to optimization of flows and by-product re-use) • Maintenance costs
Without optimization	$\mathrm{Rasis_n}$	n-company's gain obtained without changes on the flows identified by the optimizator. They could come from: • Still existent by-product flows
	$\mathrm{Casis_n}$	n-company's costs obtained without changes on the flows identified by the optimizator: • By-product purchase costs • Raw material costs • Energy costs • Disposals/emissions taxes • Maintenance costs

Eq. 1 indicates that the economic balance of the optimal scenario at least is the same of the AS-IS one. This doesn't mean only that all costs are covered, but also that the lack of profit must be repaid. More details are explained in the following paragraph. From Eq. 1 other important formulae are:

$$(\mathrm{Rsym_n} - \mathrm{Rasis_n}) - (\mathrm{Csym_n} - \mathrm{Casis_n}) = \begin{cases} \text{Operative Gain} & \text{if} \geq 0 \\ \text{Operative Cost} & \text{if} < 0 \end{cases} \qquad \text{Eq. 2}$$

$$(\mathrm{Rsym_n} - \mathrm{Rasis_n}) = \Delta\mathrm{R_n} \qquad \text{Eq. 3}$$

$$(\mathrm{Csym_n} - \mathrm{Casis_n}) = \Delta\mathrm{C_n} \qquad \text{Eq. 4}$$

Other aspects to consider are investments that companies incur. The unified vision allows to consider all the investments for different flows creation, part of a biggest one that all the network must sustain. In this way, it is necessary to introduce a second constraint:

Investments need to be repaid in a defined time lapse

that could be represented by the following equation:

$$\left(\sum_{t=1}^{T} \frac{Pnetwork_t}{(1+r)^t}\right) - I \geq 0 \qquad \text{Eq. 5}$$

where:

n	Company involved in the symbiotic optimization
t	Time units whose sum is equal to T that is the period after which it is possible to repaid the investments
r	Discounting rate
I	Sum of the investments necessary to implement the flows identified by the optimizator. For example, the costs for pipelines, grid, etc. The investment is supported at the beginning of the symbiotic initiative and it is repaid in the time unit T. More detail about who sustain the investments in the following paragraphs.
$\mathrm{Pnetwork_t}$	$\mathrm{Pnetwork_t} = \sum_{n=1}^{N} \text{Operative gain}_{n,t} - \text{Operative cost}_{n,t}$ Eq. 6

The unified vision allows to implement the flows that outside the context of the symbiotic network could not have been considered for economic reasons.

In this sense, the proposed business model consists not only of a group of tools, but it is also an enabler for symbiotic behaviour.
The proposed BM should also support economic transactions and contracts management in order to provide a balanced redistribution of economic benefits between all involved companies. To do this, it is necessary to introduce a new element for the BM, we call the "symbiosis-enabling *bank*".

3.3.4 The symbiosis-enabling *bank*

In this paragraph the bank functioning and its role during the execution of the BM, and consequently the adoption of the optimized solution, are explained. The main functions covered by the bank are the following:

- Management of revenues and costs: it manages the revenues of the companies adhering to the optimized solutions and redistributes the income to the same companies minus the costs of investments and maintenance;
- Calculation of companies investments share: it provides to the companies a comprehensive evaluation of the investment contribution through the Eq. 5.
- Provision of support to economic transaction and contract agreements: it provides support during the implementation phase of the symbiotic scenario helping companies in the contract stipulation and enhancing the communication among the different actors.

In order to ease the understanding of how the bank works, an explanatory situation is here described, considering 4 companies (A, B, C, D) that are "asked" to adhere to the optimization tool results. Before the execution of the optimization tool, companies could be (i) completely disconnected one from the other or (ii) connected in terms of flows exchanges (see Figure 25).

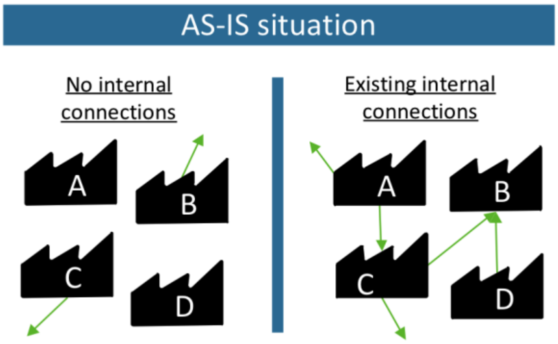


Figure 25: Examples of connections among companies within an EIP

The application of our approach results into an optimized flows configuration at network level. In order to analyse the bank behaviour, companies' operative gains need to be evaluated at time t_0 and at time t_{i+1} (actual or final situation), since operative gains are time-sensitive and change in time.
By using equation 2, it is possible to calculate *Forecasted Operative Gains (FOGs)* or *costs (FOCs)* for each company at time t_0. FOGs and FOCs that could change positively or negatively in time and at time t_{i+1} are called respectively *Actual Operative Gains (AOGs)* and *Actual Operative Costs (AOCs)*.
Two scenarios have been detailed in order to ease the understanding of the bank functioning:

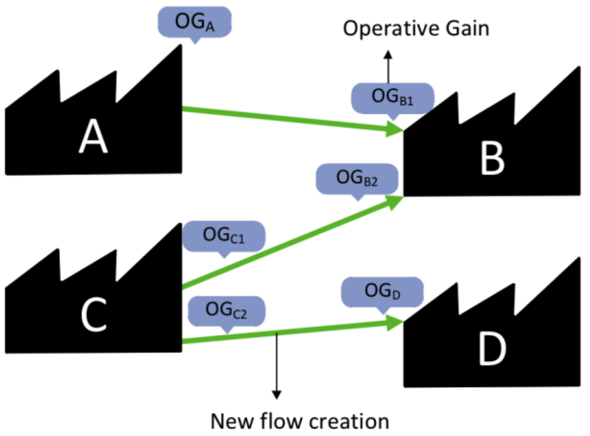
1. Best-case scenario: the optimization tool proposes a solution implying that all the companies involved in the proposed flows exchange configuration get only economic advantages;
2. General scenario: the optimization tool proposes a solution implying that one or more companies involved in the proposed flows exchange configuration get economic advantages but the remaining companies have economic disadvantages adhering to the proposed solution.

In both cases, environmental and social aspects are not considered, since overall network negative results concerning sustainability aspects are not feasible in the proposed context. But, as mentioned in the previous paragraph, looking at the single company, negative results, from the economic point of view, could occur.

Scenario 1: Best case

At time t_0 all the companies (see Figure 26 for a schematic representation) are expected to have only gains (these profits are related to lower material costs, lower energy costs, lower disposal taxes, etc.).

Figure 26: Scenario 1



New flows and connections could be already available, but others need to be created and investments are necessary. The entire amount of the investments is in charge of the single involved companies proportionally to their own FOGs. For example, in companies are supposed to have different FOGs. The single contribution of the companies to the whole investment is calculated through the equation below.

$$\%FOG_n = \frac{FOG_n}{\sum_n FOG_n} \qquad \text{Eq. 7}$$

Company	FOGs	% contribution	Final company contribution
A	10	$\%FOG_A = 25\%$	$ContrA = \%FOG_A * I = 25\% * I$
B	4	$\%FOG_B = 10\%$	$ContrB = \%FOG_B * I = 10\% * I$
C	8	$\%FOG_C = 20\%$	$ContrC = \%FOG_C * I = 20\% * I$
D	22	$\%FOG_D = 45\%$	$ContrD = \%FOG_D * I = 45\% * I$

Table 8: Investment contribution calculation

Since FOGs could vary at $t_{i+1,}$ the distribution of investments contributions has to be recalculated and potentially adjusted. This adjustment can be made every predefined time period (adjustment period) calculating the FOGs variations from time t_i to t_{i+1}.
How to manage the differences between AOGs and FOGs? In order to avoid companies retain FOGs and re-invest or spend them during the time between the execution of the optimization and the first adjustment, thus not having sufficient liquidity to fix potential negative variations between AOGs and FOGs, FOGs are expected to be managed by the bank. In particular, the bank is entitled to collect companies' FOGs, pay occurred costs (e.g. maintenance), and redistribute the remaining amounts of money to companies at t_{i+1}.

Scenario 2: General case

As shown in Figure 27, when our approach is implemented (TO-BE Forecasted condition) the four involved companies could have advantages or disadvantages in economic terms. In this specific example one of the companies (A) has economic losses (FOC), while the others have advantages (FOGs). It is clear that in this case the sum of the operative gains is major than the operative costs, because of equation 1. The bank is in charge of withdrawing FOGs, withholding AOCs paid by company A during the adjustment period (balancing the losses of the company occurred due to the implementation of this solution), eventually distributing the remaining amount of AOGs.

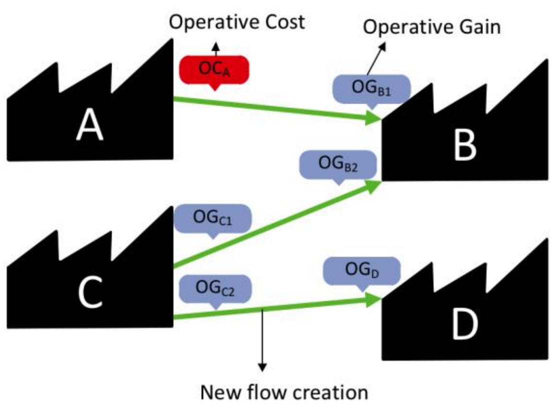


Figure 27: Scenario 2

In this case, investments are covered only by the companies that have FOGs (Company B, C, D), leaving out companies which does not have economic advantages (Company A) in adhering to the proposed solution. The percentage contribution to the investments of the single companies is calculated according to Eq. 7, as for the previous scenario, considering only the FOGs.

Main bank flows

The previous scenarios give a description on the distribution of investments and costs between tenant companies according to their advantages and disadvantages when adhering to the optimized solution. Summarizing, the companies with operative gains transfer their gains to the bank that, at first, re-pays operative costs and pays maintenance of infrastructure (considering only the costs that are accountable to the coordinator[4]), and then distributes the surplus to participating companies. The investments are repaid according to Eq. 5.

According to the defined constraints, operative gains are higher than operative costs. Therefore, the bank has to manage the surplus defined as $Pnetwork_t$.

$Pnetwork$ could be distributed proportionally to four different elements:

- $\%_1$: coordinator revenue
- $\%_2$: reward to companies based on their operative gain
- $\%_3$: reward to companies based on compliance with choices suggested by the optimization tool
- $\%_4$: deposit for future investments

Every percentage should be decided by the coordinator in agreement with selected stakeholders, in particular with tenant companies and investors.

Coordinator revenue

According to our approach adoption, it is necessary that an entity manages its tool and coordinates the development of the network. The cost of this entity are compensated through the companies' operative gains generated when adhering to the proposed optimal solution. The coordinator is a private company, it is necessary to guarantee him a profit.

Reward to companies based on their operative gain

Companies with operative gains are the only ones that contribute to investment. These must be re-paid in order to guarantee a return on investment in a defined time unit T. The reward to every n-company, in the time unit t, is calculated through the following formula:

$$Reward\ based\ on\ operative\ gain\ for\ company\ n = \%_3 * \%FOG_n * Pnetwork_t \quad \text{Eq. 8}$$

Reward to companies based on compliance with choices defined by optimization tool

The optimization tool provides, for every time lapse, an optimal configuration of flows. The realization of every flow depends by companies' actual choices. The symbiotic cluster monitoring tool and the coordinator need to control how much every company's flow is compliant with the optimization result. This aspect is crucial. If a company does not follow instructions of the tool, the overall network is affected. It must be considered that there will be some contracts that define the main commitments and duties of a specific company, but it is not likely they regulate every specific flow.

In order to prevent the creation of sub-optimal scenarios and to foster companies to fully collaborate, it is necessary to use a rewarding system based on compliance with choices defined by the optimization tool. For every time lapse, it is necessary to measure the difference between what the tool has proposed and what really happens. In fact, companies can decide if adhering or not to the solution proposed by the optimization tool. Thanks to the reward based on compliance to symbiotic optimization, the coordinator could decide how to penalise the incompliant companies. Penalty definition should be based on overall sustainability performances losses, impacts on the network and difference between the company's behavioural choice and the suggested behaviour. It is necessary to consider also the existence of contracts, which could include penalisation rules in case of incompliance.

Deposit for future investments

A part of the profit could be saved for future development in order to avoid or decrease companies' investment.

[4] Non-accountable costs are maintenance costs of infrastructures owned by one of the tenant companies and that are not accountable to the coordinator but cover by the tenant company that owns those infrastructures.

In Figure 28 the main flows that characterize the bank are represented. Three types of flows are considered:

- Information flows: flows that allow to quantify costs, revenues and contributions of each companies.
- Cash flows at t_0: cash flows that allow to implement the network in the initial phase.
- Cash flows at $t_{\square+1}$: cash flows that allow to maintain the flows, reward companies and make profit for coordinator.

Every specific scenario could include or not all flows, depending by decision making entity. It must be considered that all incurred flows and their related amount of gain have a relevant impact on scenario's development. The definition of the percentages of rewarding to companies and coordinator revenue could have a huge impact, too: these values must be chosen with particular attention. A wrong decision could preclude the involvement of some companies, that require a higher retribution. Otherwise, excessive redistribution of network profit revenue to companies, based on % of operative gain, reduces the possibility to have a strict control on companies' compliance and to increase the amount of money hold for future investment.
Since the profit of the network is equal to the sum of the 4 above-defined shares, if $\%_2$ related to the companies' operative gains is high, the others shares are lower as consequence. In this sense, the lower is $\%_3$ related to companies compliance, the lower is the chance that companies are compliant with the optimum scenario. If companies receive a small reward for their compliance with tool suggestion, probably they are not enough motivated to behave in the suggested way.

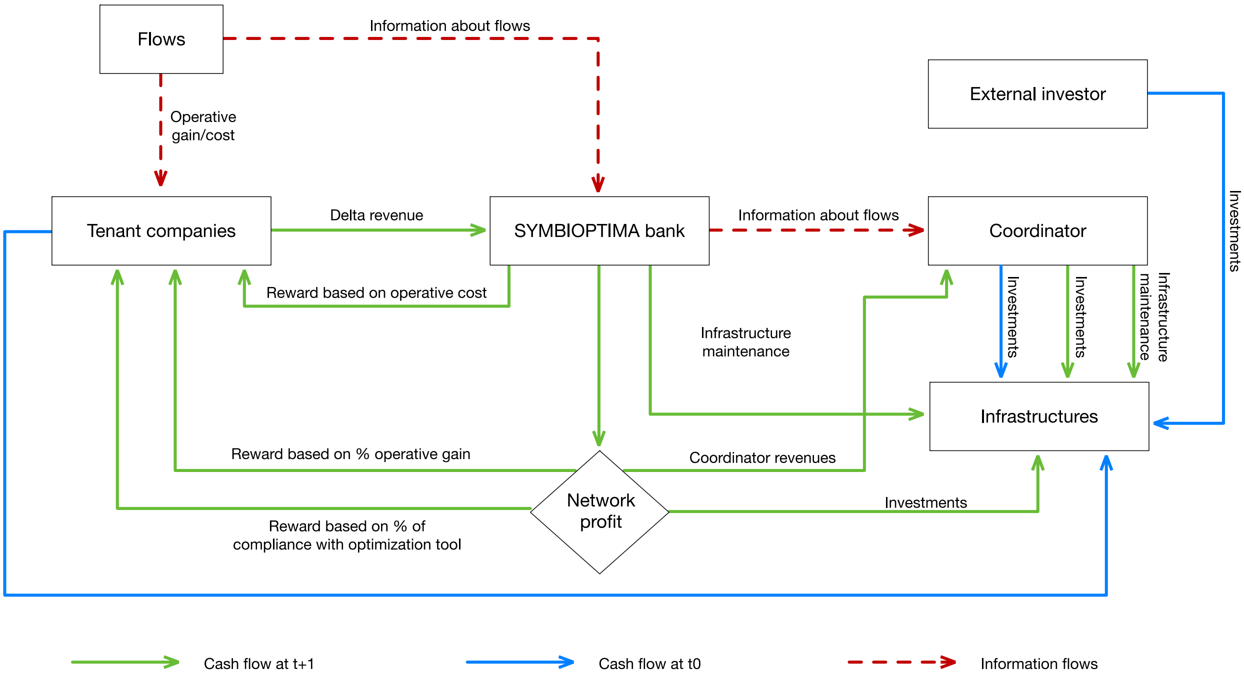


Figure 28: Main bank flows representation

Why not a sustainability-based rewarding?

The proposed approach is based on the optimization of economic, environmental and social performance of a network of companies. The rewarding system presented in the previous paragraph is based only on an economic perspective. This choice is performed starting from the following considerations:

- The optimization results from the sum of the contributions of the single companies in terms of realized activities and flows. These are based on what the optimization tool suggest to do. The single company's performances are responsibility of the optimization tool choices. As [94] states, it is not right rewarding or not-rewarding an entity for choices that it does not make.
- Which are the companies that contribute more to the creation of the specific flow? The merit of the creation of a new flow could not be assigned to one of the involved companies.

For every flow there are some companies that receive a flow as an input, others that yield it as an output.

- The contribution to sustainability could not be calculated as a unique KPI. Environmental, economic and social KPIs are dimensionally different and quantitatively comparing them is critical. For example, it is not possible to affirm if the emission reduction of CO_2 is more or less relevant than the increase of job creation.
- The corporate behaviour is based on an economic perspective. The calculation of rewarding percentage is based on companies' operative gains, as well as the contribution to investment and maintenance. If the rewarding system is based on sustainability contribution, probably the companies that are also investors are not re-paid proportionally with their effort because part of the total revenues is given to the companies that contribute to environmental or social aspects and not to the investment.

Investments

As Heress states in [106], EIP projects initiated by companies with only financial and advisory support from government and university are more successful than those initiated by governments that see the project as a way to improve regional economy and increase job opportunities and promotes an unattractive agenda from the companies' perspective.

Despite this, an involvement of public sector is necessary for a good development of the proposed symbiotic vision. To build the infrastructures such as pipelines or grids, necessary for the creation of the collaborative network, some permissions and authorizations, and also some investments, could be necessary, coming from: (i) companies; (ii) government; (iii) lenders; (iv) sponsors and investors; (v) the bank. The role of each of these actors could be different for every specific scenario and it should be analysed with a particular attention:

(i) Companies: the best way for symbiotic cluster development is that companies sustain all the costs and investments required in order to maximise the self-sufficiency and independence. If a company uses a loan to sustain the investment, it is not seen as a direct involvement of a lender, because the contribution still comes from the company.

(ii) Government: in many cases the provision of incentives is necessary and they must be managed through a specific contract. In this case, the entities, that provide the investment, usually impose some constraints, that must be taken into account during the optimization phase. In many cases it is necessary that the government guarantees a minimum payment to involved private companies in order to foster their cooperation ([107]).

(iii) Sponsors and investors: every project could have a company or an entity that has particular interest on its development. For example, for electricity grid development, the energy distributor could contribute to its construction.

(iv) Lenders (if the business model is adopted by an independent entity): banks and specialized lending institutions should contribute to the investment. In this case, the debt is owned by the coordinator. Usually, infrastructures have a long live. The debts should be financed through on long term contract.

(v) The bank (depends on the specific case and on the BM adopted): the bank could have some revenue, that could be distributed between symbiotic entity's companies, saved, or used to finance some projects. In particular, this are useful in those that are not economical sustainable for companies involved.

Other aspects, that should be considered, are:

- If involved companies have financial location on countries with lower financial pressure, it is possible to benefits of investments with lower tax fees in these countries ([107]).
- Bankruptcy costs: in the case of infrastructure, they are tangible assets, but based on companies' flows. If they are created and maintained through contributions of companies, a particular attention should be taken for those that have taken a loan to sustain costs. In case of bankruptcy of these companies, it is necessary to prevent/avoid the interference of the bank.

3.3.5 The Symbiotic Business Model

The approaches to implementation and the possible BMs to adopt could be different, depending on the specific case. Every case will be here characterized by an entity that manages and/or takes advantage of the Symbiotic set of tools (portfolio). The Symbiotic portfolio of tools must be managed by an entity that is also in charge of the coordination and cooperation management with others stakeholder. In general, this coordination entity should ([92]):

- Promote and coordinate inter-firms contacts and collaboration
- Establish a platform for dialogue and information sharing for all involved stakeholders
- Manage infrastructure and services
- Recruit companies, providing support for development and information sharing
- Identify opportunities and then push companies to implement the possible solution
- Ensure the formulation of integrated development plans
- Drive processes for requesting or raising funds to finance infrastructure and facility projects, and ensure the right connections to funding pools are in place

These activities could be managed in different ways, depending on the type of coordinator and how it integrates the Symbiotic BM approach to its BM.
The possible applicable BMs characterize specifically the coordinator that uses SYMBIOPTIMA tools to facilitate a symbiotic behaviour at network level. They are the output of a deep investigation of BMs of several industrial agglomerations (reported in §3.3.1). In particular, three BMs differ in the form of the entity that manages the Symbiotic-enabling portfolio of tools:

- a private major user company,
- a private services provider company,
- public government,

Symbiotic BM adopted by a private major user company
This scenario foresees the presence of an entity that performs the role of coordinator of a group of companies (tenant companies), because it owns infrastructure and it is the major user of utilities and services of the area. Its main business is not park management, but its core business is different, generally in the manufacturing sector, for example the park management of Schkopau (Dow) is a chemical company. Major user coordinator takes advantage from its influence on the tenant companies and from the possibility to cooperate with neighbouring companies, in order to reduce utilities and services supplying cost thanks to principles of economy of scale. It is necessary to underline that the major user does not provide directly utilities and services. It only carries out the role of intermediary.
Adopting the Symbiotic BM, the coordinator could increase the value proposed to tenant companies introducing:

- Detailed analysis and optimization of flows
- Provision of advanced collective purchasing (smart purchasing)
- Identification of new opportunities of collaboration

In this case, a particular attention should be taken on economic aspects. A private business company has as objective to make profit. Since the core business of the coordinator is not park management, a big issue regards its selfishness and low interest in network benefits. When adopting the Symbiotic BM, it is necessary that the coordinator of the park changes its BM. The management of the park can’t be a secondary/complementary activity, but needs to be the main activity necessary to guarantee the best execution of its core business. Although, it is necessary to consider that chase the maximum possible profit it is not always the best approach, since it can limit the companies’ opportunities of growth and their subsistence in the long term
The advantages to apply the Symbiotic BM in an existent park with a major user as coordinator are:

- In many cases the major part of infrastructures are already present
- The relationships between coordinator and tenant companies are already established
- Coordinator owns the infrastructure

The disadvantages are:

- Coordinator’s BM focuses on activities not compliant with the Symbiotic BM integration
- Contracts and agreements already regulate companies’ resources management

The major user model is not the best framework for the development of an industrial park and of industrial symbiosis, although the application of the Symbiotic BM could increase the level of collaboration and the efficiency of the overall park.

The BM has been represented in Figure 29, adopting the point of view of the private major user. The items related to company's core business are highlighted in red, the aspects related to AS-IS BM are in black, the aspects related to BM modification due to the introduction of the Symbiotic BM are in green.

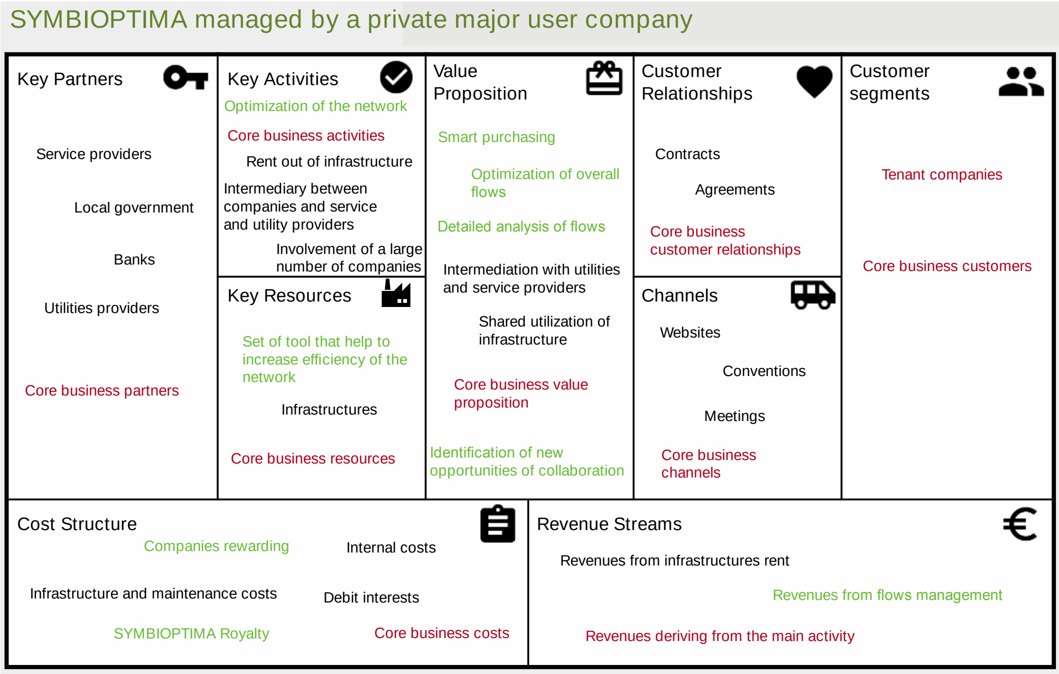


Figure 29: Canvas BM of a major user that adopts the Symbiotic BM

Key partners: considering that the main activities of the major user are not related to the network management, the Symbiotic BM manager as major user is not able to supply all services and utilities that companies require. In this sense, it must manage the relation with all service providers in order to guarantee the best solutions in terms of requirements fulfilment and prices. Another relevant partner is the government. Primarily, infrastructures require licenses and permits for their development and maintenance, that are established by the public authority. Secondarily, thanks to the introduction of the Symbiotic BM, it could obtain benefits for itself, for tenant company, and also for community (increasing environmental and/or social performance). The major user could negotiate with government in order to obtain advantages for the area (tax and fee reduction, incentives etc.). As owner of infrastructure, large investments are required by the coordinator. A relation with banks and lenders could be necessary to sustain them.

Key activities: in addition to its core activities, the major user coordinator must manage the optimization of the network, in compliance with the Symbiotic optimization tool output and considering the involvement of the largest number of existent companies, and also possible new ones. An activity related to the implementation of the optimal scenario is the intermediation with services and utilities providers. A good execution of this activity could help to reach easier the optimal scenario. As owner of the infrastructure, the major user's responsibility regards also the rental and maintenance of infrastructures. This allows to manage and control flows more easily, but it increases costs and commitment. As previous said, these listed activities should not be seen as secondary activities, but as the necessary ones for an optimal execution of the core business.

Key resources: adopting the Symbiotic BM, tools become a relevant resource for the coordinator. Planning, analysis and monitoring are carried out by using the proposed tools by the Symbiotic initiative. Infrastructures are key resources as well, since they enable flows creation and management.

Value proposition: thanks to the Symbiotic initiative tools, that enable a detailed analysis of flows, the collective purchasing effectiveness is increased. Utilities and service should be provided according to the optimization tool output in order to obtain the best possible benefits for the network. In addition to this, the major user coordinator is able to propose new values to its customers. First, it is able to provide a detailed analysis of customers' flows and can propose solutions that optimize overall sustainability without changing the customers' economic balance. Second, it provides to companies a new vision and new methodologies to increase their business opportunities.

Channels: the major user, in addition to its classical channels deriving from the core business, should deliver new symbiotic value propositions through website, meeting, and conventions communicating a digital visualization of sustainability performance improvement that the Symbiotic BM portfolio could bring at the whole network.

Customer relationship: The relationships between customers are managed through contracts and agreement in order to reduce risks for every involved actor. Specifically, the coordinator must take care of existent contracts and agreements, and formulate new ones that could be suitable with the optimization result.

Customer segments: in addition to its main customers, the coordinator must take care about tenant companies. It must collect their requirements and encourage their participation in order to adhere to the optimal flows configuration scenario proposed by the optimization tool.

Cost structure: in addition to main activity costs, that could be reduced thanks to the application of the Symbiotic BM, the coordinator (as the owner of infrastructures) must cover the costs for infrastructures development and maintenance already existing in the park. Those infrastructures, that are introduced only to sustain the Symbiotic BM scenario, are paid by the tenant companies as presented in §4.3. According to the management system proposed by the *bank*, it must reward companies involved in the network. If it has undertaken some loans to sustain infrastructure development, it must pay debit interest. In the end, it is possible that it could sustain royalty or license costs concerning the adoption of optimization tools.

Revenue streams: in addition to its main activity revenues that could be increased thanks to the application of the Symbiotic BM, it could withhold a percentage of the network profit. Infrastructure rental is another source of revenue, which could be increased thanks to the identification and implementation of new flows.

The Symbiotic BM adopted by a private services-providing company

The coordinator's main activity is services and utilities providing. The main difference with the previous example is that the coordinator provides directly services and utilities to tenant companies, it is not an intermediary. It offers to tenant companies a portfolio of services such as infrastructure, utilities and waste management, logistics, PR and communications (for example the service provider Infracor within Marl park).

A service provider coordinator is more suitable than a major user one for the Symbiotic BM implementation. It could be more interested in network development and optimization.

The advantages to apply the Symbiotic BM in an existent park with a service provider as coordinator are:

- In many cases the major part of infrastructures has been already
- The relationships between coordinator and tenant companies are already established
- Coordinator owns part of the infrastructure
- Part of flows already controlled by the coordinator

The disadvantages are:

- Coordinator BM revenues depends on provided services and utilities
- Contract and agreement are still present

The BM has been represented in Figure 30, adopting the point of view of the private services provider company. The items related to company's core business are highlighted in red, the aspects related to AS-IS BM are in black, the aspects related to BM modification due to the introduction of the Symbiotic BM are in green.

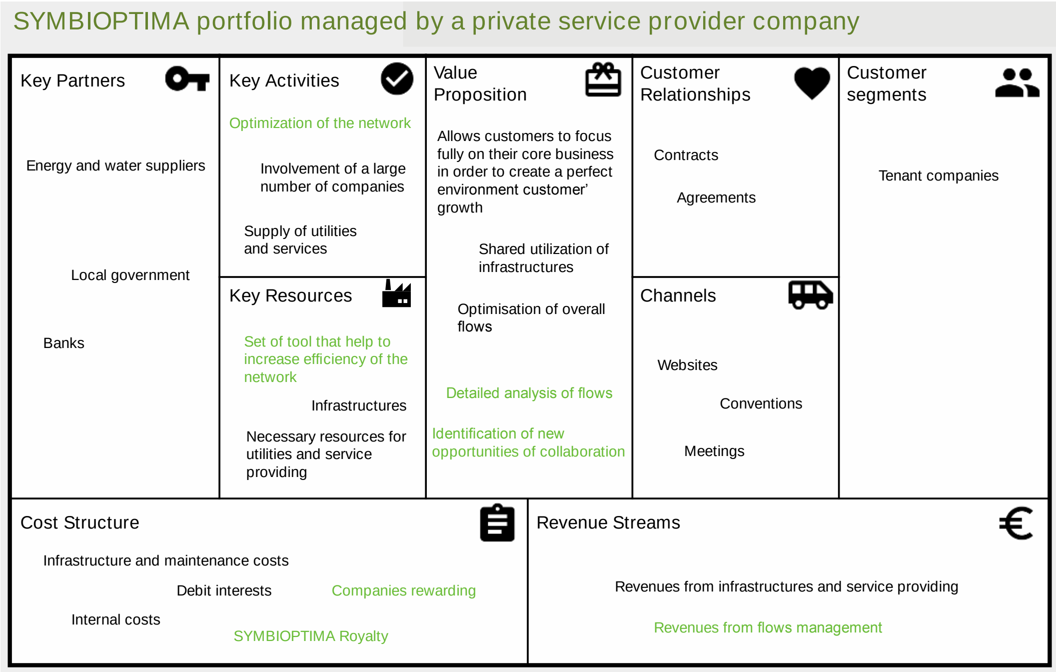


Figure 30: Canvas BM of a service provider that adopts the Symbiotic BM

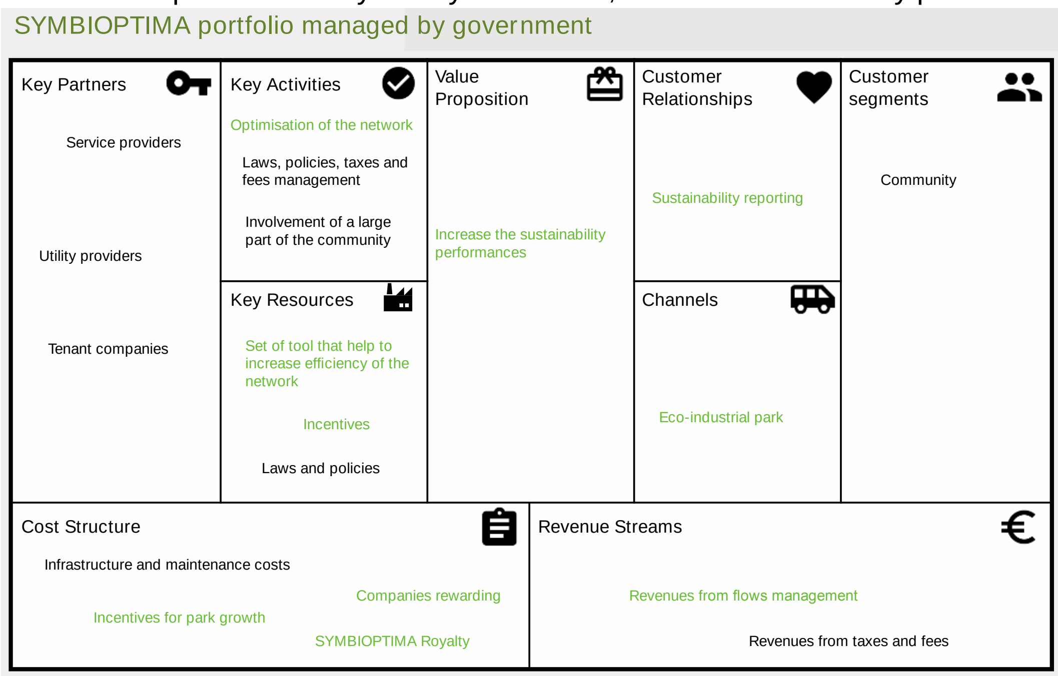
Key partners: the main activities of the service provider coordinator is providing directly the largest part of services and utilities required by the company of the area, including water and energy. These utilities are usually managed by big supplier. The coordinator buys them and distributes to tenant companies. The relationship with government and bank is similar to major user coordinator.
Key activities: main activity of service provider coordinator is supplying of utilities and services. This activity must be combined with the adoption of the Symbiotic BM approach and its proposed optimization of the network. The involvement of the largest part of the network companies is an enabling activity for the adoption of the Symbiotic BM towards an optimization at network level.
Key resources: the Symbiotic portfolio makes available several tools to manage and increase network flows' efficiency. Infrastructures are key resource for the creation and management of these flows. Others key resources are those that allow to supply service and utilities in order to reach customers' requirements combined with the Symbiotic optimization tool.
Value proposition: customers can focus fully on their core business. The optimization of overall flows and the detailed analysis of flows allow to increase this value contribution. The coordinator must take care about activities that are not core business of the customer including the sustainability development. Thanks to the Symbiotic tool, it can propose a new approach to secondary activities, in order to increase their sustainability (including economic) without interact with primary ones.
Channels: the service provider must be able to deliver the Symbiotic BM value proposition solution to its customers' segment and attract new customers to enter the industrial park and consequently adhere to the Symbiotic BM vision. This should be accomplished through website, meeting, and public events participation, and communicating a digital visualization of sustainability performance improvement that the symbiotic tools portfolio could bring to the whole network.
Customer relationships: the relationships among customers are managed through contracts and agreement in order to reduce risks for every involved actor. Specifically, the coordinator must take care about existent contracts and agreements, and formulates new ones that could be suitable with Symbiotic optimization.
Customer segments: the main customers remain the same of the BM without the Symbiotic BM. It is necessary to consider that the relation and the interaction with them are stricter because customers could also provide some flows and does not receive only utilities and services.
Cost structure: in addition to internal costs (due to services and utilities providing), that could be reduced thanks to the application of the Symbiotic BM, the coordinator (as the owner of infrastructure,) must cover the costs for infrastructures development and maintenance already existing in the park. Those infrastructures that are introduced only to sustain the Symbiotic scenario are paid by the tenant companies. According to the management system proposed by the bank, the bank must reward companies involved in the network. If it has undertaken some loans to

sustain infrastructure development, it must pay debit interest and it is possible that it could sustain royalty or license costs related to the adoption of the Symbiotic tools.
Revenue streams: the main revenues come from % of flow management and for infrastructure and service providing. A possible approach could be embracing a low-profit principle, which enables the possibility to involve a bigger number of companies and to attract new ones.

The Symbiotic BM managed by government

In the industrial areas where companies are not prompt to, or event aware of, sustainability performances improvement in terms of environmental and social aspects, government could be interested in the application of the Symbiotic BM tools. The government could entrust the management of the coordination to a public/private company or take care itself.
Government's main objectives are basically aligned with the Symbiotic BM aims: it is usually prone to involve the highest number of companies in order to increase economic, environmental and social performances of the area through custom policies and laws. In this way, influencing the behaviour of all stakeholders, including tenant companies, could be easier than the previous two cases. The Symbiotic BM portfolio could be a useful instrument for a government that wants to increase optimally the performances of an area by the provision of new policies that limit the sustainability impact. The Symbiotic BM becomes an instrument to retrain areas where environmental and social performances are not addressed. The Symbiotic BM can be also an instrument for supporting government in proposing new sustainable solutions to drive companies towards the achievement of the sustainability requirements.
The main differences between government model and private model regard the customer segments and cost structure/revenue streams. As public entity, the government could not focus its commitment on tenant companies, but its activities must give advantages to all the community. Nevertheless, companies are the main actors that allow the implementation of the aims of the Symbiotic BM. In this sense, they must be involved with particular attention. Since the objectives are more oriented to environmental and social aspects, a government coordinator could take less care about economic aspects and foster the creation of sustainable flows, potentially providing also incentives.
The advantages to apply the Symbiotic BM managed by government are: no cash flow issues; possibility to release new laws and policies; imposition of taxes and fees; easily understanding of overall sustainability objective; collective objective and connection with community and partners
The disadvantages are: less control on flows; ownership of infrastructure is more complicated to manage
In Figure 31 the Canvas BM is represented in order to have a representation of the main aspects. In green are represented the aspects added by the Symbiotic BM, in black those already present.

Figure 31: Canvas BM of a government that adopts the Symbiotic BM



Key partners: the government coordinator should interact with different partner in order to develop the scenario proposed by the application of the Symbiotic tool. In this case, tenant companies are not customers, but partners because they are the main entities involved into the implementation of the optimal solutions suggested by the government. Service and utilities providers are partners because they are assigned by the government to supply all necessary resources to the park respecting the Symbiotic optimized solution.
Key activities: the government should emit laws, policies, taxes and fees in order to easily perform the activity of the optimization at network level. Moreover, the optimization should not be achieved only thanks to taxation, but also thanks to the involvement of a large number of companies. Differently to previous business model, the government coordinator performs merely this role.
Key resources: the Symbiotic BM portfolio makes available all the tools to manage and increase network flows' efficiency. The major commitment of the coordinator is to adapt laws, policies, incentives and to coordinate all flows in order to support the development of the optimum scenario.
Value proposition: the value proposed by the coordinator is the increase of overall sustainability. A government adopts the Symbiotic BM on a specific area in order to guarantee better condition to its community, for example by increasing job opportunities or reducing CO_2 emission of a specific area.
Customer relationship: the coordinator relates with community through reports that allow to show the expected/obtained results.
Channels: in this case the coordinator, being the government, should deliver the new value proposition provided by the Symbiotic tools portfolio, through the eco-industrial park itself. This happens because the sustainability reporting is made considering the park behaviour and how much is in compliance with the Symbiotic BM suggestions.
Customer segments: the coordinator activities must provide advantages for all the community, not only for companies.
Cost structure: the government coordinator could contribute with incentives to the development of flows and infrastructure. Moreover, it should manage and reward the companies involved in the optimum scenario. In this case, a larger part of the infrastructures is owned by the tenant companies, but some, such as waste dump and water sources, could be owned by the government. These must be maintained. It is possible that it could sustain royalty or license costs relative to the adoption of the Symbiotic tools.
Revenue streams: revenues come from taxes and fees imposed to all community in the area, in particular from companies, and from the % of flows management. the coordinator should re-use all these revenues in order to contribute to the development of the optimum scenario.

3.3.6 Management of inter-network flows

Another open issue regards the inter-clusters optimization. So far only intra-network flows have been considered. As for the definition of industrial symbiosis in, the key factors for IS are collaboration among actors and the synergistic possibilities offered by geographic proximity ([91]). However, as Porter reported in [105] about cluster:
"A cluster is a geographically proximate group of interconnected companies and associated institutions in a particular field, linked by commonalities and complementarities. The geographic scope of clusters ranges from a region, a state, or even a single city to span nearby or neighbouring countries (e.g., southern Germany and German-speaking Switzerland). The geographic scope of a cluster relates to the distance over which informational, transactional, incentive, and other efficiencies occur."
In this sense, it does not make sense to force a maximum allowed distance for the implementation of actions within a specific network. The optimization tool should consider the distance between different companies, the required resources to connect these ones and the physical obstacles (mountains, lakes, streets).
If the resources to activate a flow between "far" companies are not covered by the obtained benefits, the optimization tool does not consider automatically it, without any range constraint.
It is necessary to consider that reaching the optimum scenario does not mean that all possible flows between companies are feasible and thus activated, or that all companies' secondary output

are transformed in input for other companies. A secondary output could not have a matching company able to assimilate it. In this case it will be dispose as a waste.
A possible solution is to introduce a bidding platform where all the Symbiotic BM adopters could interact in order to exchange waste that could not be assimilate in their network. This platform works without any principles of optimization; it allows only to further reduce waste and it works based on economic principles, as every online market place.
Two real cases as examples of B2B marketplaces applied to closed-loop system and sharing/cooperative economy are:

- http://austinmaterialsmarketplace.org/ : platform that brings together businesses of all sizes and entrepreneurs in the City of Austin and Travis County to create closed-loop systems in which one company's waste is another company's raw material. It works as follow
  - A company posts materials and resources available
  - Through data and ID, the platform identifies potential resource matches
  - After check of the feasibility, the exchange is done
- http://www.floow2.com/sharing-marketplace.html: FLOOW2 is a B2B Sharing Marketplace where companies and institutions can share equipment, services, and the skills and knowledge of personnel.

These examples are applied to companies characterized by proximity. In our case, the coordinator of every network identifies and posts all unassimilable resources on the bidding platform. The coordinator that identifies a needed resource buys it through the platform. Revenues will be divided between coordinator and company that make available the resources. This mechanism is based on economic principles, but it increases the overall sustainability.

Business Models currently adopted to manage Industrial parks and, especially, eco-industrial clustering initiatives, just partially cover the deployment challenges induced by the industrial symbiosis paradigm: fostering a sustainability-oriented optimization at a cluster level, new streams or organisational revisions improving the overall sustainability profile of the network but worsening the financial flows for single participating companies may occur. This requires the adoption of institutional entities (such as a bank) and policies (rewarding/penalty issuing criteria) complementing and supporting the Symbiotic business model implementation.

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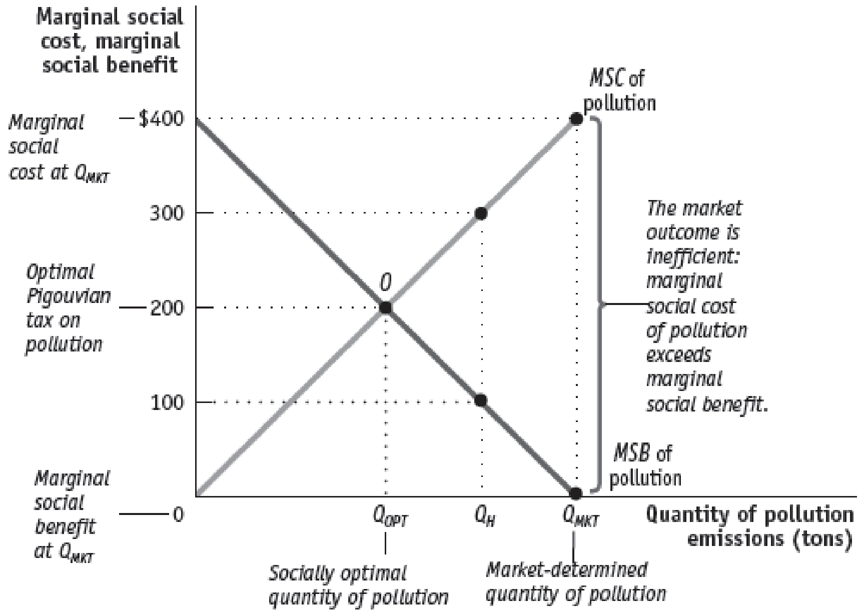
4 Communicating and reporting sustainability performances

4.1 The role of legislation and regulations

Let's start using a chart from Paul Krugman (2011) [110].

Figure 32: Public costs of pollution



This chart can be used to talk about "externalities" or "external costs". In a market economy without government intervention to protect the environment (but also the social impacts), those who derive the benefits from pollution (the polluters) don't have to compensate those who bear the costs, so the marginal cost of pollution to any given polluter is zero. Polluters have no incentive to limit the amount of emissions.

a. The marginal social benefit (MSB in the chart) of a unit of pollution is the saved opportunity cost from not having to reduce pollution by that one unit. The MSB is enjoyed by the polluter.
b. The marginal social cost (MSC) of a unit of pollution includes the health and other costs of a unit of pollution. The MSC is borne by society.
c. The polluter has a nonzero private MC of pollution only if it is required to pay for the right to pollute.
d. If the polluter is not required to pay for the right to pollute, its private MC is zero. It will therefore produce pollution up to the point where the MSB of polluting is also zero. Polluters, therefore, will spend nothing to reduce the amount of pollution they generate.

Also from an economical point of view, excess pollution causes inefficiency: considering the whole society point of view, exceeding a given amount of pollution is economically worse than having less. This not withstanding, without public intervention polluters are not forced to behave in order to maximize the overall (economic) benefit for the society: this is one of the (few) situations where the "Invisible hand" fails.

In order to mitigate/control externalities, it is possible to use two alternative ways: according to the Coase theorem, a private agreement between parts (e.g.: polluters and society) can efficiently solve the problem because even in the presence of externalities an economy can always reach an efficient solution as long as transaction costs —the costs to individuals of making a deal— are sufficiently low. Unfortunately, in many situations involving externalities, high transaction costs prevent individuals from making efficient deals (namely: the agreement between a polluting company and the county it is placed in would require proper regulations, meeting of several stakeholders, accurate quantification of the economic impacts deriving from pollution, etc.).

When transaction costs are high, private agreements do not solve the externalities problem, thus requiring the intervention of the public.

Several measures are available to the government to keep pollution (and other environmental or social externalities) under control. Citing again Krugman ([110]), we can mention three options:

- Environmental standards, namely rules that protect the environment by specifying actions by producers and consumers. In particular, limits on maximum emissions of given pollutants or thresholds on amounts of raw materials to be used are example of environmental standards.

- Emissions taxes are fees a company pays in accordance to the amount of pollution it produces. An emissions tax is more efficient than environmental standards because it ensures that the marginal benefit of pollution is equal for all sources of pollution while an environmental standard does not. The main problem with emissions taxes is that government officials in practice usually are not sure how high the tax should be set.
- Tradable emissions permits are licenses to emit limited quantities of pollutants that can be bought and sold by polluters. The key point is that these permits are tradable. Firms that find it easier to reduce pollution will sell some of their permits to those that find it more difficult. Just like emissions taxes, tradable permits provide polluters with an incentive to take the marginal social cost of pollution into account. The main problem with tradable emissions permits is that it is difficult to determine the optimal quantity of pollution, so governments may issue too many or too few permits.

According to Garretson ([111]), environmental legislation appeared in the U.S. in the 40s with the Water Pollution Control Act (1948), followed by the 60s' Clean Air Act (1963) and the National Environmental Policy Act (1969). Soon after, in 1970, Environmental Protection Agency (EPA) came into being. Similar laws were adopted worldwide: the Japan's Pollution Diet (1970), the West Germany's Federal Environmental Agency (1971), These local polices become international starting from the late 80s' with the already mentioned Brundtland report (1987), Earth Summit in Rio (1992), and Agenda 21 (1992). One of the latest evolutions of the legislation on environmental issues is the COP21, adopted in 2016. Several social policies and legislations may also be mentioned with similar timeframes.
In order to be sure to comply with such regulations, several companies started to create and adopt standardized paths also supporting them in communicating the environmental and social performances of the productions and products.

4.2 Voluntary labelling

As discussed in the initial paragraph of this chapter, sustainability labelling can be seen as a way to support public value appropriability from sustainability-driven innovators.
In fact, how should the customers of a green solution distinguish sustainably produced products from those that have been labelled merely as green? How an effective sustainability label can be designed and implemented in an industrial context claiming more and more information concerning the environmental, economic and social performances of the produced products?

Pushed by the European Commission, national policymakers and the market, European firms are striving for the development and adoption of practices able to minimize energy consumption, CO2 emissions and supporting safety and fairness compliances. In this context, the analysis and reporting of the obtained results have become instrumental to comply with national/international regulations, to protect local markets from unfair competition, to allow manufacturers to differentiate their products and to improve consumer awareness on the sustainability topic. Sustainable consumption has thus become a crucial objective of the new millennium for companies and government policies ([112]) that are stimulating innovation through marked-based instruments that, encouraging alternative consumptions habits, aim to reduce the damaging effects of industrial activities on environment and society ([113]). The market pressure towards environmentally- and socially-compliant products gas slowly but continuously increased in the last two decades (114). The actual application and implementation of sustainability concept within the industrial activities is becoming a "must" in order to access most demanding customers that desire to preserve the high standard of living achieved by industrialized societies ([131]). The research performed by Eurobarometer, focusing on the environmental area of sustainability, highlights that a large part of the market (more than the 80%) actually buy or is interested in buying green products since, with the same functionality of the traditional products, they can "make the difference" for the environment, even though only the half of the consumers believe that green products are easily available in the shops and they are easy to be recognized by the other products (Flash Eurobarometer report, 2013 [133]). Summarizing: market wants sustainable products but is not always able to distinguish them from "mainstream" one.

Sustainability declarations have born, above all, with the aim to fulfil this need and today are recognized as one of the main important instruments to promote sustainable consumption and production ([115]; [116]). Communicating objective information is recognized as one of the main factors for adopting a label as sustainability communication tool ([117]). The recent literature suggests that obtaining these labels provides a real and growing competitive advantages, so much that, in some cases, the absence of the label may act as barriers to trade, even though this effect is explicitly undesired by the majority of the certification schemas ([118]). Thus, labels represent a powerful tool to support a conscious and sustainable consumer choice providing customers with the possibility to maintain the royalty of its decisions ([112]).
In addition to the communication valence, sustainability labels own an interesting side effect such as the promotion of eco-innovation that arises through the circular interaction of the three actors involved in the sustainability market *drama*: consumers, firms and institutions ([119]). As already cited, consumers benefit the sustainability performances data provided by the label, exploiting it in making more conscious choices; at the same time, the information increases the awareness of the market on sustainability. Pushed by more conscious customers, firms are encouraged to present precise and reliable information and, implementing innovation, to reduce the sustainability impact of their activities and products ([113]). Eventually, institutions and governments exploit labels as a mean to promote and encourage cleaner and fairer production and consumption.

In the last decade, a multitude of public and private initiatives have started communicating sustainability-related indexes of products. Ecolabelindex.com reports 465 labelling schemes in 199 countries and 25 industry sectors (data retrieved in 2016 first trimester). These schemes aim at communicating to consumers whether a product complies with more sustainable or less sustainable practices. Indeed, according to de Boer ([120]), product labels are distinctive symbols that reveal differences in terms of sustainability amongst products or during time: labels become an instrument for establishing product differentiation.

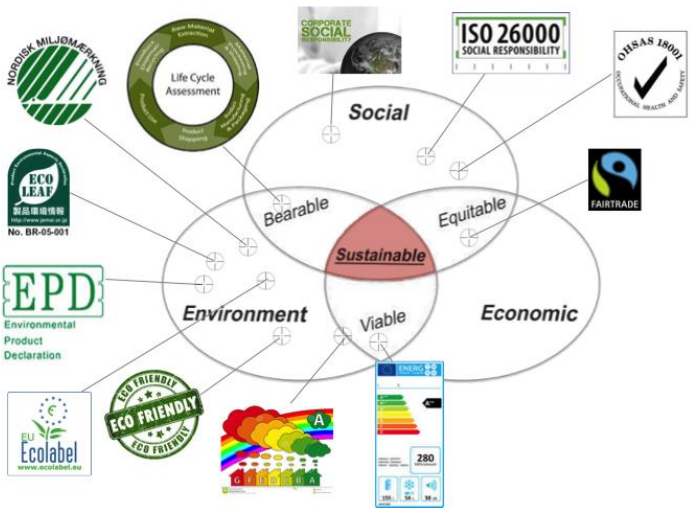


Figure 33: Some examples of labels

Three are the main issues that drove the here presented investigation. Firstly, literature studies demonstrate that the growing number of labels, mostly not comparable one with the others, and related communication initiatives have led to information overload and gaps in understanding of the sustainability concept itself and of the label meaning, thus arising confusion to the consumers and limiting the use of such labels ([115]). Secondly, the information provided by the labels is not always reliable even though labels have been designed exactly in order to avoid what in the case of environmental claims is named as Greenwashing ([121]) – see §2.1 for more details on this topic. In the case of environmental labelling, for instance, the Eurobarometer research highlights that only half of the consumers trust the claims concerning the environmental performances of the products ([133]). The accuracy and the credibility of the provided communication is a prerequisite for an effective sustainability label. Eventually, the third main driving issue, there is a shortage of communication of the sustainability aspects as a whole. Existing labels provide customers information mainly on environmental and social aspects (with a prevalence for environment), and generally not on all the three aspects of sustainability: it is important to distinguish sustainably-produced products from those that have been labelled merely as green.
In the following discussion, the existing labels and the related regulations have been investigated, with the goal to contribute the understanding of currently adopted sustainability labels, and define the gaps to be solved for the definition of an exhaustive and reliable picture of the sustainability impacts of a certain product.

The study has been structured in three sections. The first one is devoted to an analysis of the existing sustainability labels (claiming all the three aspects of sustainability or even only one of the three) and of the current regulation in the context. The analysis brought to the identification of several label dimensions to be taken into account in the design phase of a comprehensive sustainability label. The second section is dedicated to the analysis of the communicative characteristics of a label according to customer's perception. This drove to the identification of the elements to be included in a label that are also referenced to label dimensions. Starting from these investigations, a procedure for the design of self-declared sustainability labels have been drafted (in the third section), with the goal to guide companies in identifying their sustainability-related communication needs and to develop a label according to them. For each label dimension, the elements to be included in the label design have been explained, together with some criticalities to be considered in this phase. This procedure has been eventually applied in a real case for the design of a sustainability label for a company leader in mould & die sector (see the Practical application section).

4.2.1 Existing sustainability labels

The number of product labels related to eco-friendly, fair trade, locally produced, convenience and healthy attributes has grown rapidly in the last decade and often it is not clear which attributes labels are addressing and what the considered criteria are. Voluntary environmental labels and accompanying initiatives have started three decades ago, while labelling programmes at national and European levels have started just in the 21st century: most of the European member states have introduced national eco-labelling programmes, where the term eco-label is referred to a "label which identifies overall environmental preference of a product or service within a specific product/service category based on life cycle consideration" ([116]). In addition to these environmental labels, in the last few years great attention was devoted to the development of social and ethical labels, dealing mainly with working conditions and price guarantees ([116]; [123]). These labels show the emerging consideration of sustainability aspects, including economic and social evaluation in addition to the environmental one. In order to cover all the three aspects of sustainability (environmental, economic and social) at the same time, labels with sustainability claims are now emerging worldwide, but, differently from the standardized existing labels, they still are sector- and lifecycle phase- specific. Many example can be found in the sectors of buildings, fisheries and marine life, food and beverages, forest management and wood products, and tourism (e.g.: the Marine Stewardship Council fisheries standard, the PEFC Sustainable Forest Management certification or the Sustainable Tourism Education Program). Another interesting example is offered by the sustainability claims reported by goodguide.com that, with an holistic approach, allow the consumer to know the environmental and social impacts of a wide range of products, from personal care to household. Indeed, in goodguide label, the only aspect directly related to the product is the health one, while the other social issue and the impacts on the environment are related to the company characteristics. In order to perform a more complete analysis of the existing labels, the database of Ecolabelindex.com has been examined. It lists about 460 labelling schemes focusing on sustainability-related issues. The database has been investigated defining a set of dimensions helping in labels classification and understanding:

- the focus of the sustainability assessment: this dimension specifies the subject of the assessment: the product/service, the process or the organization;
- sustainability coverage: this dimension identifies which of the three aspects of sustainability is communicated through the label;
- certification standard: this dimension establish which standardisation scheme has been adopted to evaluate products, processes or organizations towards the achievement of sustainable development.

Concerning the focus of the assessment, about 60% of labels are certifying products (e.g. Bio Suisse, Blue Angel, Energy Star); 25% of labels are certifying organizations (e.g. Fair Trade, Sustainable Tourism Education Program, Green Business Bureau); less than 15% are certifying services (e.g. LEAF). This distribution is reasonably related to the existing certification schemes that are mostly intended for product and organization certification.

About the coverage, though stored labels are focused on reporting the sustainability attributes of a certain product, less than 10% of label embraces all the three aspects of sustainability. This result doesn't change significantly even if we consider labels that embrace environmental and social aspects at the same time, but not the economic ones. Some labels have "sustainability" or "sustainable" in their name, but they encompass mostly environmental and social aspects (e.g. Sustainable Forestry Initiative, Sustainable Green Printing Partnership, Roundtable on Sustainable Biomaterial). Certification schemes and evaluation criteria which labels are relying on are set for the specific sustainability issue they cover: ISO 14021:1999 is expressly intended for environmental self-declared claims of products; while ISO 21929-1:2011 establishes a core set of indicators covering all the three aspects of sustainability for assessing the sustainability performance of new or existing buildings, related to their design, construction, operation, maintenance, refurbishment and end of life.

This investigation gives evidence of the predominant focus on product's environmental attributes regulated by the several different standards. This is also confirmed by organizations such as the UK House of Commons Environmental Audit Committee or the American National Institute of Governmental Purchasing that, in the last few years, are demanding for the unification and simplification of existing sustainability-related product information schemes into some form of overarching labelling scheme ([115]).

Labels address different standardisation schemes that vary significantly in the issues that they highlight (fair trade, safe and sustainable agriculture, eco-tourism, etc.), the sustainable aspects they cover (social, environmental, economic) and the processes by which they came into being (private, public, or mixed initiatives). The mostly adopted reference standards are: standards for product and system certification and conformity assessment (ISO/IEC Guide 65; ISO 17000 family; ISO 19011; EPA), standards for environmental and sustainability assessment (FTC; EMAS; ISO 14000 family).

The adopted standards reveal that the proliferation of labels follows the multitude of standardization schemes meant to evaluate products, processes and organizations for certification and labelling purposes. In particular, the International Organization for Standardization (ISO) have started to structure and classify environmental labels by developing ISO 14020 family, in order to classify the eco-labelling programmes and to establish international convergence. The overall goal of these environmental labels and declarations is to encourage demand for and supply of products that cause less stress on the environment. This standard aims at identifying and categorizing the characteristics of eco-labelling. ISO divides the environmental labels into three types:

- type I (ISO 14024:1999): voluntary, multi-criteria third-party programmes intended for end consumers. It identifies products which are determined to be environmentally preferable within a particular product category;
- type II (ISO 14021:1999): self-declared environmental claims without third-party certification;
- type III (ISO 14025:2006): quantified un-weighted environmental data based on lifecycle assessments intended for business-to-business information.

From the analysis of these standards and other classification in literature ([115]), other four useful dimensions (verification type, goal of communication, target, and evaluation methodology) for labelling classification have been defined, as shown in Table 9. The dimensions identified within the ISO 14020 family and the ecolabelindex.com database screening will be used as support for the definition of guidelines for the design of a sustainability label.

Table 9: Synopsis of ISO 14020 product environmental labels

	TYPE I – ISO 14024 3d-party labelling	TYPE II – ISO 14021 Voluntary labelling	TYPE III – ISO 14025 *Ecoprofile*
Object	Product	Product	Product
Use	Selective	Informative	Comparative
Customer	Consumer	Consumer/Business	Business/Consumer
Certification entity	External	Internal	External
Evaluation methodology	• Use of quantitative indexes • Entire lifecycle of the product • Performance thresholds matching	Specification of the claim	• Life Cycle Assessment Product Category Rules • Quantified data
Example	*Ecolabel*	*CO_2-neutral*	*EPD*

4.2.2 Communicating sustainability through labels

In order to gather valuable inputs for designing an effective label for communicating sustainability performances, a thorough analysis has been performed considering: (i) pattern, contents and appearance of existing sustainability and environmental labels; (ii) audience perception of existing ecolabels (as reported in selected surveys).

In general, labels differ one another in terms of provided data and communication patterns. The performed analysis aimed at investigating these two elements using two, complementary, points of view:

- "value proposition" – which are the data included in existing labels? How are they communicated? This issue is investigated performing a semi-quantitative evaluation of existing labels contents and communication choices;
- "value perception" – how does the target audience perceive the provided information? What are their understanding of current labels? Which are their expectations on labels content and appearance? This topic has been explored mainly analysing surveys and questionnaire reports.

Besides communicating sustainability-related information, the identification of the items to be included in a sustainability label has been performed, examining existing labels, literature studies and ISO standards. A list of elements to be included into a label has been defined, according to the possible values the label dimensions can take, but not limited to (see Table 10). In particular, the elements have been divided into two macro-categories, according to the different goals they pursue:

- Data-elements: specific elements intended to explicit to the label recipient the information on the analysed subject and on the evaluated sustainability performances,
- Format-elements: elements intended to ease the perception of sustainability impacts depending on the specific target audience and label goal.

	Label elements			Link to dimension(s)	
	Item	**Meaning**	**Options**	**Options**	**Dimension(s)**
Data element	Scope	Which is the subject of the analysis? What is the label referring to?	Scope selection and its detail	Product Process Company	Scope
	Sustainability coverage	Which aspect(s) of sustainability has(-ve) been addressed through the label?	Sustainability issue(s) addressed	1 or 2 aspects of sustainability Triple bottom line	Sustainability coverage
	Certification data	What is the adopted standard during the analysis (if any)? What is the adopted	Reference to certification standard, evaluation	N/A	Certification standard & methodology

		methodology? Is it LCA-based? How has the assessment been verified?	verification and adopted methodologies		
	Indicators	What indicators have been evaluated?	(Global) aggregated indicator	B2C	Target audience
			Disaggregated indicators	B2B	
	Online data	Where can further information be found?	QR/Bar-code URL	B2B	Target audience
Format	Indicators values	What are the sustainability impacts?	Calculated values	B2B/Comparative	Target audience Goal
			Ranking (letter-based or point-based)	B2C-B2B/Informative	
			Values of easy-benchmarks	B2C/Informative	
	Legend	What is the range of indicators evaluation?	N/A	N/A	Target audience
	Colour Scale	What is better and what is worse?	N/A	N/A	Target audience Goal

Table 10: List of elements to include in the sustainability label design

The inclusion of all the elements in the label design is not mandatory but, as for the performed study, it allows to reach an effective communication of the sustainability performances of a certain subject through the label. The approach of identifying a list of minimum elements has been triggered by the necessity to deliver a procedure to be applied to design sustainability labels not limited to a specific sector or category. Depending on the specific application and on the company's objectives and requirements, the un-necessary elements can be taken off.

In the table, the elements have also been linked to the different label dimensions used to characterize and describe a label. The goal was to ensure that the designed label contains all the information needed to the recipient to understand the label and to be able to use correctly the conveyed information. In particular, from this exercise, it can be noted that some information (characterizing the context and registry data) lead to a direct link between the element and the dimension (e.g.: if the label scope is a company, the company name and its most significant characteristics need to be included in the label design), while the communication of other information (i.e. the evaluated sustainability impacts) need to be modulated according to the label goal and the target audience.

Grunert et al. ([124]) noted that any label advertising effect depends on the consumer's opportunity to process information, on the consumer's ability to interpret the information and on his motivation to process the information. In fact, sustainability labels give consumers the possibility to make environmental and ethical considerations when choosing a product. However, even without the label, the consumer has the possibility to make such evaluation (whenever possible), considering for example the raw materials origin, the production distance, company fair trade aspects, etc. Such evaluation performed by consumers that are un-literate in the specific sector is highly subjective and doesn't consider the performances in a lifecycle perspective: the evaluation performed without following predefined and standardized criteria can be only partial, simplistic and, most of the time, wrong. However, the more motivated consumers are to make use of sustainability information, the more they are willing to put effort into understanding labels and using them in products/companies choices.

In order to be communicative, a label should:

- transmit benefits deriving from the product choice. This option is strongly depending on which the target of communication is: benefits for companies are different from the ones for consumers;
- be easy to read and understand. Also this option is strongly depending on which the target is: manufactures and retailers are expected to be aware of the context, while generally the

consumer is not aware of it and is unfamiliar with the idea that products can have environmental impacts across different categories over their entire life cycle;

- report information with high confidence rate. Whilst the goal of the communication influences the type of information conveyed, the target influences the way of communication of the data. The combination of these two aspects may lead to a lower degree of reliability due to incomplete or simplified information ([125]).

During the label design phase, taking into account the goal and the target audience of the desired communication is fundamental.

A study on different options for communication environmental information for products (BIO Intelligence Service, [126]) reports a conducted consumers' survey on the perception of different design of labels communicating environmental impact of products. Indeed, the study aimed to examine different mechanisms and means for communicating products-level environmental information to consumers, to determine which mechanisms can maximize consumers' understanding and ability to compare between different substitutes. Main key findings are:

- communicated information needs to be obvious (impossible to miss) and explicit (impossible to misunderstand);
- a global aggregated indicator allows easy comparison amongst products;
- the combination of an aggregated indicator, with up to three individual indicators, has been recommended as an effective presentation of data, but more than three indicators lead to customers' confusion;
- a colour coded scheme help consumers in understanding quicker the information;
- the confidence in the communicated information is encouraged by reporting data and the methodology supporting the sustainability assessment;
- link to additional information increase customer's confidence, even if not having access to them;
- general terms for indicators are preferred over technical description by consumers.

Considering these results and the characteristics required for an effective communication, 5 main communication requirements have been identified and listed in Table 11, first column. These requirements have been matched with the label elements, in order to understand which element contributes to the fulfilment of any communication requirement. As shown, all previously identified elements contribute to at least one communication requirement, meaning that all elements are necessary for having effective communication.

Label communication requirements				**Indicators**			**Indicators value**				
	Scope	**Sust. coverage**	**Certification data**	**Aggregated ind.**	**Disaggregated ind.**	**Online data**	**Calculated values**	**Ranking**	**Values of easy-bench**	**Legend**	**Colour scale**
Easiness of legibility and understanding	■	■		■				■	■	■	■
Impossibility to misunderstand		■		■	■					■	
Impossibility to miss				■				■			
Easiness of comparison				■							
Increase of consumer confidence			■		■	■	■				

Table 11: Label communication requirements vs. label elements

When considering existing well-structured labels such as the product environmental ones regulated by ISO 14020 family in the proposed framework, it can be noted that each of the three types of label doesn't fulfil completely the proposed requirements. Type III label provides high level of data confidence, nevertheless, being it a declaration intended for businesses, its legibility is not as immediate and understandable as the other Type I and II labels. At the same time, these latter two labels lack in exhaustive data communication since they are selective in the delivered information. No one of them is definitely more communicative than the others. In order to achieve an effective communication, the most communicative label should be made by merging specific characteristics of all the three types of label.

4.2.3 Sustainability label design

The performed investigation allowed to point out the existing gaps in the design of a product sustainability label and to define a tentative procedure for label design of heterogeneous goods, processes or organizations. The proposed procedure for the design of a sustainability label is meant to guide companies in identifying their sustainability-related communication needs and to develop a label according to them. The presented study has been restricted to companies' self-declared certifications, that is the case of a shortage of documentation (unless for the environmental second type labels, regulated by ISO 14021:1999).

The dimensions adopted for the ecolabels screening are here used as "path" to be followed in the design of an effective sustainability label. Coherently with the followed path, the elements to be included in such a label have been identified (see Table 3) and their meaning and potentialities have been discussed in the previous chapter.

Goal of communication. This dimension has been selected when analysing ISO 14020 family and refers to the way and purpose the sustainability attribute of the label subject is communicated. Labels can be (i) selective, showing whether the product achieves specific environmental requirements, (ii) informative, communicating to the label addressee one or more environmental claims, (iii) suitable for comparison with other labels, including the complete information of the evaluation performed in a post-processed way, in order to make the product analysis comparable to the one performed on products of the same category underwent to the same kind of assessment. The identification of the goal has to be made at the beginning of the design phase, since the specific goal will affect the label design. Despite the possibility to respond to own communication requirements by choosing one of the three kinds of label, the selective label doesn't contribute to fulfil communication requirements (especially the reliability of data to increase consumer's confidence) and it is suitable for labels reporting one single attribute or aspect of sustainability (an overarching indicator for sustainability still does not exist). As regarding (ii) and (iii) labels, the assessment results need to be clearly included (the way report these data will be discussed below).

Target audience. In this phase it is fundamental that the company defines if the customers whom the label is intended to are consumers (B2C) or companies as well (B2B). This distinction impacts on the way and on the type of information to communicate. In order to fulfil the communication requirement of easiness of understanding, the performance data to be communicated has to be screened considering the field-education of the customer type. Moreover, this information has also to be pondered according to the benefits the targeted customer needs to perceive.

Scope of the assessment. In order to ensure easiness of understanding, it should be clear if a label is intended to accompany the communication of a product, a service or an organization. The necessary information on the focused subject has to be included in the label design in order to allow the addressee to clearly understand the subject of the certification. When selecting the information to report, the communication objectives and target have to be taken into account: the subject details reported in the label should conveyed all the meaningful information to customers, at the same time the information should be essential for the specific purposes.

Sustainability coverage. Due to the misleading use of the sustainability claims, previously documented, it is important to distinguish among which sustainability aspect/-s is/are addressed by the label. The reference to covered sustainability aspect and to the focus of the assessment steers the consumer on the label focus and content and gives evidence of the sector.

Certification standard, evaluation verification and methodology. These dimensions have been merged since the adopted methodology for the performances assessment is strictly connected to the certification standards. Different tools and methodologies are available to perform sustainability assessment and to report about the resulted performances (e.g. Life Cycle Assessment (LCA), Sustainable Development Indicators, Sustainability Reporting) ([127], [128]). Each methodology is based on the calculation of a set of indicators, properly selected according to the focus of the performed assessment. Set of indicators covering all the three aspect of sustainability can be derived from the LCA and Life Cycle Cost LCC methodologies, or adapting GRI (Global Reporting Initiative) guidelines generally intended to assess and communicate sustainability performance of an organization. In Bettoni e al. ([129]) a sustainability assessment model is meant to evaluate all the aspects of sustainability by a set of 35 indicators taking a lifecycle perspective. Set of indicators for the evaluation of only one of the three aspect of sustainability can be extracted from the already mentioned ones, or can be retrieved from ISO 14000 family for the environmental assessment. Moreover, in particular for the buildings sector, ISO 21929-1:2011 establishes a core set of indicators to take into account in the use and development of sustainability indicators for assessing the sustainability performance of new or existing buildings, related to their design, construction, operation, maintenance, refurbishment and end of life.

In order to make the label easy to understanding and reporting information with high confidence rate, the applied certification standard (if the case) and/or the evaluation methodologies have to be clearly stated in the design of the label. Besides this, how to include the assessment results in labels?

According to Engels ([125]) and Cowburn ([130]), consumers process numerical product information more easily than non-numerical one, which requires the interpretation of text or symbols. Differently from what happens to mere environmental assessment with the endpoint Life Cycle Impact Assessment (LCIA) methodologies, still there isn't any standard for the sustainability assessment that allows to get one single aggregated value of sustainability performance or even one aggregated value for each of the three aspects of sustainability. However the possible simplification of performances to an overall performance index can lead to a loose of information that can be acceptable depending on the target of label communication and on the information that the company wants to deliver. Thus, in the case the label goal is comparative, it is convenient for companies to include in the label the calculated indicators and obtained results; in the case the label goal is informative it is convenient to include indicators value by using a ranking system o meaningful values for general consumers, properly selected on the basis of the label target (respectively B2B and B2C).
Moreover, ISO 14024:1999, when defining the procedure for the development of product environmental criteria, states that, once a criterion that reflects a specific environmental aspect has been set, the numerical value to be assigned to can take the form of minimum value, threshold level, scale-point system or other appropriate approach. Accordingly, a portion of environmental labels show a rating of the attribute they communicate (e.g. the EU energy label). Indeed evaluated performance indicators can be difficult to be understood by consumers that prefer general terms for indicators over technical descriptions (BIO Intelligence Service, [126]). In sake of this, indicators value can be communicated via a rating system or recalculated values referred to selected easy-benchmarks, as like the case Nescafé environmental performance label (e.g.: the environmental impacts during the production phase have been expressed in terms of consumed water glasses and covered meters by car).
The possibility to adopt a sustainability rating for each considered impact indicator makes the label communication more effective and allows an easier comparison amongst similar products (whose label refers to the same certification standard). The definition of sustainability categories which the indicators values can be associated to is necessary for easing the assessment results understanding and comparison and to make the label easier to legibility. This classification can be performed identifying a suitable number of classes for the product category (for example the energy efficiencies categories adopted for the EU energy labels), or defining sustainability

performance scores (as the points scoreboard adopted by SMaRT consensus sustainable product standards). Some criticalities have been identified in order to implement the mentioned rating:

- normalization: it indeed concerns two different aspects. On the one hand, indicators concurring to the evaluation of sustainability impacts of a certain category of products for a specific company have to be normalized on the basis of the same functional unit so that, within a common certification scheme, the indexes values can be compared. On the other hand, normalization is needed when an overall performance index approach is chosen. In this case, the first step to be performed is to normalize the indicators results through a reference value (e.g. the average CO2 emissions in Europe in 2014), a value that is not always available or calculable, mainly in economic and social fields;
- benchmarking: it is necessary to set benchmark values which the calculated indicators can be compared to. The benchmark can be properly selected on the basis of the products type and on the certification purposes. The benchmark has also to be re-set (updated) after a predefined period of time to monitor the company's progress in sustainability performances achievements during time, and to be aligned to the company's progress in terms of sustainability performances. In the performed investigation different potential benchmark types have been identified:
    - the sustainability impacts values of a real product are set as benchmark. This approach usually considers an approach based on the "worst product" chosen as the reference (e.g. the EU energy efficiency labels). A couple of problems can be envisaged for this option. First of all, there is the possibility that the selected benchmark indeed doesn't correspond to the worst case for every sustainability impact. Then, the benchmark product can be selected only after having performed the sustainability assessment of all the products to be labelled.
    - mock sustainability impacts values are set as benchmark. This benchmark is created considering the worst case of each indicator calculated for all the company's product: this allows to avoid the two previous problems, by selecting a threshold for each indicator that makes evidence of the sustainability gain for each indicator. However setting the worst values still remains a criticality, not being regulated by any standard and being depending on the product type.

4.2.4 Practical application

The proposed procedure has been eventually applied for creating a label in the manufacturing context of mould production. In particular the considered case study relies on the sustainability assessment of a mould for the injection of plastic components used in material handling systems, performed according to the assessment model reported in Fontana et al. ([131]) that is based on well-recognized methodologies such as LCA and LCC, and resulting in the calculation of 9 indicators (Boër et al., [132]). Through the screening of the company's communication needs, matched with label classification dimensions, the adopted methodology brought to the development of a mould sustainability label. All the minimum elements suggested in the procedure have been included in the design in order to fulfil each requirement (see Table 12 for the label requirements, and Figure 34 for the tentative label design).

Table 12: Characteristics of the drafted label for mould industry

	Label elements		Link to dimension(s)	
	Item	**Options**	**Options**	**Dimension(s)**
Data	Scope	**Mould product**	Product Process Company	Scope
	Sustainability coverage	Sustainability issues addressed	1 or 2 aspects of sustainability Triple bottom line	Sustainability coverage
	Certification data	**Sustainability Assessment Moulding platform based on LCA and LCC**	N/A	Certification standard & methodology
	Indicators	(Global) aggregated indicator	B2C	Target audience
		Disaggregated indicators	B2B	
	Online data	**Report on-shelf**	B2B	Target audience
Format	Indicators values	Calculated values	B2B/Comparative	Target audience Goal
		Ranking (**Sustainability rating: 4 classes (A – D)**)	B2C- B2B/Informative	
		Values of easy-benchmarks	B2C/Informative	
	Legend	**Rating scale**	N/A	Target audience
	Colour Scale	N/A	N/A	Target audience Goal

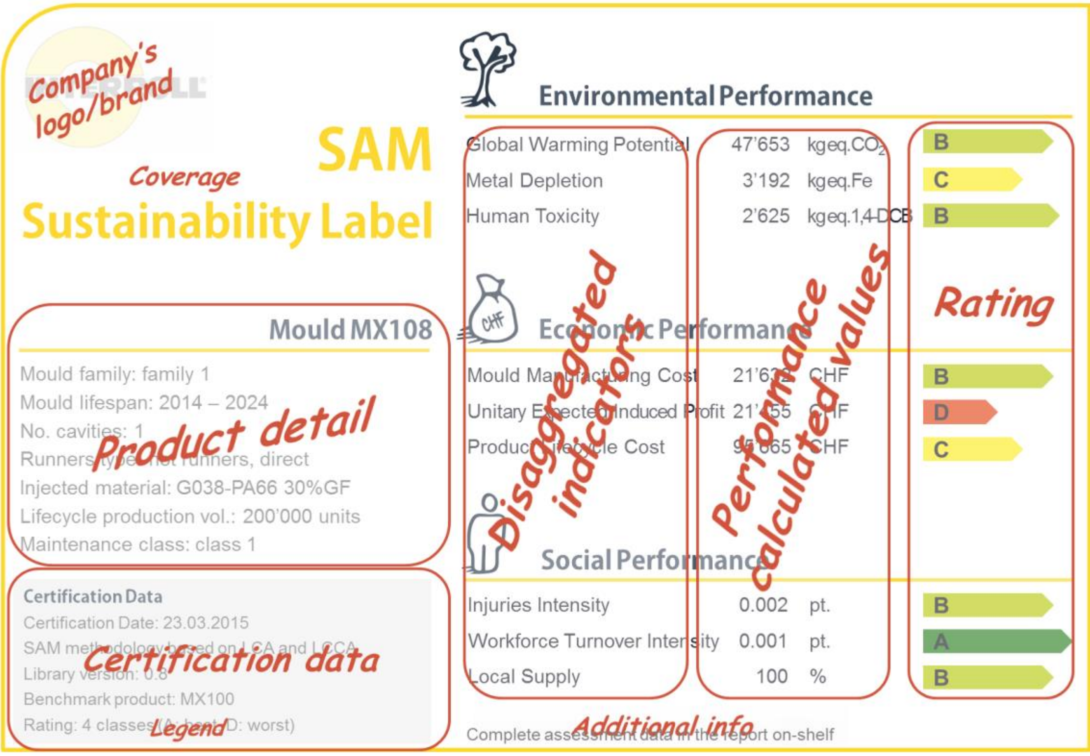


Figure 34: Draft of a sustainability label for mould industry (Fontana et al., [131])

4.2.5 Final remarks

Triggered by the question how to distinguish sustainably produced products from those that have been labelled merely as green? An analysis of existing sustainability-related labels and regulation have been performed and in this paper presented. This analysis brought the opportunity to start defining a path for the creation of an overarching sustainability label to be applied for heterogeneous goods in different sectors, that is one of the desiderata of international governmental organizations.

A procedure for the design of self-declared labels is drafted, with certain assumptions and restrictions. The procedure has been also applied to a real case study and a tentative label for mould industry has been depicted. Data on customers' perception of the proposed label are still under evaluation and they will allow to refine the procedure for the design of a label.

Next steps are the application of the proposed procedure to other industrial cases and its validation.

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5 Conclusions

The increasing pressure public opinion and legislation put on sustainability resulted into several privately- and publicly- promoted initiatives ranging from research, innovation, training and communication, (correctly or wrongly) addressing different sustainability aspects.
Literature on the topic has become extremely wide and over 100 papers are published on a yearly basis aimed at investigating every single pillar or definition from the sustainability world, even if a bit of mess is sometimes made between terminologies and concepts, being sustainability a still young research area.
This is especially true for the manufacturing arena: most farsighted manufacturing companies are exploring and adopting sustainability-related strategies to re-define their business processes, sometimes pulled by their end customers, and sometimes, and less virtuously, interested in catching the latest marketing wave. Still, publications, white papers, and analyses on the topic are scarce and the body of knowledge on sustainable manufacturing appears patchy, incomplete and hard to be translated into actually implementable guidelines.
The here presented research tried to provide a comprehensive vision on almost all the aspects concerning sustainability and sustainability concepts and paradigms implementation in manufacturing companies. All the discussed and presented steps are of major interest for both prospective adopters of the sustainability guidance, and for managers already dealing with the sustainable manufacturing practices. The work investigates traditional and novel definitions and approaches that can be grouped and summed up as follows:

- assessment. Standardized methodologies are discussed and validated in real production contexts enabling effective diagnostics of manufacturing performances with respect to environmental indicators: screening LCA and environmental auditing have been used to assess a single mould and a textile supply chain (respectively), highlighting the required effort and the amount of gathered information. Gaps to be bridged to achieve a comprehensive vision of the sustainability performances of selected targets have been identified, discussed and validated with industrial representatives. A valuable Sustainability Assessment Tool, relying on properly selected sustainability metrics, has been finally designed and deployed (together with software development colleagues) aimed at providing a novel point of view on sustainability assessment in manufacturing contexts, with an explanatory application in the mould&die sector;
- sustainability-driven innovations were classified using a novel framework and discussed in detail ranging from technologies to innovative business models. In fact, initiatives and investments aimed at improving sustainability performances of products, companies or groups of companies can address (also simultaneously) different elements of a company business profile: the technology they use, the way they design product or processes, the way they create value and the underlying business model, regulations they need to comply with. Three specific projects have been developed during the work:
  - a new (patented) technology intended to threat silk processing by-products, converting waste into a valuable ingredient for the cosmetics industry;
  - a novel (patented) process exploiting silk scraps to produce a novel medical device for the treatment of bedsores;
  - a new business model developed for a symbiotic cluster of companies addressing a “beyond symbiosis” sustainability-enhancing approach for production districts;
- reporting and sustainability labelling is finally presented as a means companies have to exploit and communicate to their customers the achieved sustainability performances. A new label has been designed and is here proposed.

The whole discussion aimed at providing a guided reference framework that can be used by prospective adopters interested in implementing the concepts underlying the sustainable manufacturing paradigm. Some of the newly developed solutions (such as the metrics, the assessment model and part of the business model) have an almost generalist character, representing a useful operative reference for different industries and product contexts. Other applications (such as by-product treatment technologies) are, necessarily, extremely vertical and have a merely inspirational role.

Further research is recommended on many topics concerning the sustainability body of knowledge. Here we mention some of the most critical issues:

- metrics. The developed sustainability assessment tool is based on a set of metrics that have been derived from literature, revised in accordance to necessities of a specific company, and finally validated. Further evolutions in this area are recommended:
    - it is of uttermost importance to define proper sustainability metrology standards enabling, at least, infra-sector comparisons. Using specific metrics for each adopter makes results questionable, thus limiting benchmarking capabilities and improvement opportunities. A unique non-sector-specific standard should be very effective (it would allow to compare a Cola can with… a t-shirt, thus resulting in extremely worthwhile awareness creation and responsible behaviours), but several constraints have to be faced, especially concerning quality and availability of gatherable data;
    - social metrics are still unripe: indicators are available addressing the society as a whole, or complete industrial sectors, but their instantiation on a single company or on a specific product is often awkward and not causal. Further studies are needed to identify best indicators for manufacturing contexts and how to causally allocate the gathered entries on specific processes and products;
- data collection. Again in the assessment phase, some challenges are still open concerning the following aspects:
    - products are always manufactured by supply chains involving many companies. Actual product-related impacts are a thoughtful composition (sum) of sustainability-related impacts of all these actors, but several problems arise concerning data sharing, data homogeneity and comparability, data allocation methods. A unique, centralized (and anonymizing) data management platform is thus needed based on a common data model and data protection functionalities;
    - lot-wise and real-time data. A final requirement derives from a preliminary investigation performed by the author in textile companies (see the environmental auditing campaign mentioned in §2.3.3). Analysing gathered data it emerged that environmental impacts strongly vary according to the specific product/batch actually manufactured. For example, although using the same autoclave for processing the same yarn, a yarn dyeing process may require between 4 and 6 kWh/kg just varying the colour intensity. This variance is even higher when you change the colour, the kind of ink (acid, reactive or disperse dye inks) or the kind of yarn. Moreover, when a batch needs to be re-worked, its environmental impacts necessarily increase. Traditional LCA-based environmental assessment methodologies provide average values not keeping into account such variations: a product or a batch processed in a given production line results in a set of pre-calculated mean impacts. If users could monitor environmental (and, more extensively, sustainability) performances of each single batch, they would be able to dramatically increase the amount of information used to improve the overall performances of a company: dark yarns almost double the required energy to be processed, re-worked batches almost double the overall environmental impacts… are we sure we want to re-work this given lot or we can keep it as it is? Do we actually need a dark colouring or a lighter one is ok? Lot-wise impacts reporting may result into extremely virtuous behaviours and manufacturing choices;
    - Industry 4.0-compliant solutions, sensors, Cyber Physical Systems and Internet of Things technologies are rapidly widening their application contexts. These solutions may provide a significant step forward towards lot-wise and real-time data collection, thus enabling decision-making with a high level of granularity and constant improvement opportunities. A strong focus should be placed on the interaction between Industry 4.0 technologies and sustainability assessment;
- Improving entrepreneurs access to "Best Available Techniques" information data in order to support their implementation in everyday decision making. This would require the

development of sustainability-centred Design tools including Advisory capabilities: when the designer creates a new product/process, proper guidance and suggestions are provided driving towards sustainability-conscious product and process development;

- labelling. The label proposed in §4.2 should represent a good starting point for a manufacturing-wide communication of companies and products sustainability impacts, but strong validation is required in different sectors in order to reach a shared communication template towards heterogeneous stakeholders.

6 Attachments

6.1 Attachment 1: Ecoinvent impacts of a mould

Unit Process Exchanges		Match	Average [%]	Weighted Average [%]	Mean value	Unit	CML2001			IMPACT2002+ [points]			
Code	Name						GWP 100a [%]	EP [%]	HTTP [%]	CC [%]	EQ [%]	HH [%]	R [%]
From Nature	*injection moulding, RER, [kg]*												
resource/in water													
3899	Water, cooling, unspecified natural origin				0.011	m3	0%	0%	0%	0%	0%	0%	0%
From Technosphere	*injection moulding, RER, [kg]*												
chemicals/organics													
416	lubricating oil, at plant	0	0%		0.00303	kg	0%	0%	0%	0%	1%	0%	0%
443	solvents, organic, unspecified, at plant	9	8%	5.9%	0.0447	kg	8%	3%	27%	7%	3%	7%	11%
382	chemicals organic, at plant	5	2%	0.0%	0.0128	kg	2%	1%	4%	2%	1%	1%	3%
chemicals/inorganics										0%	0%	0%	0%
355	titanium dioxide, production mix, at plant	1			0.00199	kg	1%	0%	1%	1%	1%	1%	1%
314	pigments, paper production, unspecified, at plant	0			0.00756	kg	0%	0%	0%	0%	0%	0%	0%
wooden materials/processing										0%	0%	0%	0%
2526	EUR-flat pallet	3	10%	2.1%	0.00146	unit	1%	1%	4%	1%	7%	1%	1%
paper & cardboard/cardboard & corrugated board													
1703	solid bleached board, SBB, at plant	0			9.94E-05	kg	0%	0%	0%	0%	0%	0%	0%
1697	packaging box production unit	4	2%	0.2%	1.43E-09	unit	1%	1%	14%	1%	3%	2%	0%

Unit Process Exchanges		Match	Average [%]	Weighted Average [%]	Mean value	Unit	CML2001			IMPACT2002+ [points]			
Code	Name						GWP 100a [%]	EP [%]	HTTP [%]	CC [%]	EQ [%]	HH [%]	R [%]
plastics/polymers													
1830	polyethylene, LDPE, granulate, at plant	0			0.00169	kg	0%	0%	0%	0%	0%	0%	0%
1834	polypropylene, granulate, at plant	0			0.00358	kg	1%	0%	0%	0%	0%	0%	1%
electricity/production mix													
664	electricity, medium voltage, production UCTE, at grid	10	60%	59.9%	1.48	kWh	59%	91%	37%	60%	76%	72%	59%
natural gas/heating systems													
1351	heat, natural gas, at industrial furnace >100kW	8	11%	6.5%	4.21	MJ	23%	1%	8%	23%	3%	4%	20%
oil/heating systems													
1582	heat, heavy fuel oil, at industrial furnace 1MW	4	1%	0.0%	0.229	MJ	2%	0%	3%	2%	1%	3%	1%
transport systems/road													
1941	transport, lorry 3.5-16t, fleet average	9	3%	0.6%	0.142	tkm	3%	2%	2%	3%	6%	6%	2%
waste management/municipal incineration													

Unit Process Exchanges		Match	Average [%]	Weighted Average [%]	Mean value	Unit	CML2001			IMPACT2002+ [points]			
Code	Name						GWP 100a [%]	EP [%]	HTTP [%]	CC [%]	EQ [%]	HH [%]	R [%]
waste management/underground deposit													
2250	disposal, hazardous waste, 0% water, to underground deposit	0	0%		3.31E-05	kg	0%	0%	0%	0%	0%	0%	0%
waste management/sanitary landfill													
2223	disposal, municipal solid waste, 22.9% water, to sanitary landfill	0	0%		0.000895	kg	0%	0%	0%	0%	0%	0%	0%
Reference product	injection moulding, RER, [kg]												
plastics, processing													
1853	injection moulding				1	kg							
To Nature	injection moulding, RER, [kg]												
air/high population density													
2979	Heat, waste				5.33	MJ	0%	0%	0%	0%	0%	0%	0%
water/river													
4603	COD, Chemical Oxygen Demand				9.28E-06	kg	0%	0%	0%	0%	0%	0%	0%

Table 13: Unit Process Raw data analysis