

Strategic Action Line LI2: Industrial Sustainability



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Abstract Over the past 20 years, sustainability has become a central issue on the manufacturing and political agenda, and it has recently grown in importance in light of increasingly powerful and devastating climate events. In this chapter, a strategic action line to support companies is proposed to implement industrial sustainability (LI2) by means of strategies, methods and tools to implement sustainable production processes at an environmental, economic and social level, reducing dependence on the external supply of critical production resources or on resources penalized by the laws in force. Priority research actions proposed concern new solutions to reduce noxious or polluting emissions from production processes; methods and techniques for strategic product-process evaluation from a Life-Cycle-Thinking perspective; technologies and processes for the reuse, re-manufacturing and recycling of products, components and materials from used products or maintenance processes; systems and methods for measuring and implementing Sustainable Supply Chains and Closed-Loop Supply Chains.

Keywords Industrial sustainability · Design · Raw materials · Circular economy

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1 Introduction

Over the past 20 years, sustainability has become a central issue on the manufacturing and political agenda, and has recently grown in importance in light of increasingly powerful and devastating climate events. Against this background, industrial sustainability plays a fundamental role in responding to environmental, social, and economic challenges and transforming the Italian manufacturing sector.

Not only can the industry reduce its environmental impact, but it can also manufacture products that, on the one hand, solve various environmental problems and, on the other, have a limited impact during their life cycle.

This requires raising awareness on the need to transform industrial processes and conceive new products with a view to a circular economy to significantly reduce carbon emissions and improve energy efficiency, reduce, and rationalize water consumption, foster and promote resource recovery. In a circular economy, there are two types of material flows: biological, suitable to re-enter the biosphere, and technical, intended to be reused without entering the biosphere. In line with this vision, all the activities carried out in the industrial system, starting from extraction and production, must be organized in such a way that the waste produced by one sector can, after appropriate transformations, become a resource for others. In addition to material recovery, recovery of a product's functions is also very promising, as it makes it possible not only to recycle raw materials but also to avoid losing the value of the activities carried out to transform the material into a product. These changes require the introduction of new processes, new machines, and new systems, creating an in-depth review of the domestic production base, and laying the foundations for new capital goods markets in which Italy may assume a leadership role.

These systems should be consistent with the evolution of markets and enabling technologies, using technology as a competitive lever with respect to the three dimensions of sustainability (economic, environmental, and social). In this new perspective, the role of the manufacturing industry is fundamental towards the implementation of a circular factory concept. The manufacturer can design products that can be disassembled after use, integrating an increasingly larger fraction of secondary raw materials. In addition, it can manage product information along the value chain with a view to improving the efficiency of component and material recovery after the use phase, thus increasing value for money in reusing them.

In this context, the issue of “de-and re-manufacturing” is gaining ground, because of the increase in the cost of raw materials and the specific laws introduced by the European Union, which require an improvement in the recovery rate of materials. Furthermore, critical raw materials and primary resources are increasingly scarce (e.g., water) or more expensive (e.g., energy), and their current use levels are no longer sustainable. The demand for critical raw materials in the manufacturing of high-tech products is constantly increasing in Europe, their procurement causing major economic and strategic problems. It is therefore necessary to study how to use electronic waste as a source of rare materials for new technologically advanced products (Fig. 1).



Fig. 1 Strategic Action Line 2 -Industrial Sustainability

The Importance of a rational use of energy and water resources that are essential for various production processes should also be emphasized, through the promotion of practices aimed at an efficient use of these resources, reduction of consumption, reuse, and optimization of residual flows with a view to closing the cycles and recovering resources, for example from thermal flows, wastewater and sludge generated from their treatment.

In Italy, this line of intervention is aimed at the study and development of strategies, methods, and tools to implement more sustainable production processes at an environmental, economic and social level, reducing dependence on the external supply of critical production resources or on resources penalized by the laws in force. Priority research actions in this sector mainly concern new solutions to reduce noxious or polluting emissions from production processes; methods and techniques for strategic product-process evaluation from a Life-Cycle-Thinking perspective; technologies and processes for the reuse, re-manufacturing and recycling of products, components and materials from used products or maintenance processes; systems and methods for measuring and implementing “Sustainable Supply Chains” or “Closed-Loop Supply Chains”.

To encourage the change described above, it is therefore necessary to:

- promote the development of an industrial system that can implement circular economy solutions;
- enable better understanding of how sustainability can change the planning process in manufacturing firms;
- determine what changes are required at a firm’s level, to improve sustainability performance;
- identify the system-level changes required to increase sustainability;

- activate company-level experimentation through new business models and improve the ability of the industrial sector to systematically act towards the implementation of a circular economy.

Expected impact of the strategic action line: minimization of the environmental impact of manufacturing with specific focus on increasing the efficiency of natural and energy resources; control and minimization of the environmental footprint at the level of the entire product/process/system life cycle; creation of value in cross-sectoral supply chains; improved ability to recover secondary raw materials and recover the functionality of products; improved recovery and valorisation of waste; improved ability to recover products and transform waste into inputs thanks to industrial symbiosis models.

The research and innovation priorities of the strategic action line on Industrial Sustainability are:

PRI2.1—Design and development from a life-cycle thinking perspective.

PRI2.2—Monitoring of the environmental footprint of products.

PRI2.3—Systems for secondary raw materials.

PRI2.4—Technologies, processes and tools for the reuse, re-manufacturing and recycling of products, components, and materials.

PRI2.5—Modelling and simulation for the Sustainable supply chain.

PRI2.6—Models and tools for “Circular Economy”.

2 PRI2.1. Design and Development from a Life-Cycle-Thinking Perspective

Product complexity has increased in several respects, due to the expanding use of innovative materials, materials with key functions and combinations of different types of components. The technological difficulty of separating the various product components limits the development of circular economy strategies, which involve repairing, updating, and remanufacturing to prevent the waste of the precious resources contained in those products.

In this context, the design and development of products from a life-cycle-thinking perspective is one of the key issues of circular economy.

Therefore, it is of strategic importance to consider, from as early as a product's design phase, the use of recycled materials or components that can be reused after their first use phase, in line with the business alternatives offered by circular economy. The goals of this research and innovation priority are related to:

1. Tools for the analysis and design of product functions from an eco-design, design-for-environment (DFE) perspective to develop innovative products with a view to exploiting the multifunctionality of a product and its components. Applying principles of Eco-design, Design for Environment (DFE) will help design sustainable products that use fewer resources, materials, components and that can be reused or re-manufactured after their end of life;

2. Integration of advanced tools of Life Cycle Environmental Cost Analysis (LCECA), Life Cycle Cost (LCC) and Life Cycle Analysis (LCA) to enable the quantification of the potential environmental impact of designed products (in terms of resource consumption, waste and emissions) from as early as their design phase integrating these information into PLM systems;
3. Design tools with appropriate functionalities to facilitate the development of modular and repairable/upgradeable products designed for multiple use cycles and suitable to respond to evolving customer requirements, through subsequent upgrades of functions and components during the product's life; such tools should also optimize, for instance, the use of contaminants, which could be subject to limitations and prohibitions over time, support the design of product and service systems in a circularity perspective, i.e. based on production-use-repair cycles, reconfiguration, reconditioning, recycling.

Interaction with Other Strategic Action Lines

PRI2.4—Technologies, processes and tools for the reuse, de- and re-manufacturing and recycling of products, components and materials.

Time Horizon

Short-term goals (2–3 years):

- use of simplified LCA, LCECA, LCC tools to design products according to the principles of eco-design and circular economy.

Medium-term goals (4–6 years):

- definition of product design techniques to promote energy and water efficiency, the integration of recycled materials or re-generable components.
- design solutions to facilitate the development of modular and repairable/upgradeable products designed for multiple use cycles.

Long-term goals (7–10 years):

- design solutions for upgradeable products through multiple use cycles to respond to evolving market requirements.

3 PRI2.2. Monitoring of the Environmental Footprint of Products and Processes

The identification and monitoring of the environmental footprint of products and processes are fundamental in providing with a choice-evaluation element the stakeholders involved in a product life cycle (like consumers, entrepreneurs, and policy makers), especially in view of the ambitious strategies and objectives at European

level for the next few years (e.g., “Energy Roadmap 2050”, “2030 EU Climate and Energy framework”). One of the problems consists in the unavailability of a complete, uniform, updated and available data set for the entire industrial sector and the complexity of modelling particular processes to monitor all its phases. The goals of this research and innovation priority can be grouped in different categories:

- **Tools and methodologies to configure sensorized systems for the monitoring and control of the environmental impact with a greenfield and brownfield perspective** (considering machine revamping). Sensor connectivity allows the operation of the Internet of Things (IoT) and the cyber-physical systems (CPS) in which objects and machines interact with each other and with the physical world. These technologies require research and development to help control carbon emissions, energy, water, and material consumption processes, by monitoring production systems and environmental conditions. This opens up new opportunities for companies to assess system production performance more effectively, including in a perspective of LCA systems application.
- **Tools and methodologies for monitoring and controlling energy and environmental consumption and emissions during the product use phase:** recent advances in digital tracking and traceability technologies, such as digital identifiers, physical markers, or sensors, offer opportunities to capture post dynamics—sales at product, component, and raw material level. New systems are to be studied to store information on product composition and disassembly instructions and track changes to product conditions on PLCs using digital formats. Furthermore, it is necessary to study data integration models through new data acquisition systems from different sources (shopfloor, machines, products etc.), and which allow the integration of such data within tools such as LCA and LCC with the aim of analysing specific sectors, products and processes that have a specific interest in tracking the energy and environmental footprint of the entire supply chain.
- **Analysis models** that, connected to plant sensors and management systems, can acquire and handle process, consumption, and emissions data to provide dynamic product and process LCAs. The goal should be to have homogeneous production batches with a certified LCA.

Interaction with Other Strategic Action Lines

- **PRI2.1. Integration of design and development processes in a life-cycle-thinking perspective:** identification of useful indicators for LCC and LCA analyses whose parameters (in full or in part) would be monitored within the activities dealt with in PRI2.2.
- **PRI6.2 Components, sensors, and intelligent machines for adaptive and evolutionary manufacturing:** The objective of PRI6.2 is to obtain greater flexibility and adaptability of the machines in the face of changes in set-up and production, to ensure process continuity and adapt to the growing need for product customization. The PRI 2.2 is largely based on the monitoring of operational parameters that are affected by production set-up and context.

- **PRI7.3 Models and tools for monitoring production and managing production assets.**
- **PRI7.4 IIoT models and tools for factory data management:** With regard to priority 7.4, an important synergy can be created by integrating technologies for the generation (micro sensors and connected MEMS), collection, processing, integration and sharing of raw data from the field, to improve productivity.

Time Horizon

Short-term goals (2–3 years):

- Configuration of sensorized systems to support the monitoring and control of the environmental impact from a greenfield and brownfield perspective.

Medium-term goals (4–6 years):

- Methodologies to define the optimal configuration of integrated sensor systems.
- Integration of the automated traceability of environmental impact data with product and process parameters, in order to produce models and indicators that can always better describe the broader and more complex concept of sustainability also from an LCA perspective.

4 PRI2.3 Systems for Secondary Raw Materials

Today, Secondary Raw Materials (SRMs) are few, scarcely available and tend to be more expensive than “traditional” raw materials. This lack of choice, availability and price competitiveness is the first major obstacle to their diffusion and their use on an industrial scale. Furthermore, the properties and volumes of SRMs are often difficult to predict, poorly repeatable and not suitable for large-scale industrial applications. To date, no competition is possible on large numbers with traditional raw materials, due to their scarce availability, competitiveness, and performance repeatability. Most of the industrial efforts conducted to date have focused on scale economies and the optimization of production processes that assume an enormous availability of basic raw materials of the same quality over time.

The goals of this research and Innovation priority are related to:

- **Production systems for SRMs:** these systems should help increase production in terms of flow stability, quantity, quality, competitiveness (i.e., price/performance ratio) and their use in high value product manufacturing. There is not as much of a need to replace the raw materials’ production processes currently in use as to support them with new, more flexible, robust, and controlled processes that guarantee repeatable outputs and quality levels in compliance with the specifications even if they contain SRMs, and as to use tools to promote industrial symbiosis processes for a simple and systematic exchange of resources. This challenge therefore requires thinking in terms of integration about the characteristics of the products, of the production processes that transform the mix of raw and secondary

materials into finished products, and of the systems that must implement these processes. The most advanced zero-defect manufacturing and industry 4.0 techniques can be extremely useful in providing current manufacturing systems with the soundness and flexibility required for this purpose.

- **Development of systems to facilitate the acquisition, maintenance and transfer of information relating to the quality of SRMs** with a cross-sectoral approach, to attain certification levels for the properties of these materials that are comparable with those of raw materials.
- **Innovative solutions and products based on SRMs for sustainable materials and processes.** Development of new materials or advanced solutions based on industrial waste, creation of synergies for the development of new materials created, for example, from the recycling of glass, fibres, or construction products. The goal is to develop a new model for the use of SRMs, by connecting different industries and decision makers, to track and model SRM flows, and share knowledge and information along the value chain.
- **New applications for SRMs:** almost all the process chains are “market driven”, so it is essential that the markets know and appreciate products made with SRMs, to promote their diffusion. The success of products that are, even if not overtly, made entirely or partly of SRMs significantly increases recourse to SRMs in production processes. For the market to receive, evaluate and appreciate/accept products of this kind, it is essential that designers or product development managers begin to introduce this type of raw material as widely as possible.

Interaction with Other Strategic Action Lines

- LI1 Customized product systems: smart materials
- PRI2.1. Integration of design and development processes in a life-cycle-thinking perspective: integrating product-process-system modelling for eco-efficiency from a life-cycle-thinking perspective is one of the keys to encouraging the transition to circular economy and can only increase the overall impact of the roadmap
- PR2.5 Technologies and tools for intelligent re-and de-manufacturing
- PR2.7 Business models for Circular Economy

Time Horizon

Short-term goals (2–3 years):

- Integration of SRMs in high value-added products.

Medium-term goals (4–6 years):

- Ensure the acquisition and transfer of information relating to SRMs.
- Tools for the design of products based on SRMs.

Long-term goals (7–10 years):

- Study of new integrated product-process-system schemes in order to support the implementation of a large-scale manufacturer-centric and repeatable circular economy model.

5 PRI2.4 Technologies, Processes and Tools for the Reuse, De- and Re-Manufacturing and Recycling of Products, Components and Materials

Complex products, consisting of several materials significantly different from each other (for example metals and polymers) are particularly difficult to recycle through mechanical processes, unless one is prepared to forgo the properties of individual materials and significantly downgrade them. The technical difficulty of separating constituent materials or the excessive cost of doing so suggests a different approach for the management of these types of products/materials.

In metal recycling, the greatest criticalities are observed with respect to precious metals and metals defined as critical. The system for closing the processing cycle according to the principles of Circular Economy is still incomplete for these metals, unlike what happens for ferrous and non-ferrous metals, which can count on a consolidated supply chain. In fact, the infrastructures for the recovery and purification of these materials from industrial by-products and waste and from technological waste (e.g. lithium batteries, permanent magnets, WEEE, red sludge) are still very limited in Italy. The state of the art is that hydrometallurgical technologies are the most suitable to pursue these objectives, for which investments are necessary in order to open new branches of research.

The objectives of this research and innovation priority focus on de- and re-manufacturing processes for the recovery of functionality and/or intrinsic value of materials from end-of-life products, by-products, and industrial waste. To this effect, the following actions have been identified:

- **Disassembly and re-assembly solutions for functionality recovery:** the goal is to focus on innovative and complex high-value end-of-life products, for which priority must be given to functional recovery with a focus on reuse. In this context, it is necessary to develop innovative technological solutions for automated disassembly with high levels of automation, control, inspection, testing, regeneration, and reassembly. In a subsequent step, these de- and re-manufacturing solutions will have to include a combination of design and production systems, with a view to a new integrated manufacturing paradigm that can ensure greater efficiency and sustainability;
- For metal materials, it is necessary to develop processes that can improve **selectivity, characterization, sorting, and separation**. They are currently widespread in industrial contexts as recycling business options, but not sufficiently optimized. For example, it would be desirable to study how the synergistic use of advanced

optical multi-sensor systems, the use of robotics solutions, including collaborative ones, the use of multi-physical separation processes, in synergy with modern collection techniques, modelling, data analysis and control deriving from industry 4.0, for example the use of feed-forward control systems and cyber-physical systems, can be extremely efficient in complex context;

- For polymeric materials, on the other hand, it is necessary to **research new systems and methods for the integration of** advanced chemical (solvolysis), thermochemical (pyrolysis) and mechanical (defragmentation) **technologies** that could be a valid solution to carry out a depolymerization in such a way as to obtain polymer fractions and/or polymer chains, which would be the elementary building blocks of a new chemistry based on the formulation and reaction of these organic decomposition products. Similarly, it is possible to design polymers with chemical constituents that more easily undergo depolymerization processes by solvents (design for solvolysis) or pyrolysis (design for pyrolysis). These processes, together with mechanical ones, help us extend material recoverability to almost all the products/materials commonly in use today;
- In addition, in production processes aimed at **recovery and enhancement of industrial waste and by-products**, particular focus is to be given to biological processes for circularity. Production processes concerning, for example, agri-food/agro-industrial productions generate a large amount of waste, by-products and wastewater that can be part of new transformation processes and be fully exploited even in production sectors that are very different from those that originated them (Pharmaceuticals, Cosmetics, Construction).

Interaction with Other Strategic Action Lines

- PRI2.1—Integration of design and development processes from a life-cycle-thinking perspective. Technologies, processes and tools for the reuse, re-manufacturing and recycling of products, components and materials should be developed with support of design processes (and vice versa) in order to maximize the results of the industrial sustainability roadmap.
- PRI2.6—Business models for Circular Economy. Need to develop and test suitable business models that allow the large-scale diffusion of economically sustainable factories, including “small” size or mobile ones, and the aforementioned de- and remanufacturing techniques.

Time Horizon

Short-Term Goals (2–3 years):

- Creating appropriate infrastructures for the demonstration of scientific research applications (e.g. laboratories / workshops for the construction of prototypes, pre-industrial scale plants, networks, etc.).
- Methodologies for the optimization of de- and re-manufacturing processes.

Medium-Term Goals (4–6 years):

- Developing processes to improve selectivity, characterization, sorting, and separation, which are currently widespread, but not sufficiently optimized, in industrial recycling business contexts.
- Developing technological solutions and de- and re-manufacturing processes to recover the functionality and/or intrinsic value of materials from complex end-of-life products, by-products and industrial waste, according to an upcycling approach.
- Increasing the degree of automation of de- and re-manufacturing systems.

Long-Term Goals (7–10 years):

- Designing production and de-production systems jointly, with a view to a closed-loop reuse.

6 PRI2.5 Modelling and Simulation for the Sustainable Supply Chain

Industrial sustainability is a complex concept that requires the combination of different players (companies, institutions, governments, etc.), it impacts different sectors and presents a non-linear and non-rational behaviour. To describe these interactions at best, one needs to devise an approach that combines both the bottom-up (industrial and business dimensions) and the top-down (political) perspectives. Traditional approaches (such as the General Equilibrium Model, the Input–Output analysis) cannot fully grasp these dynamics. For this reason, the approaches developed in recent years start with the theory of Complex Adaptive Systems (CAS) and are based on a combination of different approaches, giving rise to hybrid models that allow for a responsible management, from a social, environmental, and economic point of view, of all procurement, production, and distribution processes.

Sustainable supply chains can exploit the benefits generated by hybrid modelling approaches to support decisions, achieve quality, efficiency and productivity goals and solve specific sustainability problems such as those pointed out in the Sustainable Development Goals (United Nations, 2015). When it comes to selecting or designing a sustainable supply chain, hybrid models are considered particularly appropriate for the way they manage flexibility in their analyses.

The goals of this research and Innovation priority are:

- **Methodologies and models based on hybrid approaches:** These models based on data collected from different sources along the production chain (production process, design, distribution, use, etc.) are meant to:
 - o Analyse the dynamics and impacts of sustainable business models on supply chains (including the analysis of the industrial symbiosis potential);
 - o Evaluate the impact of government laws and incentives that can influence the behaviour of supply chains from a sustainability point of view;
 - o Provide sustainability metrics to support decision making;

- o Provide cooperation patterns between companies and public bodies to enable the improvement and optimization of production flows;
- o Provide indications and metrics related to the social dimension of sustainability, including information on the impact of physical-cognitive ergonomics on industrial processes' operators.
- **Models and tools for cross-sector supply-chain design:** Sustainability issues are so complex that no company can tackle them on its own. To cope with the pressures from governments and corporations, companies seek to improve the management of their supply chains from both a social and an environmental point of view. New modelling approaches are necessary to support supply chains through a cross-sector cooperation (for example, industrial symbiosis). One of the challenges is to model these networks from the point of view of the value creation process (design problems, distribution problems, types of partnerships and level of interaction between companies/supply chains).
- **Models for forecasting product and material return flows (based on use, average life of the products, consumer attitudes):** Implementing sustainability strategies in manufacturing environments gives rise to several risks, including mismatches between fluctuations in demand, supply, and value of components used, causing uncertainty about costs and return on investment. A further issue is lack of information on the condition, availability, and location of resources in service. The gradual spread of technologies based on the principles of Industry 4.0 offers the opportunity to overcome some of these obstacles to the full implementation of sustainability principles in the manufacturing sector. In fact, data driven models (based on the use of technologies such as simulation, digital twins, IoT and sensors) can handle information such as product conditions and consumer habits, facilitating the study of forecast models for the return flows of products and materials.

Interaction with Other Strategic Action Lines

LI5: Innovative production processes.

LI6: Evolutionary and resilient production.

LI7: AI, Digital Platforms, Cyber-Security.

Time Horizon

Short-term goals:

- Hybrid approaches for sustainable supply chain management.

Medium-term objectives:

- Models and tools for cross-sector supply chain design.
- Models for forecasting product and material return flows (based on use, average life of the products, consumer attitudes).

7 PRI2.6 Models and Tools for the “Circular Economy”

Circular economy is emerging as an economic rather than a purely environmental strategy that requires not only a change in production processes, but also in value creation activities, and consumption. This research and innovation priority aims to promote the development and implementation of tools and models for supporting circular economy, by reducing demand for resources and raw materials, increasing the value of scraps and waste, and arranging for their recovery and reuse. The main goals of this research and innovation priority are:

- **Models for the management of discrete products in a circular economy perspective:** Development of appropriate models for the management of return flows of materials; models for the management of reverse logistics processes; methods to handle integration between organizations, suppliers and customers which, based on the information collected by the various players involved, can manage and direct the flows to recovery, recycling and transformation centres.
- **Models for the management of industrial symbiosis:** Models for the integrated management of shared resources in continuous processes (materials, water, by-products, waste) according to a cooperative approach, in which the output of a company can be used as input by a third-party for its manufacturing process. New models are needed to support industrial symbiosis, for the diagnosis, use and management of resources at company and at system level, taking into account the various local contexts.
- **Models for the development of circular economy strategies in SMEs:** business models, strategies, and tools developed specifically for SMEs, to support them in the implementation of the circular economy paradigm and for an easy definition of a “virtuous” supply chain of raw materials and waste.
- Solutions to actively support **conscious consumption by end users:** tools that, based on the data collected during the product’s use phase, encourage an approach to consumption based on circular economy models, favouring actions such as upgrades, repairs, maintenance, product/function sharing with other users.
- Actions for fostering collaborative and inclusive approach such as **networks** and **citizen engagement:** models and tools based on the territorial analysis that can encourage a co-design of circular economy solutions, dialogue and good practices exchange.
- **Circularity measurement tools:** performance assessment systems at both factory and supply-chain level to monitor and evaluate the level of implementation of circular economy and support relevant decisions, through suitable indicators to overcome the limits of current assessment systems, integrating indicators at the macroeconomic level (countries, regions), and indicators at the micro level (products, companies).

Interaction with Other Strategic Action Lines

LI15: Processi produttivi innovativi.

Time Horizon

Short-term goals:

- Circularity measurement tools.
- Solutions to actively support informed consumption by end users.

Medium-term objectives:

- Models for the management of discrete products in a circular economy perspective.

Management models for industrial symbiosis.

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